Technical Report

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Seafloor Sediment Composition in Massachusetts Determined Using Point Data

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Commonwealth of Massachusetts
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Paul Diodati, Director

Abstract: Grab samples, video data, photographic data, and trawl hang data from 47 seafloor survey datasets were uniformly classified using a modified Folk code and used to create a Thiessen polygon interpolation of the distribution of sediment in Massachusetts territorial waters. Sandy bottom represented 55% of the area mapped, muddy bottom 21%, gravelly bottom 16% and hard bottom 8%. It is assumed that these results under-represent harder bottoms since 91% of the dataset used techniques that could not adequately sample coarser grains such as pebbles and cobbles. The data quality of the 16,657 individual points used for the interpolation was assessed using an index that incorporated age, sampling technique, analytical technique, and data density. Forty-five percent of the mapped area had the lowest data quality and 11% had the highest data quality. There is not enough high quality data to conduct reliable statewide mapping of substrate with only point data. However, several harbors and small portions of Massachusetts and Cape Cod Bays do have high quality datasets.

Introduction

There is a rich history of seafloor sediment grain size data collection in Massachusetts waters, but consolidation and analysis of these data has only recently been made easily accessible to the management community with the advent and spread of GIS technology. Seafloor sediment grain size is critical baseline information for the mapping of both mineral and biological resources. There is evidence that sediment grain size and biological community are well-correlated (Laidig et al. 2009; Zajac et al. 2000; O'Connell and Carlile 1993; Weston 1988) and that hard bottom seafloor habitats are linked with higher juvenile survivorship for some demersal fish species (Lindholm et al. 2007; Lindholdm et al. 1999; Gotceitas and Brown 1993; Stephens et al. 2006). Therefore, seafloor sediment grain size is frequently used in concert with other data types such as bathymetry to develop marine habitat maps (Romsos et al. 2008; Kostylev et al. 2001; Stewart and Hargrave 2002; Greene et al. 2010; Zajac et al. 2000; Banner and Schaller 2001). A necessary first step in the mapping of sediment grain size is assembling existing data and analyzing its quality. This report covers the processes used to assemble, map, and assess the quality of sediment data available in Massachusetts territorial waters. Several individual grain size datasets were combined in a standard database format to create a seafloor grain size distribution map for seafloor habitat studies and ocean planning exercises occurring in Massachusetts. A quality assessment technique was developed to identify limitations of the seafloor grain size interpretation throughout state waters.

Methods

Database format. An Excel spreadsheet format was used to contain the multiple datasets identified through literature searches and interactions with colleagues conducting sediment mapping efforts in Massachusetts. Because some of the existing datasets were not available online or in the same format, all data sources were reformatted and consolidated into a single database that is maintained by the Massachusetts Division of Marine Fisheries (*MarineFisheries*) in its south coast field office. Data were collected from shore to a 10 km buffer of the state territorial boundary. The data were analyzed for consistency and replicate samples were removed whenever they could be clearly identified.

Classifying sediment types. The Folk and Shepard classification codes (Folk 1954, Shepard 1954) were calculated for the individual data records using the SedClass tool (Poppe et al. 2003). Some records had values for percent gravel, sand, silt, and clay that did not add up to 100%. For those samples, the classification codes were maintained from the original dataset or they were assessed based on the dominant grain size type. Each record was further coded by a numeric code based on two simplified versions of the Folk code (Figure 1) to enable gridding. The dataset maintains these interpretation codes in order to address various user needs. The Folk code is more useful for seascape characterization and biological interpretations than a grain size scale (such as Wentworth or phi) since it provides a descriptive, easily interpreted product that maintains a significant portion of the original information in a straightforward way. The U.K.

SeaMap programme used the Folk code with four classes for seafloor characterization (Connor et al. 2006). All datasets have Folk code values, but only lab-processed grain size samples have both phi and Folk values. A simplified Folk code with four classes was used for the mapping reported herein (Figure 1).

sampling, or had other variables that indicated redundant samples. If the samples differed in any way such that a conclusive determination of redundancy could not be made, the samples were kept (because of the possibility that some samples were taken in the same location at different times).

A.

mm	phi(Ø)	Size Class
0.5	1.0	Coarse sand
1.0	0.0	Very coarse sand
2.0	-1.0	Very fine gravel
4.0	-2.0	Fine gravel
8.0	-3.0	Medium gravel

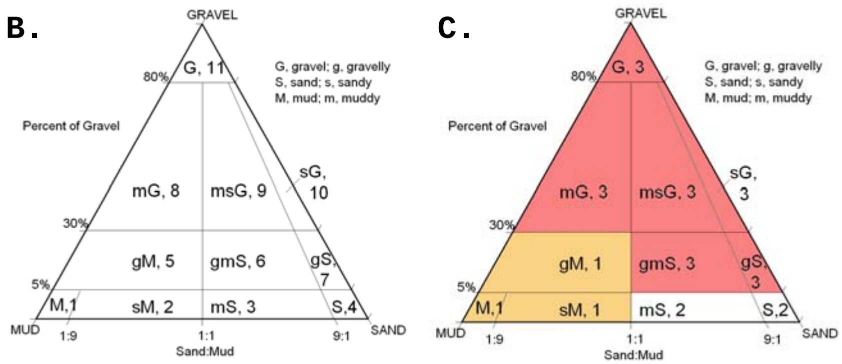

Figure 1. The grain size scales available in the grain size dataset. A.) A portion of the full phi scale used in the dataset. B.) The Folk classification with 12 classes. The text code is followed by the numeric code assigned in the dataset; anything larger than gravel is Hard, 12. C.) The Folk classification with four classes; anything larger than gravel is Hard, 4. The colors identify different Folk text codes that were given the same numeric code in the dataset.

<u>Sediment datasets used.</u> There were five data sources representing 47 individual surveys consolidated for this effort (Table 1):

1. U.S. Geological Survey (USGS) usSEABED;
2. Massachusetts Coastal Zone Management (CZM) mapping cooperative with USGS;
3. Massachusetts *Marine Fisheries'* stratified ventless lobster trap survey; resource assessment survey;
4. U.S. Environmental Protection Agency (EPA) National Coastal Assessment;
5. Massachusetts Water Resources Authority's (MWRA) monitoring program.

Points within Massachusetts territorial waters including a 10 km buffer were extracted from the above datasets (Figure 2). Overlapping data points were checked to see if they had different dataset keys, different grain size values, different dates of

USGS usSEABED. The most consolidated and comprehensive dataset is the usSEABED dataset. This dataset was compiled by the USGS's National Benthic Habitats and Marine Aggregate Resources and Processes Projects and includes 40 individual data sets collected by the USGS and other research groups across the entire coast of the United States (Reid et al. 2005). This dataset includes samples processed in the USGS sediment laboratory and datasets compiled from gray literature or unpublished sources dating back over a century. Both the extracted and parsed datasets were used.

CZM-USGS. In 2003, the CZM-USGS Seafloor Mapping Cooperative was established to comprehensively map the topography and geology of the seafloor in Massachusetts. To date, nearly 1450 km^2 of the seafloor environment is mapped from the New Hampshire border to Cape Cod Bay and in Buzzards Bay (W. Barnhardt, personal communication[1]). The project collects depth and backscatter data using an interferometric multibeam system

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[1]2009, USGS principal investigator of CZM-USGS Seafloor Mapping Cooperative.

Table 1. Description of datasets used in this report.

Dataset	Survey	Description	Year	Number of samples
MWRA	MWRA Data-GRNSZ	Laboratory analysis of grain size grabs	1991-2008	73
	MWRA Data-SPI	Sediment profile imaging data	2007	28
EPA	National Coastal Assessment, Massachusetts	Laboratory analysis of grain size grabs	2000-2001	82
	National Coastal Assessment, Rhode Island	Laboratory analysis of grain size grabs	2000-2001	8
MarineFisheries	Stratified Ventless Trap Survey	Photographs	2006-2007	1723
	Resource Assessment Trawl Survey	Otter trawl hangs	1978-2007	115
USGS sediment lab	USGS-CZM mapping cooperative; Ipswich and Gloucester	Laboratory analysis of grain size grabs	2004-2006	423
USGS usSEABED	Office of Naval Research, Cape Henlopen cruise off Martha's Vineyard	Laboratory and visual analysis of grain size grabs and vibracores	2002	47
USGS usSEABED & USGS OFR 00-427	Western Massachusetts Bay USGS cruise ISBL99024	Laboratory analysis of grain size grab samples	2000	186
USGS usSEABED	U.S. EPA: Environmental Monitoring and Assessment Program (EMAP)	Laboratory analysis of grain size grab samples	1991-2000	38
USGS usSEABED	USGS/WHOI CONMAR analyses, part 2	Laboratory analysis of grab, core, and dredge samples	1971	489
USGS usSEABED & USGS OFR 03-001	Barnhardt96-98 Maine Inner Continental Shelf Sediment Data	Grain size grab samples	1984-1991	118
	Anan71 Neritic sediments of the Merrimack Embayment		1971	116

Table 1. Description of datasets used in this report (continued).

Dataset	Survey	Description	Year	Number of samples
USGS usSEABED & USGS OFR 00-358	East Coast Sediment Texture Database	Laboratory analysis of grain size grab and core samples	1967-1999	1773
USGS usSEABED	Hersey67	Photographs	1967	1
USGS usSEABED, National Geophysical Data Center (Deck41)	U.S. Navy Hydrographic Office: National Oceanographic Data Center (NODC) Ref. 501	Multiple sampling or analytical techniques	1964	1
	U.S. Coast and Geodetic Survey: (NODC) Ref. 503		1964	147
	Hough, J.L., Sediments of Cape Cod Bay, Massachusetts. (NODC) Ref. 512		1951	155
	Cornell University: Final Harbor Report New York Harbor Channel Study Data. v. 3 (NODC) Ref. 514		1951	4
	Hough, J.L., Sediments of Buzzards Bay, Mass. (NODC) Ref. 515		1934	189
	Parker, F.L. Foram. distribution on the Long Island Sound - Buzzards Bay area. (NODC) Ref. 517		1942 & 1948	43
	Moore, J.R. III Bottom sediment studies Buzzards Bay, Mass. (NODC) Ref 519		1956	148
	U.S. Coast & Geodetic Survey (NODC) Ref 601		1966	92
	L.F. Lewis Speed of sound in unconsolidated sediments of Boston Harbor, Mass. (NODC) Ref 603		1966	1

Table 1. Description of datasets used in this report (continued).

Dataset	Survey	Description	Year	Number of samples
USGS usSEABED, National Geophysical Data Center (Deck41)	Bureau of Commercial Fisheries: Dredging and hydrographic records of the U.S. Fisheries steamer Albatross 1911- 1920. (NODC) Ref 617	Multiple sampling or analytical techniques	1920	1
	Smithsonian Institution: bottle samples from 1844-1884. (NODC) Ref 619		1884	5
	Massachusetts Department of Public Works: Proposed dredging New Bedford Harbor, vicinity of South Maritime Terminal, New Bedford. (NODC) Ref 641		1966	31
	Smithsonian Institution: Coded geology NODC forms coded by Smithsonian Institute, Sedimentology Laboratory. (NODC) Ref. 781		1895	56
	Smithsonian Institution master sediment data file		1963-1985	1658
USGS usSEABED & USGS OFR 03-001	Folger75 Bottom Sediments -Cape Ann to Casco Bay	Grain size grab samples	1975	14
	GOMCSDB Gulf of Maine Contaminated Sediments Database		1970-1996	1082
	Hough40 Sediments of Buzzards Bay, Massachusetts		1934	36
	Hough42 Sediments of Cape Cod Bay, Mass.		1935	155
	Meisburger76 Sediments of Western Mass. Bay		1976	43
	Mencher68 Sediments of Boston Harbor		1968	149

Table 1. Description of datasets used in this report (continued).

Dataset	Survey	Description	Year	Number of samples
USGS usSEABED & USGS OFR 03-001	MNHACoE Army Corps Sediment Data from Maine and New Hampshire	Grain size grab samples	1950-1993	38
	Moore63 Sediments of Buzzards Bay		1963	150
	MWRA Massachusetts Water Resources Administration Sediment Data		1991-1994	231
	Reid82 Northeast Monitoring Program Sediment Descriptions		1984	2
	Rowe78 Sediment data from Northwest Atlantic Ocean		1978	1
	Schlee73 Sediment data from Cape Ann to Cape Cod, Mass.		1973	338
	Stetson38 Sediment data from transects off the Eastern U.S.		1938	49
	Ward01 Sediment data from New Hampshire		1997-2002	18
	Wigley61 Bottom Sediments of Georges Bank		1957	1
	Wigley65 Fisheries Sediment Data		1965	3
	Willett72 Boston Harbor and approaches		1972	76
	NOSGOM NOS Cartographic Codes for Bottom Character		1931-1985	9074

concurrent with seismic data collection (USGS 2006). Photo, video, and grab samples are taken to groundtruth the backscatter data and develop surficial geology maps. For this report, analyzed photographic data were not available, so only grab samples were included.

MarineFisheries Stratified Ventless Trap Survey. The *MarineFisheries* Invertebrate Fisheries Program is responsible for overseeing the resources and regulations concerning the three American lobster (*Homarus americanus*) stock units that populate Massachusetts. In order to examine correlations between seafloor type, depth, and various life history stages of lobster, the Invertebrate Fisheries Program conducted a ventless trap survey in Buzzards Bay and Massachusetts Bay in 2006 and 2007. The survey was stratified by depth and sediment types and stations were randomly selected within each stratum (Glenn 2007). Bottom sediment was assessed by taking multiple still-photos using a frame-mounted drop camera at 140 sam-

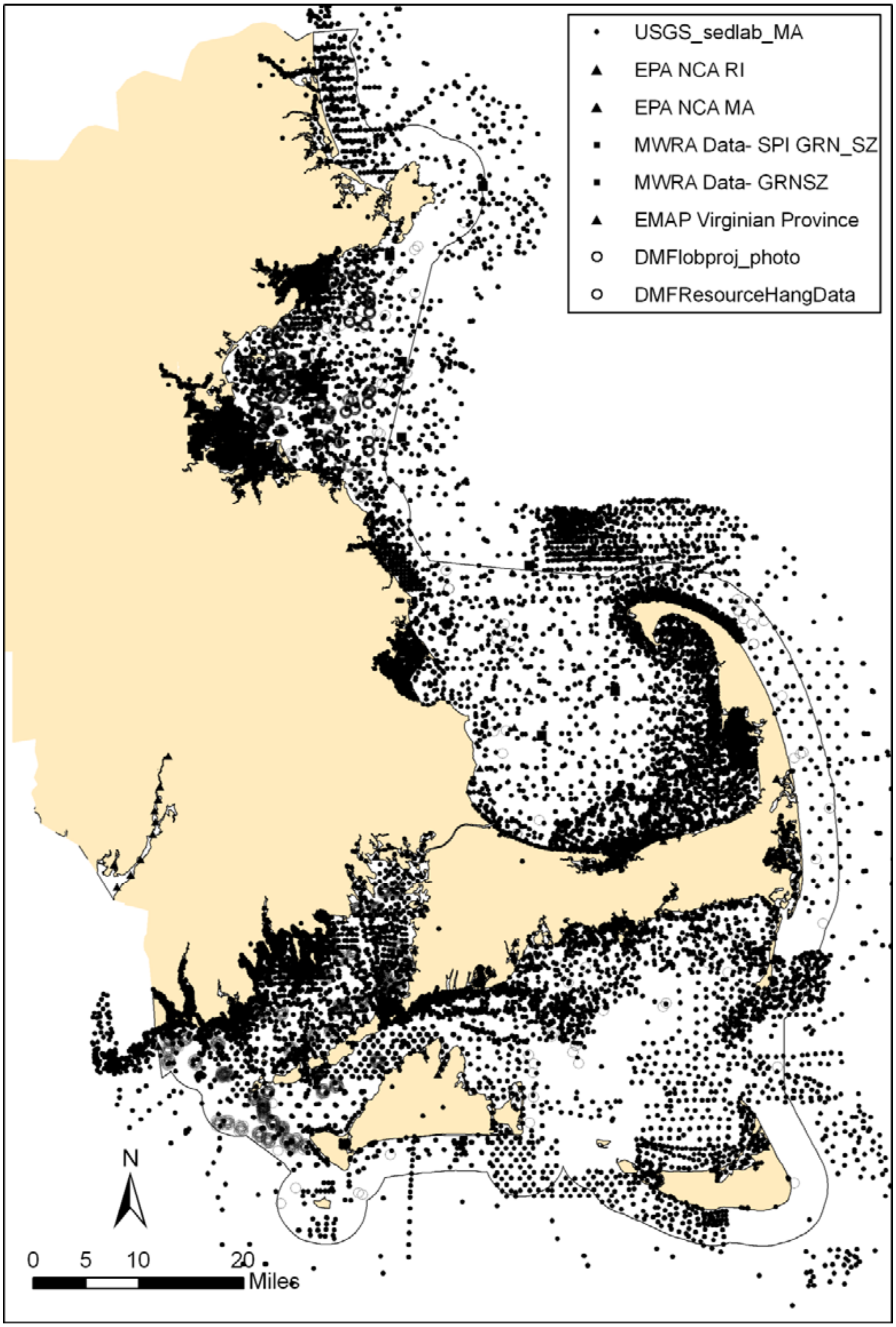

Figure 2. Surficial sediment points in Massachusetts and vicinity. A) usSEABED datapoints, B) additional datasets.

pling sites (Figure 3). The image with the best clarity was selected as representative of the station. Average percent cover for each sediment-type was visually analyzed on each digital photo using a grid overlay.

MarineFisheries Resource Assessment. The *MarineFisheries* Resource Assessment Survey has been surveying demersal fish resources every May and September since 1977 (King et al. 2010). This trawl survey is stratified by depth and stations are randomly selected within each stratum. The catch is weighed, counted, and sexed for every tow. In some cases, tows are unsuccessful and are aborted. Tows can be aborted due to the gear hanging on hard bottom, fixed fishing gear, and obstructions. When the reason for the hang could be ascertained and was relevant to sediment type, we included the point and assigned the relevant Folk code value (Table 2).

EPA National Coastal Assessment. The U.S. Environmental Protection Agency (EPA) ran the Environmental Monitoring and Assessment Program (EMAP) from 1990 to 2006 to monitor and assess the status and trends of national ecological resources (EPA 2008). The ongoing National Coastal Assessment (NCA) comprises all the estuarine and coastal sampling done by EMAP with the

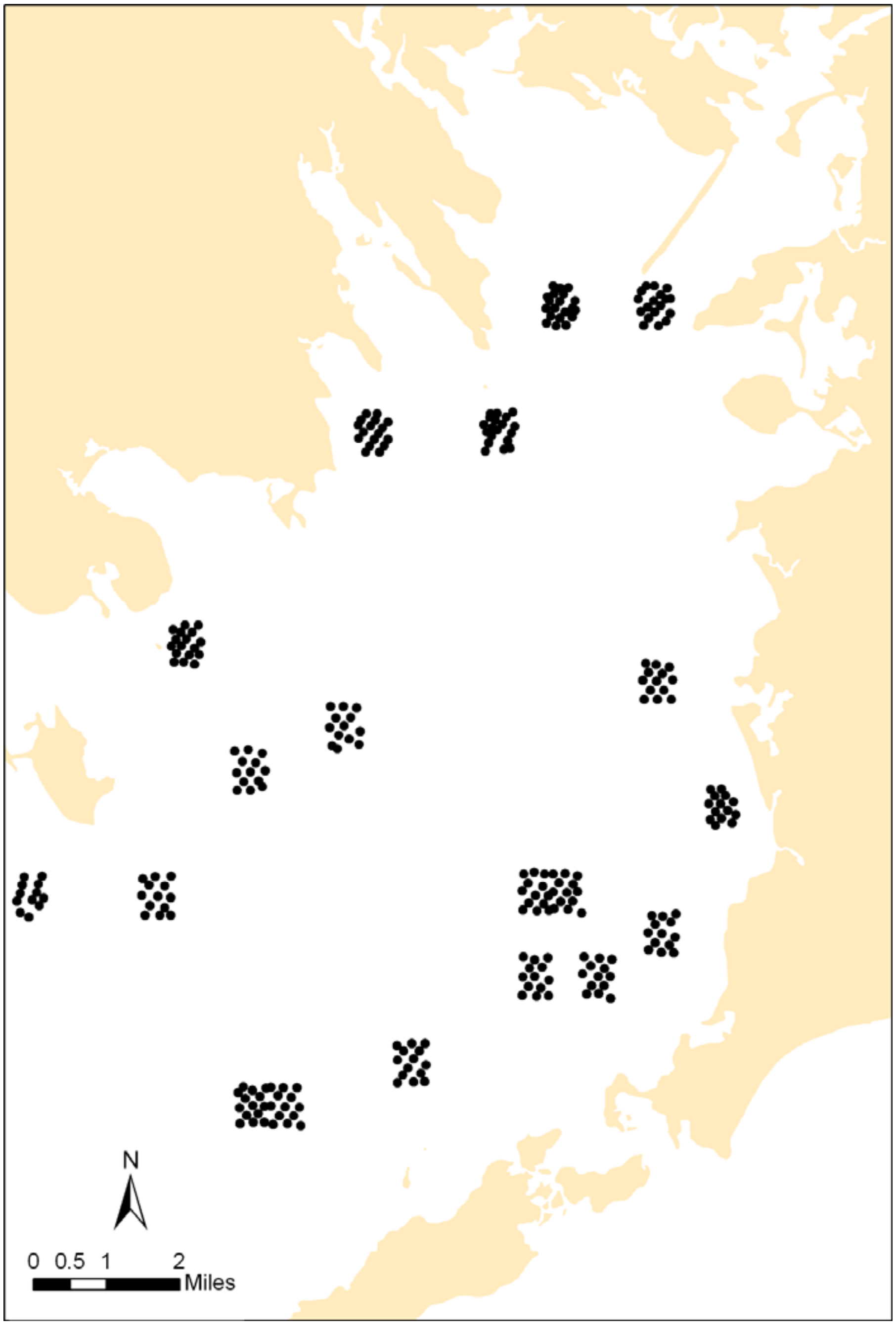

Figure 3. *MarineFisheries* Stratified Ventless Trap Survey stations in Buzzards Bay. Multiple still-photos were taken at each randomly selected site.

Table 2. Description of aborted tows and the Folk Code assigned to designate sediment type.

Trawl Database Code	Description	Assigned Folk Code	Number of Samples	Notes
hh	Hang	n/a	193	Not used since sea-floor type could not be reasonably assumed
hb	Hard Bottom	Hard	69	
ob	Obstruction	Hard	13	
hh/hb	Hang/Hard Bottom	Hard	24	
hh/ob	Hang/Obstruction	Hard	5	
hh/mu	Hang/Mud	Mud	2	
hh/sw	Hang/Sand Waves	Sand	5	
hh/wd	Hang/Weed	n/a	1	Not used since sea-floor type could not be reasonably assumed
hh/co	Hang/Coral	Hard	1	
Hh/hb/ob	Hang/Hard Bottom/Obstruction	Hard	2	
Hh/hb/np	Hang/Hard Bottom/ Net Problem	Hard	1	
hb/ob	Hard Bottom/Obstruction	Hard	6	
hb/sw	Hard Bottom/Sand Waves	n/a	1	Not used since sea-floor type could not be reasonably assumed
hb/np	Hard Bottom/Net Problem	Hard	1	
fg/hb	Fixed Gear/Hard Bottom	Hard	2	
fg/ob	Fixed Gear/Obstruction	n/a	1	Not used since sea-floor type could not be reasonably assumed
fg/np	Fixed Gear/Net Problem	n/a	1	Not used since sea-floor type could not be reasonably assumed
fg/ob/hb	Fixed Gear/Obstruction/Net Problem	n/a	1	Not used since sea-floor type could not be reasonably assumed
np/hb	Net Problem/Hard Bottom	Hard	1	
np/ob	Net Problem/Obstruction	n/a	2	Not used since sea-floor type could not be reasonably assumed

purpose of monitoring the condition of the nation's coastal resources by creating an integrated, comprehensive monitoring program among the coastal states (EPA 2010). These data include water column data, sediment contaminant and toxicity data, and benthic macroinvertebrate and demersal fish community and body burden contaminant data. The sediment grain size data were extracted for the purposes of this report. There are 38 EMAP sites in Massachusetts that were sampled in 1990-91. There were also 90 National Coastal Assessment sites sampled in 2000-01. The usSEABED dataset contained four of the EMAP data points.

MWRA Grain Size/SPI Grain Size. The Greater Boston Area sewage treatment facility is overseen by the Massachusetts Water Resources Authority (MWRA). The treatment system includes secondary treatment of sewage and the treated effluent is carried to a diffuser system located 9.5 mi offshore in Massachusetts Bay. Water and sediment quality monitoring is a component of this agency’s activities. Monitoring began in September 1991 and is conducted twice a year, in April and August, to track changes in the sediment and infaunal communities. In 2003, sampling was reduced to once a year in August; in 2004, an additional station was added in the inner harbor near a Combined Sewer Overflow (CSO). Sampling is conducted using both traditional grab sampling and a sediment profile imaging (SPI) camera to examine sediment and infaunal benthos at eight grab stations and 60 SPI stations throughout Boston Harbor (Maciolek et al. 2008). There are 29 stations around the outfall sites in Massachusetts Bay and Stellwagen Bank and two in Cape Cod Bay (Maciolek et al. 2008).

Gridding and interpolation. The point data were gridded into 250 m^2 grid cells to be consistent with other mapping efforts occurring in Massachusetts. Where multiple points fell within a grid cell, the point with the highest data quality value (as explained below in the Scoring System section) was used.

The simplified Folk code grain size scale was interpolated to create a state-wide coverage of grain size that enables landscape-scale inferences and allows multiple-scale correlations. Interpolations are very common in the geologic literature and typically rely on weighted interpolation methods, including inverse distance weighted (IDW), natural neighbor, and kriging methods (e.g., Maljer and Gunnink 200; Leecaster 2003; Verfaillie et al. 2006; Bobertz and Harff 2004; Harris and Stokesbury 2010). Interpolation requires positive spatial autocorrelation, meaning near things are more related than distant things (Tobler 1970). Spatial autocorrelation was tested on this sediment dataset using the Global Moran's I test in the ArcGIS Spatial Statistics toolbox. Inverse distance conceptualization with a Euclidean distance and no standardization were used. The test returned a value of 0.568 with a z-score of 51.51 standard deviations indicating a <1% likelihood that the clustered pattern could be the result of random chance. Therefore, the dataset is spatially autocorrelated.

Weighted interpolation techniques are most appropriately done on datasets with continuous data values, where there is a linear relationship from one class to the next. For example, in topography, the value of two meters must lie between one meter and three meters. The sediment dataset was binned into values that are increasingly coarse, but there are still inconsistencies. For example, gravelly-mud is ranked as one, and muddy-gravel is ranked as three. In fact, those two sediment types may be quite similar and should be considered adjacent on a linear scale. Instead, sandy sediments, ranked as two, fall in between. Therefore, weighted interpolation methods are not appropriate for mapping surficial geological mapping.

The simplest and most statistically sound approach was to use the tessellation method, which typically underlies IDW techniques (Sibson 1981). Tessellation creates a surface whereby polygon line segments are drawn such that all the points in the plane are equidistant to the adjacent points. Each polygon corresponds to one of the samples. The polygons are known as Thiessen or Voronoi polygons or Dirichlet cells. This is the most straightforward interpolation tool to use when dealing with non-continuous data in that it does not introduce any arbitrary values (Bonadonna and Houghton 2005), which can further confuse the quality assessment process and classification efforts. Thiessen polygons were constructed using the Create Thiessen polygons tool in ArcInfo.

Since careful validation can result in robust interpolations using weighted methods (Leecaster 2003; Me´ar et al. 2006), these will be tested in future work.

Data quality index. Since an interpolation is being used to achieve statewide coverage for the grain size distribution, illustrating the quality of the underlying data and the resulting interpolation is necessary. We considered simply removing large volumes of data with potentially questionable data quality. However, in some areas those poorer-quality samples were the only available information, so we couldn't ascertain whether or not they were, in fact, inaccurate. Therefore, we decided to establish a method to calculate a data quality value for each sample point. A data quality index was also established to account for the effects of data density on data quality.

The data quality assessment was based on three components: age of the sample, analytical technique employed, and sampling device used. Data density, as utilized in the data quality index, was determined by the size of the Thiessen polygon. Examples of similar data quality assessments include the European MESH framework (MESH 2007) and the data quality assessment associated with habitat mapping efforts in the Pacific Northwest (Romsos et al. 2008).

Age Quality. The age of the sample was determined to be the most important factor for two reasons. First, the age of the sample is directly correlated to the potential accuracy of the horizontal position of a sample due to changes in positioning methods over time. The location of a sample governs the interpretation of the sediment type in that area of the seafloor. Therefore, if the horizontal accuracy of a sample is questionable, doubt in the interpretation is introduced. Second, sediment type changes over time in a somewhat unpredictable manner. Sediment stability, especially in dynamic coastal environments, is variable. Therefore, sample age was a primary determinant of quality. The age ranges were defined by the advancements of positioning technology and the most recent samples (Table 3).

Prior to the introduction of radio telemetry navigation systems, all navigation was conducted by dead reckoning using compass and time. During World War II, the long range navigation (loran) system was built and was used for both vessel and aircraft navigation. Following the war, loran systems, including Loran-A and Loran-B, were rapidly incorporated into both recreational and commercial maritime navigation. Loran-C, with considerably superior accuracy and range than A or B (and other improvements including Cyclan and Cytac), was introduced in 1957 (USCG 1992). Because we could not identify when Loran-C was introduced into scientific sampling, we used a cut-off of 1960. Loran-C was the primary navigation tool until the global positioning system of satellites (GPS) was introduced in 1985. The GPS system further improved upon the loran system in terms of accuracy and coverage. From 1985 to 2000, the U.S. government intentionally degraded the GPS signal for national security reasons by way of a system called selective availability (SA). The SA system was variable (from 0 to 100 meters error in the position, with a typical error on the order of 10 meters), and differential GPS systems capable of processing ground station signals that corrected for SA were available and increasingly used by the scientific community. Therefore, we did not differentiate the period of 1985-2000. Lastly, we chose to highlight the most recent samples (1998-2008) to identify those samples with the least likelihood of sediment type alteration due to time. If the year that samples were collected could not be determined, date of publication was used.

Table 3. Age quality values.

Year Range		Approx. accuracy	Quality Value
1998-2008	Most recent samples	0.1-10 meters	4
1985-1998	GPS	0.1-10 meters	3
1960-1985	Loran-C	20-200 meters	2
< 1960	Pre-loran	variable	1

Sampling Device Quality. The sampling device was the secondary determinant of quality since collecting a representative sample is so critical to the proper interpretation of sediment type. The type of sampling device can largely affect the quality of the sample and the consistent measurement of surface sediment (0-2 cm). The devices were grouped based on the assumption that grabs designed for surface sampling would routinely provide a better assessment than corers, which can, as a group, degrade or miss the surface sediment. Dredges and trawls, which are dragged across the seafloor, can easily misrepresent a surface sample. They tend to winnow fine sediment, so they have a lower quality value than the sediment "capture" techniques of grabs, photos, and cores. While lead line soundings and unidentified samplers provide information, the degree of confidence in these data is low. The devices in the dataset were coded as identified in Table 4.

Analytical Technique Quality. The third determinant for data quality is how the data were analyzed. Even the best analytical technique can provide an inaccurate sediment type assessment if the collection of that sediment was done poorly. Laboratory assessments were conducted by methods that included sieves, settling tubes, or coulter counters. These lab methods produce precise sediment composition results, so the highest value was assigned to these datasets. Visual assessments were primarily done with photographs or with field assessments of grab samples. If no description of sediment analysis technique was available, it was assumed the sample was analyzed visually if the % sand, silt, or gravel values were divisible by five or 10. If no description of analysis technique was available or the description was simply textural with no % sand, silt, or gravel values, the technique quality was assessed as zero (Table 5).

Scoring system. To create the data quality value, a decimal scoring system was used. Since age was the primary determinant, it received the highest

Table 4. Sampling techniques and quality scores.

Sampling Device	**Description & Notes**	**Assigned sampling technique group**	**Sampling Device Quality**
NoCamera	B/W camera inside of a grab; photo probably not available	GRAB	0.4
BoxCore? [*sic*]	good job with sed-water interface	GRAB	0.4
DietzLaFondSnapper	not as good as box core or Van Veen	GRAB	0.4
GravityCore		CORE	0.3
HandSample	diver with a corer, good potential of maintaining surface so equivalent to a grab	GRAB	0.4
Hydrostatic Core		CORE	0.3
mini-SEABOSS		GRAB	0.4
OrangePeelGrab	not as good as box core or Van Veen	CORE	0.3
PhlegerCore(0.36kg)	piston core-like	CORE	0.3
PipeDredge		DREDGE	0.2
Core		CORE	0.3
SmithMcIntyreGrab		GRAB	0.4
Sounding	lead line sounding	LEAD LINE	0.1
UnIdCorer		CORE	0.3
UnIdGrab		GRAB	0.4
UnIdGrab? [*sic*]		GRAB	0.4
UnIdSampler	These were assumed to be grabs because samples have percentages and grainsize and sorting values listed with a precision in the tenths of percent. There are only 2 samples within usSEABED using the "UnIDSampler", both with the same location.	GRAB	0.4
Van Veen Grab		GRAB	0.4
VibroCore		CORE	0.3
VV	Van Veen grab	GRAB	0.4
Camera/ photo		PHOTO	0.4
Blank	Not listed	No technique assigned	0.0
CampbellGrab		GRAB	0.4
Otter trawl net	*MarineFisheries* Resource Assessment Trawl	DREDGE	0.2
Young- modified Van Veen Grab	1/25-m2 stainless steel Kynar-coated	GRAB	0.4
Digital sediment profile imaging camera		PHOTO	0.4

Table 5. Analytical technique quality values.

Analytical Technique Quality	
Laboratory	0.02
Visual	0.01
None listed	0.00

weighting. The age score range was 1-4 (Table 3). The sampling device was the secondary determinant. The sampling device score range was 0.0-0.4 (Table 4). The analytical technique quality value was the tertiary determinant. The analytical technique score range was 0.00 to 0.02 (Table 5). For example, a quality value of 4.42 is the highest value possible for all three variables. This value indicates that the sample was taken within the last 10 years, using GPS for location, by a sediment grab or hand sample, and analyzed using a lab sediment analysis. In contrast, a value of 1.00 is the lowest value. This value indicates that the sample was taken before 1960, using a lead line or unknown sampling method, and unknown analytical technique. Once data quality values were calculated for every record, 20 different values emerged ranging from 1.00 to 4.42.

Data density. Compared to many parts of the global ocean, Massachusetts has a high data density for sediment samples. This tends to lead to an assumption that the resulting interpolated products are more robust. In order to quantitatively assess the impact of data density on the quality of the resulting interpolation, the areas of the Thiessen polygons were used. Since the line segments of the Thiessen polygons are equidistant to the adjacent points, the size of the Thiessen polygons are determined by the proximity of nearby sites. A larger Thiessen polygon indicates that the data density is low and that a greater degree of interpolation has occurred in an area. This by itself doesn't mean the interpolation is incorrect; for homogeneous seafloor areas, this could be a highly accurate interpretation of the grain size distribution on the seafloor. But with increasing seafloor complexity or the need for greater precision, more samples are required to adequately interpret grain size distribution, so data density is a simple proxy for accuracy of the interpolation.

Data quality index. To combine the effects of the data quality and data density, a data quality index, I, was calculated as follows:

$$I = \log_{10}(D/A)$$

Where D = data quality value of the Thiessen polygon based on age, sampling technique, and analytical technique, and A = area of the Thiessen polygon.

A log transformation was used to scale the data. Polygons with high data quality and density have the highest values. This index allows users to easily assess the quality of the interpolation in a given location.

Results & Discussion

<u>Sediment data.</u> There were 16,657 sample points in Massachusetts waters and 2,553 points in the 10 km buffer zone seaward of state waters that was used to minimize edge effects of the gridding and interpolation (Figure 2). The grid analysis resulted in 11,480 250m^2 cells within state waters, which cover 0.03% of the area (Figure 4A). There were 2,963 cells with more than one point, and 1,779 of those cells had a standard deviation of zero.

There were 15,728 Thiessen polygons within state waters. The Thiessen polygons range in size from 3.4 x 10^{-5} to 17 square miles (Figure 4B). The difference between the number of points and the number of Thiessen polygons is a result of 929 colocated points.

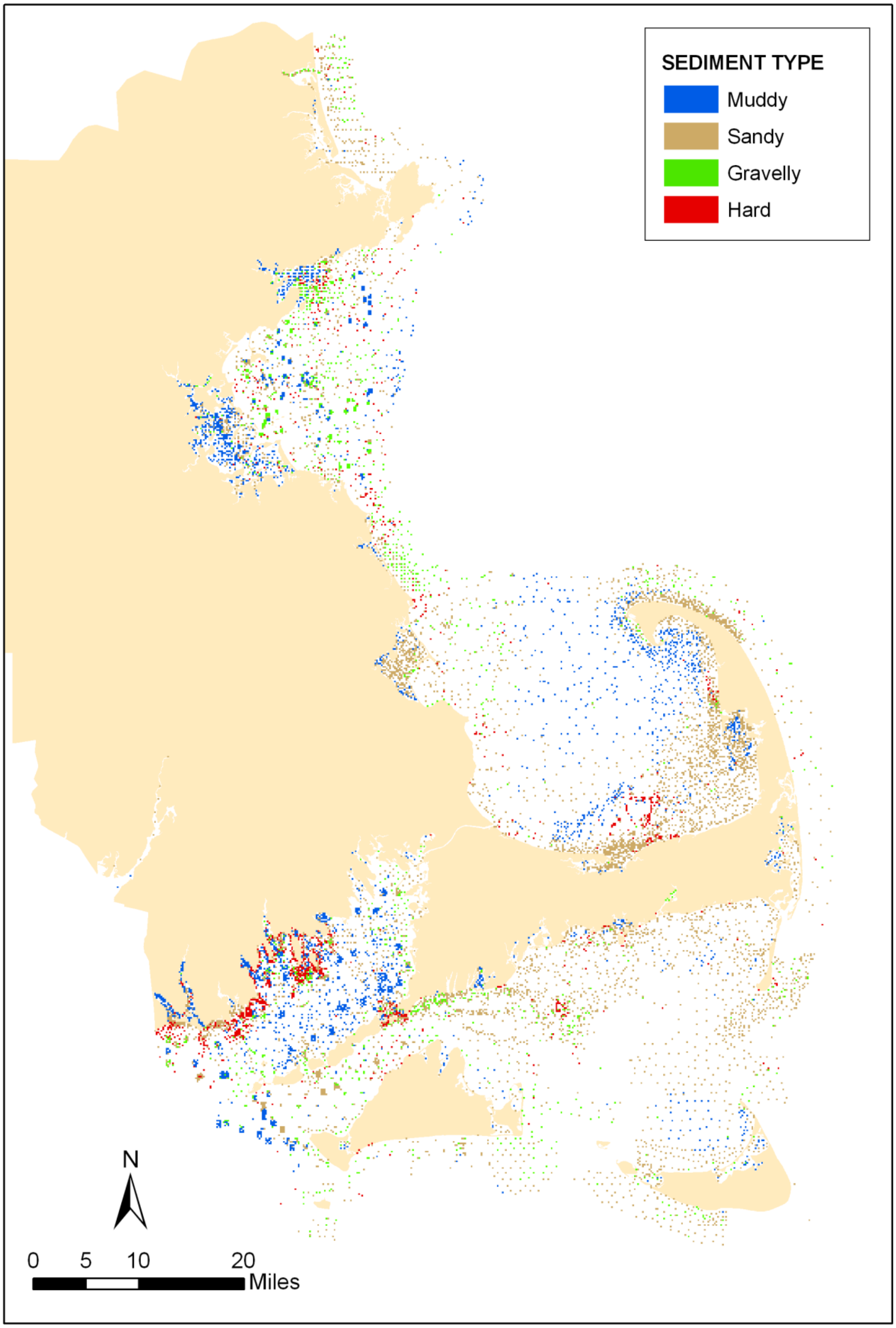

Figure 4A. Sediment distribution map gridded with 250 m^2 grid cells and B) Thiessen polygon interpolation. Blue=muddy sediment, brown=sandy sediment, green=gravelly sediment, and red=hard sediment.

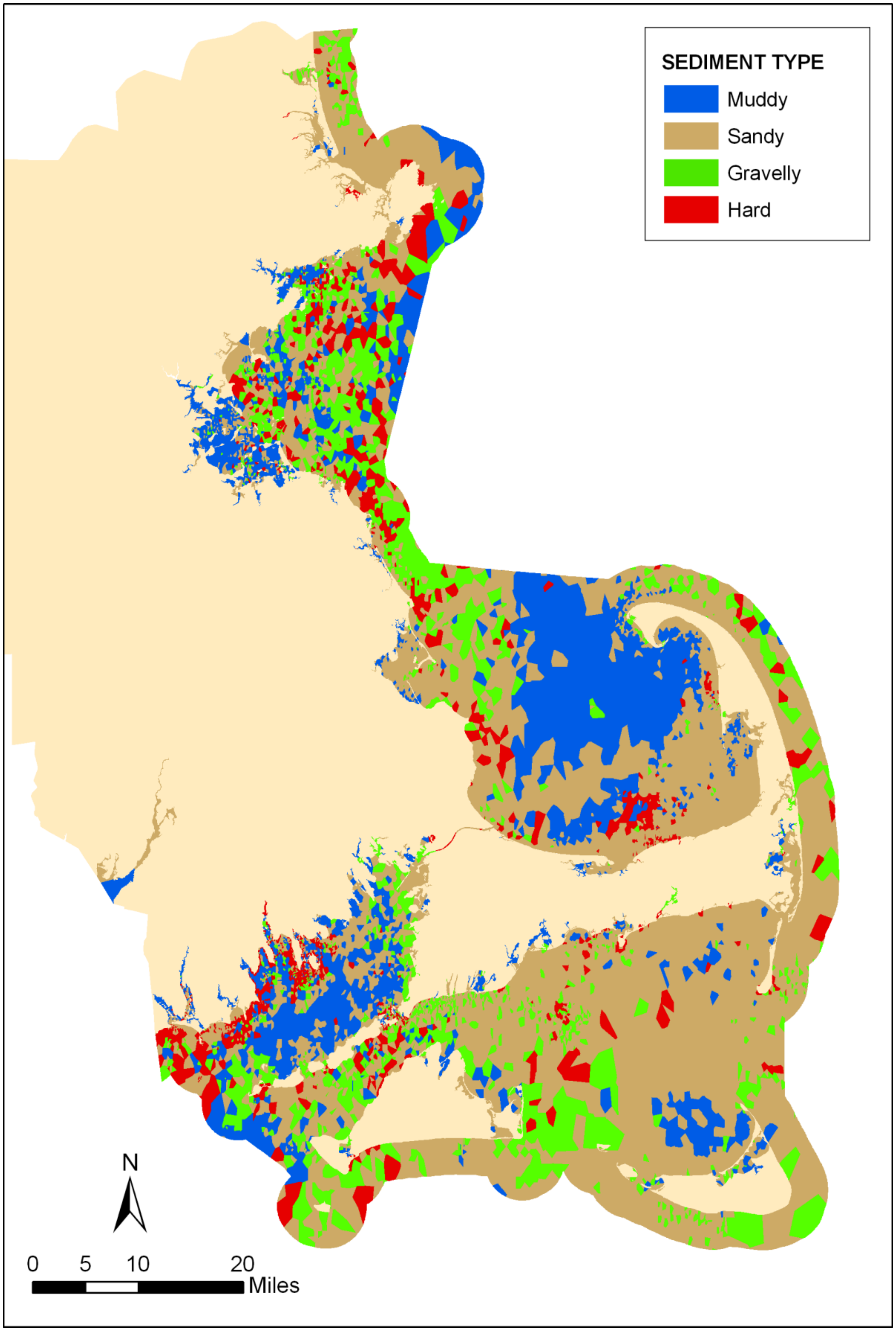

Figure 4B. Sediment distribution map with Thiessen polygon interpolation. Blue=muddy sediment, brown=sandy sediment, green=gravelly sediment, and red=hard sediment.

Sandy sediment is the most widely distributed sediment based on the interpolated dataset (Table 6). Since 91% of the samples in this dataset were collected using methods designed to sample silty/sandy sediment, the dataset is significantly biased. Therefore, its accuracy at a statewide level is questionable.

Table 6. Area covered by each grain size classification unit in the Thiessen analysis.

Folk Code	# of Thiessen polygons	Area (sq. mi.)	Area (%)
1 – muddy	4134	716	21
2 – sandy	7642	1854	55
3 – gravelly	2100	534	16
4 – hard	1852	275	8

Data quality. The sediment data within the dataset contained 18 of 20 possible data quality values, due to the wide range of temporal, spatial, and methodological variables. More than half of the samples and 45% of the interpolated area had the lowest data quality value (Table 7). Large contiguous areas of low quality data were evident particularly in Cape Cod Bay and Nantucket Sound (Figure 5).

Table 7. Percentage of points and area covered by data quality value classes.

Quality	% of points	Area (sq. mi.)	Area (%)
1 – 1.99	55	1524	45
2 – 2.99	22	1280	38
3 – 3.99	7	205	6
4 – 4.99	15	370	11

In each Thiessen polygon, the data quality value was combined with the area of the polygon (as a proxy for data density) to calculate a data quality index. This was done to better understand which parts of the state's seafloor have more robust grain size characterizations. The data quality index highlights sections of the state where both data quality and data density are low (Figure 6).

The state is dominated by low index values, so using the sediment point data to create interpolated products at a statewide scale should be done with considerable caution. However, there are specific areas where the seafloor data are robust. Gloucester Harbor, Boston Harbor, Plymouth and Duxbury Harbor, and portions of Massachusetts Bay, Buzzards Bay and Vineyard Sound all have aggregated samples taken recently using methods designed for capturing seafloor surface sediment. In these areas, local-scale interpolation and resulting interpretations should be both more accurate and precise. More advanced seafloor habitat characterization work should target these areas, while new sampling programs should target areas where data are sparse.

Future Work

The backscatter maps created under the CZM-USGS Seafloor Mapping Cooperative can be used with the point data to more precisely define sediment type boundaries. This will improve the confidence of the sediment type distribution map and minimize issues associated with interpolation technique. In some areas this work has been done. For example, multiple classification techniques were used to classify the habitats in a pilot area near Salem Sound in 2007 (Lund and Wilbur 2007) and automatic landscape-based classification techniques are being explored (Sampson 2009). By utilizing underlying geoforms, more realistic maps of sediment distribution can be achieved.

Other point datasets that are being targeted for incorporation into the *MarineFisheries* sediment database include:

- grain size data from New Bedford Harbor and Buzzards Bay as part of the siting of sewage treatment facilities
- Army Corps of Engineers sediment data
- interpreted photos from the CZM-USGS Seafloor Mapping Cooperative
- datasets associated with permitted construction projects

- Buzzards Bay, Gloucester Harbor, and Salem Sound disposal site datasets
- eelgrass monitoring and restoration grain size data from Boston Harbor, Salem Sound, Gloucester Harbor, Buzzards Bay, Pleasant Bay, and Provincetown Harbor
- Ipswich Bay geological research.

The dataset will be made available publicly at MassGIS (http://www.mass.gov/mgi) and on the National Geophysical Data Center Marine Geology Inventory (http://www.ngdc.noaa.gov/mgg/geology/seadas.htm).

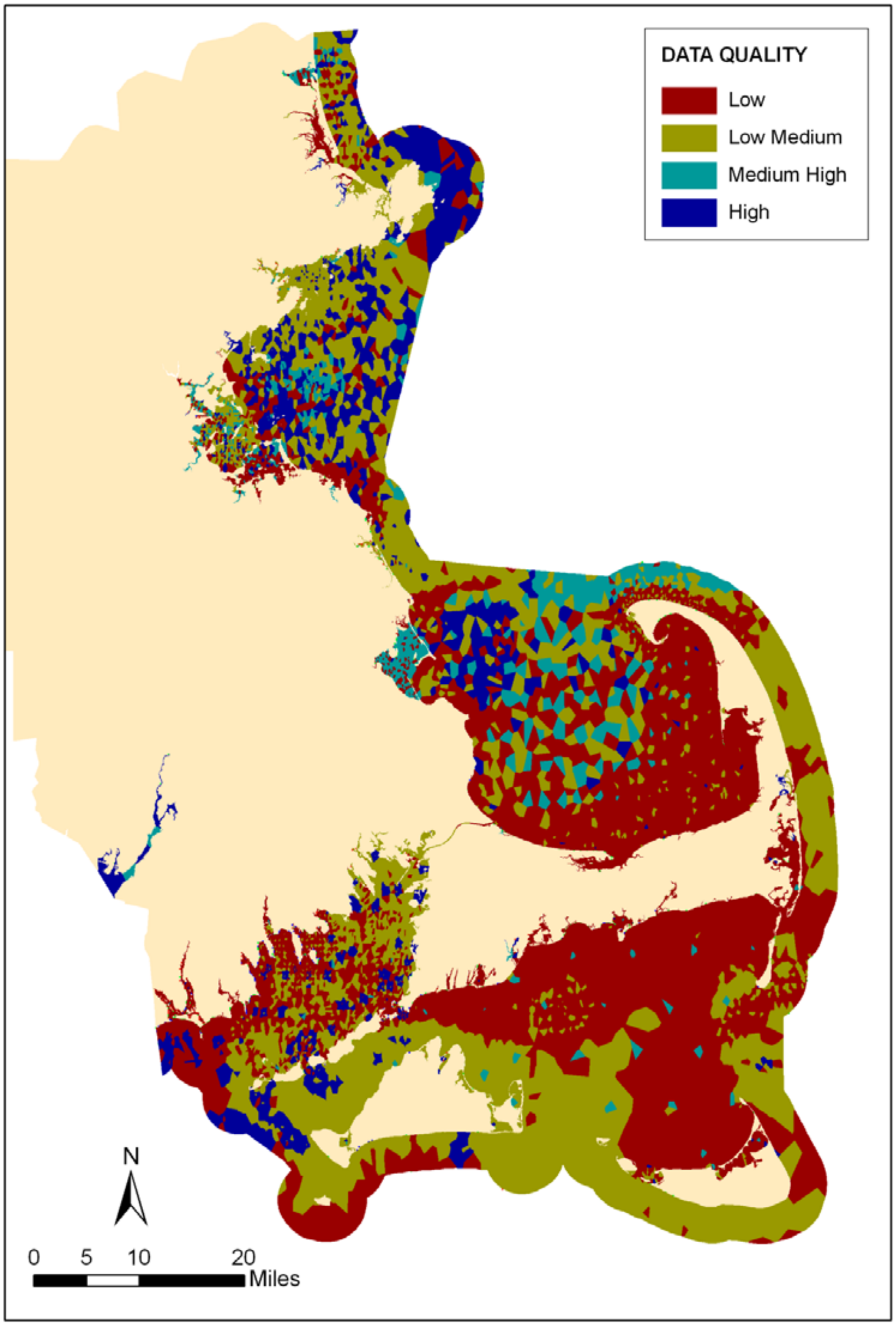

Figure 5. Spatial distribution of data quality. Red=low quality (1.00-1.99), mustard=low-medium quality (2.00-2.99), teal=medium-high quality (3.00-3.99), and blue= high quality (4.00-4.99).

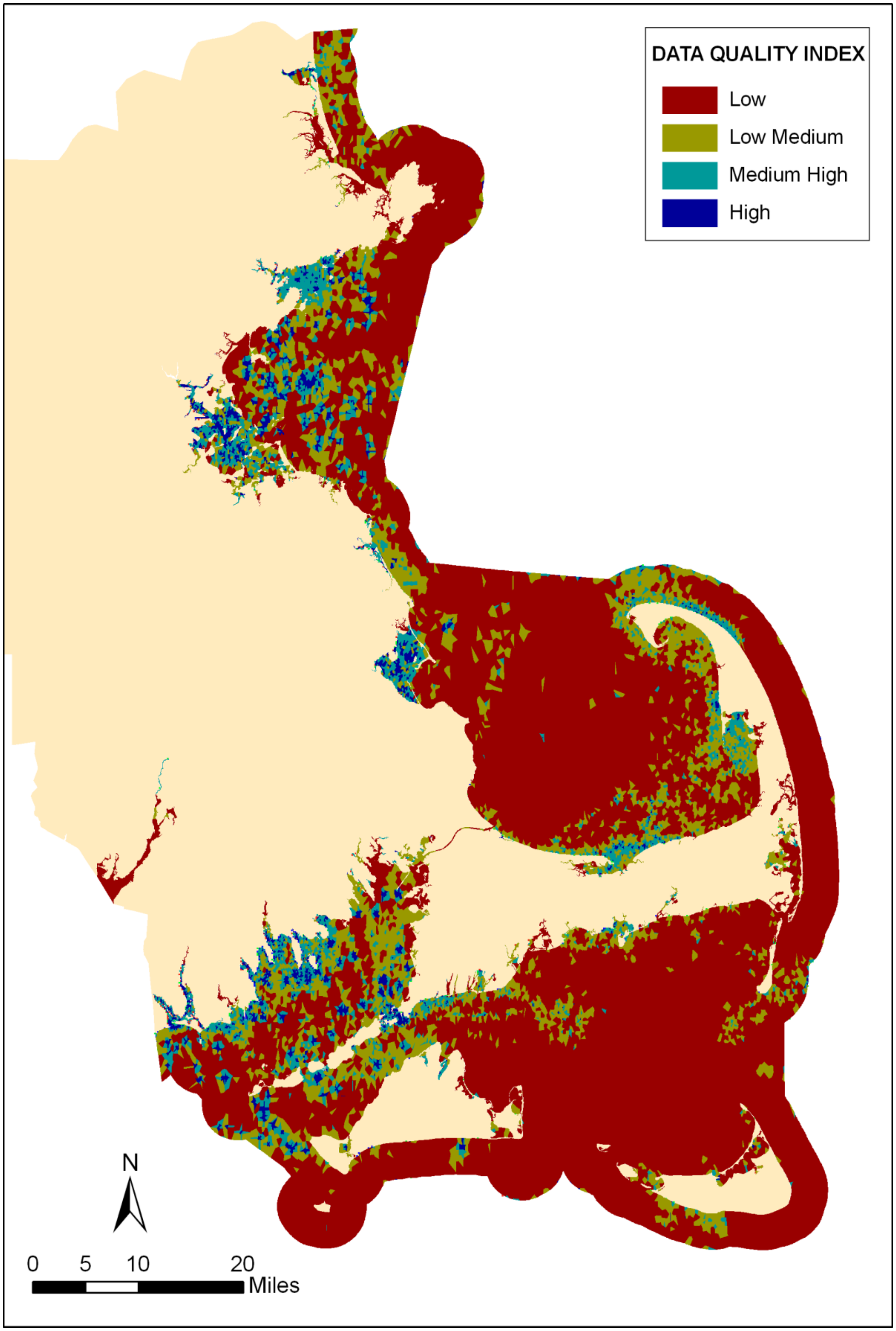

Figure 6. Spatial distribution of the quality assessment index combining data quality and density. Red=low quality (1st quantile), mustard=low-medium quality (2nd quantile), teal=medium-high quality (3rd quantile), and blue= high quality (4th quantile).

Literature Cited

Banner, A. and S. Schaller. 2001. USFWS Gulf of Maine Watershed Habitat Analysis. Gulf of Maine Progra, Falmouth, ME. Available: http://www.fws.gov/r5gomp/gom/habitatstudy/Gulf_of_Maine_Watershed_Habitat_Analysis.htm (September 2010).

Bobertz, B and J. Harff. 2004. Sediment facies and hydrodynamic setting: a study in the south western Baltic Sea. Ocean Dynam. 54(1):39-48.

Bonadonna, C. and Houghton, B.F., 2005. Total grainsize distribution and volume of tephra-fall deposits, Bull. Volcanol. 67:441-456.

Connor, D.W., Gilliland, P.M., Golding, N, Robinson, P.,Todd, D., & Verling, E. 2006. U.K.SeaMap: the mapping of seabed and water column features of U.K. seas. Joint Nature Conservation Committee, Peterborough. Available: http://www.jncc.gov.uk/pdf/pub07_ukseamap_part4.pdf (October 2009).

EPA (U.S. Environmental Protection Agency). 2008. National Coastal Condition Report III. EPA Report, EPA/842-R-08-002. http://water.epa.gov/type/oceb/assessmonitor/downloads.cfm. Accessed: 9/30/10.

EPA. 2010. National Coastal Assessment website. Available: http://www.epa.gov/emap/nca/ (September 2010).

Folk, R.L. 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. J. Geol. 62:344-359.

Glenn, R.P. 2007. Random Stratified Ventless Trap Survey Design for Pilot Study in Massachusetts Bay. Final Report. 76 pp.

Greene, J.K., M.G. Anderson, J. Odell, and N. Steinberg, eds. 2010. The Northwest Atlantic Marine Ecoregional Assessment: Species, Habitats and Ecosystems. Phase One. The Nature Conservancy, Eastern U.S. Division, Boston, MA. 400 pp. http://www. nature.org/wherewework/northamerica/states/easternusmarine/maps. Accessed: 12/1/2010.

Gotceitas, V., and J. A. Brown. 1993. Substrate selection by juvenile Atlantic cod (*Gadus morhua*): effects of predation risk. Oecologia 93:31–37.

Harris, B.P. and K.D.E. Stokesbury. 2010. The spatial structure of local surficial sediment characteristics on Georges Bank, USA. Cont. Shelf Res. In press, doi:10.1016/j.csr.2010.08.011.

King, J., M. Camisa, V. Manfredi, and S. Correia. 2010. Massachusetts Division of Marine Fisheries trawl survey effort, list of species, and bottom temperature trends, 1978-2007. Mass. Div. Mar. Fish. Tech. Report No. 38. 166pp. http://www.mass.gov/dfwele/dmf/publications/tr_38.pdf. Accessed: 12/21/2010.

Kostylev, V.E., B.J. Todd, G.B.J. Fader, R.C. Courtney, G.D.M. Cameron, and P.A. Pickrill. 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. Mar. Ecol.-Prog. Ser. 219: 121-137.

Laidig, T.., D.L. Watter, M.M. Yoklavic. 2009. Demersal fish and habitat associations from visual surveys on the central California shelf. Estuar. Coast. Shelf S. 83(4):629-637.

Leecaster, M. 2003. Spatial analysis of grain size in Santa Monica Bay. Mar. Environ. Re. 56, 1-: 67-78.

Lindholm, J., P. J. Auster, and L. Kaufman. 1999. Habitat-mediated survivorship of juvenile (0-year) Atlantic cod (*Gadus morhua*). Mar. Ecol.-Prog. Ser. 180:247–255.

Lindholm, J., P.J. Auster, and A. Knight. 2007. Site fidelity and movement of Atlantic cod (*Gadus morhua*) at deep boulder reefs in the western Gulf of Maine. Mar. Ecol.-Prog. Ser. 342: 239–247.

Lund, K. and T. Wilbur. 2007. Habitat classification feasibility study for coastal and marine environments in Massachusetts. Massachusetts Office of Coastal Zone Management.

Maciolek, NJ, RJ Diaz, DT Dahlen, and SA Doner. 2008. 2007 Boston Harbor Benthic Monitoring Report. Boston: Massachusetts Water Resources Authority. Report 2008-22.

Maljers, D and Gunnink, J 2009. Interpolation of measured grain-size fractions on the Dutch Continental Shelf. Available: http://www.coastalwiki.org/coastalwiki/Interpolation_of_measured_grain-size_fraction (October 2009).

MESH (Mapping of European Seabed Habitats) 2007. Confidence Assessment Guidelines. Available: http://www.searchmesh.net/default.aspx?page=1635 (October 2009).

Me´ar, Y., E. Poizot, A. Murat, P. Lesueur, M. Thomas. 2006. Fine-grained sediment spatial distribution on the basis of a geostatistical analysis: Example of the eastern Bay of the Seine (France). Cont. Shelf Res. 26:2335-2351.

O'Connell, V.M. and D. W. Carlile. 1993. Habitat-specific density of adult yelloweye rockfish *Sebastes ruberrimus* in the eastern Gulf of Alaska. U.S. Fish. Wld. S. Fish. Bull. 91:304-309.

Poppe, L.J., Eliason, A.H., and Hastings, M.E. 2003. A Visual Basic program to classify sediments based on gravel-sand-silt-clay ratios. Comput. Geosci. 29(6):805-809.

Reid, J.M., Reid, J.A., Jenkins, C.J., Hastings, M.E., Williams, S.J., and Poppe, L.J, 2005. usSEABED: Atlantic coast offshore surficial sediment data release: U.S. Geological Survey Data Series 118, version 1.0. Available: http://pubs.usgs.gov/ds/2005/118/ (September 2010).

Romsos, C., C. Goldfinger, R. Robison, R. Milstein, J.D. Chaytor, and W. Wakefield. 2008. Development of a regional seafloor surficial geologic habitat map for the continental margins of Oregon and Washington, USA. Pages 209-234. *In* B. Todd and H.G. Greene, editors. Mapping the Seafloor for Habitat Characterization. Geological Association of Canada, St. Johns, Newfoundland, Canada. SP-47.

Sampson, D.W. 2009. Mapping to Management in Massachusetts. Gulf of Maine Symposium, St. Andrews, New Brunswick, Canada.

Shepard, F. 1954. Nomenclature based on sand-silt-clay rations. J. Sed. Pet. 24:151-158.

Sibson, R. 1981. A brief description of natural neighbor interpolation. Pages 21-36 in V. Barnett, editor. Interpreting Multivariate Data. Wiley Press, New York.

Stephens, J.S., Larson, R.J., Pondella, D.J., 2006. Rocky reefs and kelp beds. Pages 227-252. *In* L.G. Allen, D.J. Pondella, and M.H. Horn, editors. The Ecology of Marine Fishes: California and Adjacent Waters. University of California Press, Berkeley, California.

Stewart, P.L. and B.T. Hargrave. 2002. Availability of information on benthic macroinvertebrate communitieis for classifying marine environments on the Scotian Shelf. *In* Proceedings of a Benthic Habitat Classification Workshop Meeting of the Maritimes Regional Advisory Process. June 25-26, 2001. Fisheries and Oceans Canada, Canadian Science Advisory Secretaria, Proceedings Series 2002/023.

Tobler, W. 1970. A computer movie simulating urban growth in the Detroit region. Econ. Geogr. 46:234-240.

USCG (U.S. Coast Guard). 1992. "Loran-C Users Handbook," COMDTPUB P16562.6, 160pp. Available: http://www.loran.org/ILAArchive/LoranHandbook1992/LoranHandbook1992.htm (May 2009).

USGS (U.S. Geological Survey). 2006. Mapping the Seafloor Geology Offshore of Massachusetts. U.S. Geological Survey Fact Sheet 2006–3042. Available: http://pubs.usgs.gov/fs/2006/3042/ (October 2009).

Verfaillie, E., V. Van Lancker, and M. Van Meirvenne. 2006. Multivariate geostatistics for the predictive modelling of the surficial sand distribution in shelf seas. Cont. Shelf Res. 26 (19):2454-2468.

Weston, D.P. 1988. Macrobenthos-sediment relationships on the continental shelf off Cape Hatteras, North Carolina. Cont. Shelf Res. 8:267-286.

Zajac, R.N., Lewis, R.S., Poppe, L.J., Twichell, D.C., Vozarik, J., DiGiacomo-Cohen, M.L. 2000. Relationships among sea-floor structure and benthic communities in Long Island Sound at regional and benthoscape scales. J. Coastal Res. 16:627–640.

List of Massachusetts Division of Marine Fisheries Technical Reports (continued from inside front cover)

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