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Understanding the physical and environmental consequences of dredged material disposal: history in New England and current perspectives

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Abstract

Thirty-five years of research in New England indicates that ocean disposal of dredged material has minimal environmental impacts when carefully managed. This paper summarizes research efforts and resulting conclusions by the US Army Corps of Engineers, New England District, beginning with the Scientific Report Series and continuing with the Disposal Area Monitoring System (DAMOS). Using a tiered approach to monitoring and a wide range of tools, the DAMOS program has monitored short- and long-term physical and biological effects of disposal at designated disposal sites throughout New England waters. The DAMOS program has also helped develop new techniques for safe ocean disposal of contaminated sediments, including capping and confined aquatic disposal (CAD) cells. Monitoring conducted at many sites in New England and around the world has shown that impacts are typically near-field and short-term. Findings such as these need to be disseminated to the general public, whose perception of dredged material disposal is generally negative and is not strongly rooted in current science.
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1. Introduction

The environmental impacts from dredging and disposal of sediments has been a controversial and often politically charged arena for much of the last four decades. An emphatic example of this was the 1981 *Sports Illustrated* article which showed the dismembered body of a sea turtle stuck in the cutter of a suction dredge (Rudloe, 1981). Dredging has clearly damaged seagrass beds and coral reefs (Bak, 1978; Brown et al., 1990; Onuf, 1994; Long et al., 1996). Over the years countless acres of wetlands, once considered wastelands, were filled with dredged sediments (Kennish, 2001; Summers et al., 2002). And it is clear that sediments impacted by contaminants we placed into our waterways during years of unrestrained industrialization accumulated in waterway sediments and have had persistent and severe adverse impacts (e.g., New Bedford Harbor, MA, Black Rock Harbor, CT, Bridgeport Harbor, CT, Providence Harbor, RI). However, setting aside the sensationalism and rhetoric that is sometimes used, we have made tremendous advances in our ability to evaluate and minimize the environmental impacts of dredging projects through development of testing protocols, scientific investigations, and development of management techniques and beneficial uses for sediments. While specific dredging projects often still generate considerable public debate and political wrangling, there are also many projects that are successfully completed without much fanfare because of our ability to intelligently apply the lessons we have learned as best management practices.

In New England, much of what we know about the potential for environmental impact of dredged material, and the means to minimize impacts, has been derived from a considerable body of technical investigations that were specifically developed to improve our environmental stewardship. These efforts began in 1968, initiated by people who clearly were visionaries, well before any of the existing environmental legislation was created. This series of studies, funded by the New England Division

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(now the New England District) of the US Army Corps of Engineers was recorded in a 59-report series (e.g., Saila et al., 1969; Rhoads, 1972; Bokuniewicz et al., 1976) that culminated in 1980 (Karp et al., 1980). In 1977 and for the past 25 years these studies have continued more formally under the Disposal Area Monitoring System (DAMOS). Indeed, while much of this work has had site specific application many of the findings have helped to form the foundation of our scientific beliefs in this arena.

Dredging and disposal are not without some level of environmental impact and proposed projects in New England do not escape controversy, but the information developed as a result of years of investigation has greatly minimized the uncertainties and has increased the confidence of both environmental resource agencies and the public in the ability of the Corps of Engineers to successfully conduct such projects without undue risk to the environment. In the following discourse we review the emergence of our knowledge related to dredged material management and its evolution, as society's perspectives of the environment also evolved.

2. The scientific report series

Much of our early understanding of dredged material disposal processes and impacts was derived from studies sponsored by the New England Corps of Engineers office (Table 1). The work that contributed to the Scientific Report (SR) Series resulted in cornerstone papers that established conclusions on which we continue to base our principles and decisions. The earliest of these studies developed preliminary information on multiple aspects of the impacts of sediment disposal at a site in Rhode Island Sound (Saila et al., 1969, 1971; Pratt et al., 1973; Sissenwine and Saila, 1973, 1974). The physical process of disposal and loss of sediments in a plume was first described by Gordon (1973, 1974). Bohlen and associates conducted fundamental work on plume transport and dispersion (Bohlen and Tramontano, 1974a,b; Bohlen et al., 1979; Tramontano and Bohlen, 1982). Rhoads and his students provided the foundation for understanding both benthic recovery processes and geochemical impacts (e.g., Gordon et al., 1972; Fisher and McCall, 1973; Rhoads, 1974a,b, 1976; Rhoads, 1974b). Morton and colleagues initiated the first efforts to manage contaminated sediments (Cook et al., 1977; Morton, 1980).

3. Emergence of the DAMOS program

The monitoring of dredged material disposal was formalized in the New England Corps of Engineers office in 1977 with the creation of the Disposal Area Monitoring System (DAMOS). DAMOS is a multi-disciplinary environmental monitoring program whose primary purpose is to manage and monitor New England's 10 offshore dredged material disposal sites from Long Island Sound to Maine. Since its inception, the program has produced more than 140 technical reports (the DAMOS contribution series), 80 journal or conference papers, brochures and a video, and also maintains an active mailing list and a web site (www.nae. usace.army.mil/environm/damos/splash_page.htm). Program efforts respond to concerns expressed by interested members of the public, federal resource agencies (such as the US Environmental Protection Agency), and the environmental departments of New England coastal states. The earliest objectives of the program focused on understanding the basic behavior of disposed sediment and its near-field, short-term impacts. Today the program addresses longer range, cumulative impact questions, such as food web impacts of contaminants, beneficial fishery

Table 1
Selected SR reports and related publications

SR report number	SR report authors	Related publication
4	Sissenwine and Saila (1973)	Sissenwine and Saila (1974)
7	Gordon et al. (1972)	Rhoads (1976)
8	Bokuniewicz et al. (1974)	Bokuniewicz and Gordon (1979, 1980)
12	Fisher and McCall (1973)	McCall (1976)
16	Rhoads (1974a)	Rhoads et al. (1978)
19	Gordon (1973)	Gordon (1974)
21	Bohlen and Tramontano (1974a)	Bohlen et al. (1979)
22	Bohlen and Tramontano (1974b)	Tramontano and Bohlen (1982)
23	Nalwalk et al. (1974)	Paskausky et al. (1974c)
24	Paskausky et al. (1974b)	Paskausky et al. (1974c)
25	Paskausky et al. (1974a)	Paskausky et al. (1974c)
43	Rhoads et al. (1975)	Rhoads et al. (1977)
50	Bokuniewicz et al. (1976)	Bokuniewicz and Gordon (1980)
51	Rhoads and Yingst (1976)	Rhoads et al. (1978), Yingst and Rhoads (1978)
57	Morton (1980)	Morton (1983, 1988)

effects, and long-term cap effectiveness. In addition to monitoring the 10 active New England disposal sites, DAMOS studies disposal at infrequently used sites, such as Tupper Ledge (SAIC, 2002), alternative use sites, including beneficial mudflat creation at Sheep Island (Ray et al., 1994, 1995) and Boston Harbor confined aquatic disposal (Fredette et al., 1999).

Overarching program objectives include:

- monitoring dredged material disposal sites in New England by empirical methods to ensure that no significant adverse environmental impacts result from disposal operations;
- developing an understanding of the processes and mechanisms affecting dredged material in the marine environment;
- developing an understanding of the interaction between dredged material and the biota of the disposal site;
- utilizing this knowledge to develop management techniques that will minimize the adverse effects of disposal; and
- distributing the results of the DAMOS program to provide better public understanding of the effects of dredged material disposal.

The DAMOS program employs a tiered approach to monitoring, which is designed to address: (1) compliance with disposal permit regulations; (2) model verification to check the validity of predictions and assumptions underlying the tiered sampling design; and (3) identification of long-term trends in the environment that might be related to disposal activity. In this approach, higher tiers are required only when results from lower tiers are ambiguous. The approach is designed so that monitoring efforts and costs are minimized in the lower tiers to provide rapid data return to guide management decisions. The approach recommends monitoring techniques and provides clearly defined decision points based on the data collected. The decision points require a comparison of the data collected (e.g., recolonization status) to the expected conditions (reference and model predictions). Expected results confirm predictions and invoke another assurance check at a later time, while unexpected results prompt a search for an explanation and monitoring at the next tier (e.g., more intensive or a different type of monitoring) (Fredette et al., 1993; Germano et al., 1994).

To accomplish its monitoring goals, DAMOS employs a wide range of tools and technology, including bathymetric surveys, side scan sonar, underwater photography, divers, sediment analyses, sediment profile photography, biological analyses, and submersible vessels. One crucial tool in DAMOS monitoring is the sediment-profile imaging (SPI) (Rhoads and Cande, 1971). SPI is a benthic sampling technique used to detect and map the distribution of thin (<20 cm) dredged material layers, delineate benthic disturbance gradients, and monitor the process of benthic recolonization at dredged material disposal mounds (SAIC, 2003). This instrument provides in situ imaging of organism–sediment relationships on the seafloor by making a vertical slice of the sediment–water interface and imaging the sediment in profile (Germano, 1983). These images provide measures of boundary roughness, depth of camera penetration, and area of the oxidized sediment [mean redox potential discontinuity (RPD) depth] (Germano et al., 1984). Benthic infauna may also be observed, allowing for insight into recolonization. From this information, a sample can be assigned a ranking in the organism sediment index (OSI), which uses RPD, benthic successional stage, and oxygenation information to characterize overall habitat quality. A high OSI indicates that disposed sediments were correctly evaluated pre-disposal as environmentally compatible for open water disposal. Where abnormal recovery is observed, follow-up studies and appropriate management actions are undertaken.

Another important monitoring tool is precision bathymetry. Depth-difference plots comparing pre- and post-disposal conditions are used to verify disposal of dredged material in discrete mounds on the seafloor and placement of cap sediments. Long-term bathymetry comparisons are used to confirm that the dredged material mounds are stable over time, including after extreme storm events. For the DAMOS monitoring program, most bathymetric surveying is accomplished using single-beam echosounders with line spacing of 25 m, while surveys requiring more detail employ multibeam systems, where overlapping lane spacing provides 150% coverage of the seafloor. Bathymetric surveys are accurate within 10–20 cm in the 20–90 m water depths surveyed. For shallow mounds and for determining the lateral extent of freshly deposited material, other survey techniques are used in conjunction with bathymetry, such as sediment profile photography, grab sampling, and coring.

Physical, chemical, and biological measurements have permitted detection of short- and long-term changes at disposal sites. This information is invaluable in daily permitting and management decisions concerning whether, where, and how dredged material should be deposited in marine waters. Examples of specific uses of monitoring information include: determination of proposed method and time (season) of dredging, appraisal of environmental conditions at or near the proposed disposal site, and assessment of quantity and degree of contamination of the material to be dredged. Monitoring is also used to avoid creating shallow depths that would be a hazard to navigation.

4. Lessons learned

Thirty-five years of monitoring and research has demonstrated that dredged material, evaluated through pre-project testing and deposited in properly located ocean disposal sites, will remain where it is placed and have no unacceptable adverse effects on nearby marine resources. The only discernible adverse impacts have been near-field and short-term. These conclusions are based on the magnitude of disposal activity relative to natural (e.g., storms) and other anthropogenic (e.g., outfalls) impacts (Rhoads, 1994; Rhoads et al., 1995) and the low level of disposal-related impacts that have been documented (Fredette et al., 1993).

Physical monitoring has revealed that disposed sediments are quickly transported to bottom, and short-term losses of sediment to dispersion are only 1–5% of total sediment deposited (Gordon, 1974; Bokuniewicz and Gordon, 1980) (Fig. 1). Thus, water column impacts are minimal and short-term (Tramontano and Bohlen, 1982; Arimoto and Feng, 1983). Tidal current regimes at carefully selected sites are insufficient to significantly erode the deposited sediment. When some erosion does occur, finer sediments are winnowed out of surface sediments, but a lag deposit of coarser grained sediments develops to armor the remaining sediments from erosion (Fredette et al., 1993). Mounds remain stable even after the passage of storms.

Impacts to the benthic community have been carefully studied employing a variety of techniques, mostly notably SPI (Rhoads and Germano, 1990). Direct effects of disposal have been detected only within a few hundred m of the disposal point. Farther from the disposal point, where only thin (<50 cm) layers of sediment are deposited, benthic organisms can burrow through overburden. Near the disposal point, recolonization generally proceeds rapidly. Benthic recovery proceeds in three predictable stages. Stage I assemblages consist of dense aggregations of near-surface, tube-dwelling polychaetes, which are typically associated with a shallow redox boundary. These assemblages are eventually replaced by Stage II infaunal deposit feeders. Stage III consists of deeper-dwelling invertebrates typically found in low-disturbance regimes. They generally feed head-down and thus serve to aerate the sediment, consequently deepening the redox horizon (Rhoads and Germano, 1990).

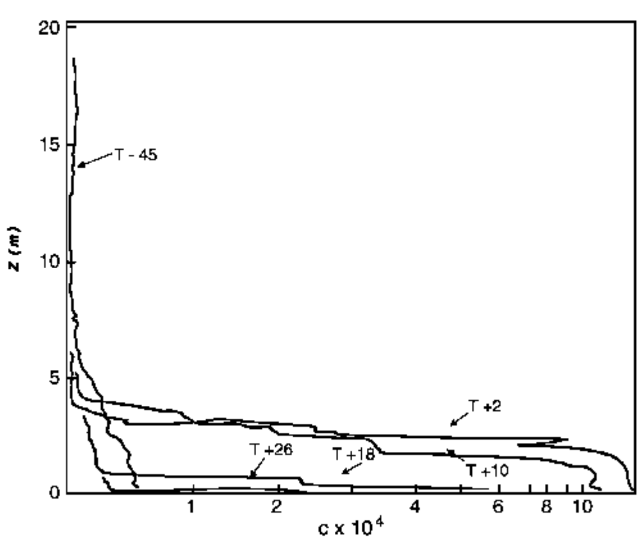

Fig. 1. Example of successive sediment concentration profiles in the water column before ($T-45$) and after barge disposal used to estimate plume losses. T, time in minutes; z, height in m above seafloor; c, concentration in weight fraction. Redrawn from Gordon (1974).

The combination of benthic activity type, redox horizon, absence of gas (methane) bubbles, and other factors have been used to develop an organism sediment index (OSI) that can be used to track benthic recovery (Rhoads and Germano, 1990). Sediments recolonizing normally attain and maintain an OSI above six (6) (Fig. 2). Sediments that have persistent OSI values less than six represent abnormal recolonization that may be an indication of adverse sediment contamination, though other factors such as systemic hypoxia or sediment disturbance (storms, trawling, etc.) also need to be evaluated.

Impacts to organisms via the water column are also generally minimal. Studies of mussel bioaccumulation have found that mussels usually show no significant bioaccumulation of contaminants (Fig. 3). However, when significant bioaccumulation has been observed, contaminant levels of affected mussels returned to those at reference locations shortly after cessation of disposal (Feng, 1982, 1983, 1984). Studies of reproductive tissue of mussels deployed at disposal sites also show little or no reproductive impairment compared to reference areas (Arimoto and Feng, 1983).

DAMOS has also surveyed a historic disposal site to assess the lingering effects of disposal. One example, the Bridgeport Disposal Site in Long Island Sound was closed in 1977 after receiving approximately 4.2 million m^3 of dredged material over a 25 year period. In 1992 a one-day survey was conducted using side-scan sonar and SPI. Side-scan sonar results indicated relic dredged material in low relief, but no well-defined mounds. SPI photographs provided evidence of past physical and biological disturbance, yet it revealed a largely healthy benthic community similar to those of reference areas. More extensive, recent work at this site and another historic site supports these earlier conclusions (Battelle, 2002, 2003a,b). These results support expectations for recovery for historic disposal sites (SAIC, 1996). Today's active disposal sites may fare even better in the future because testing protocols for dredged material were not in place when the Bridgeport Disposal Site was active.

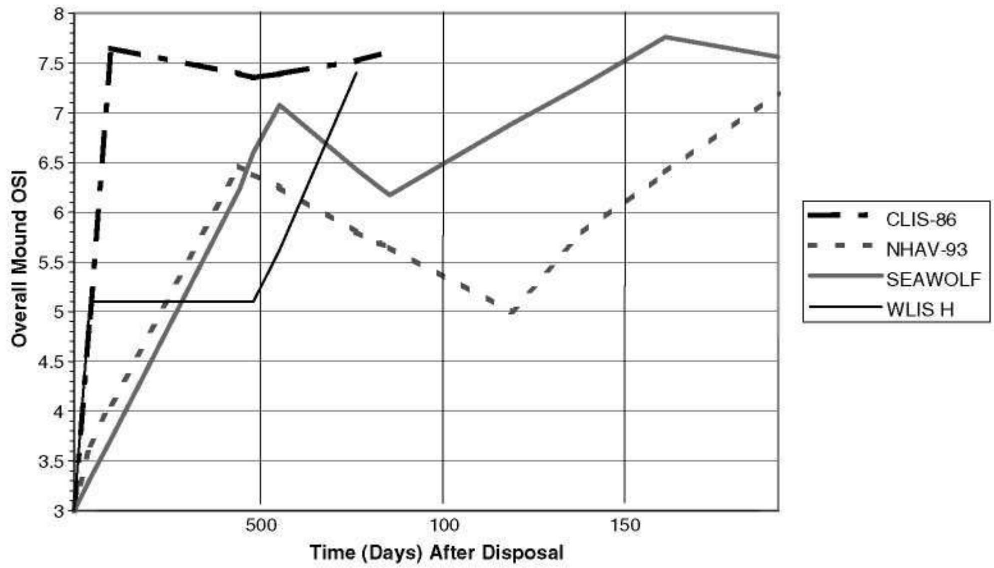

Fig. 2. Examples of change in sediment benthic conditions at four disposal mounds. The slower recovery at NHAV-93 prompted continued monitoring and assessment. Slower recovery at WLIS H attributed to regional hypoxia. Organism sediment index (OSI) used as the indicator for recovery. Origin set at three for graphical purposes.

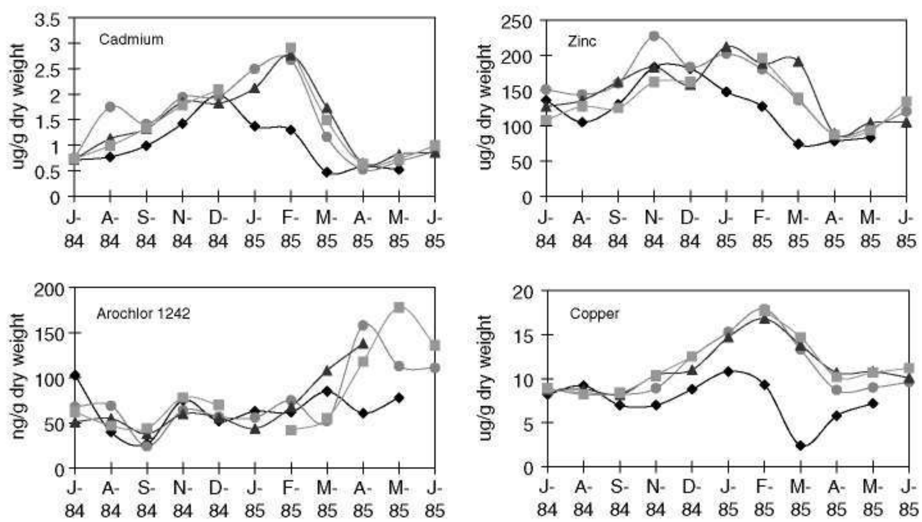

Fig. 3. Contaminant levels (cadmium, zinc, arochlor 1242, and copper) in *Mytilus edulis* tissue before and during disposal at four different locations. ▲ Near disposal mound, ■ 500 m west of mound, ● Nearby reference, ◆ Distant reference. Disposal occurred from January to June 1985. Based on data in Feng (1988).

5. Recent and on-going investigations

5.1. Capping

The capping of contaminated sediment dates back to approximately the inception of DAMOS. Extensive studies were conducted to determine whether highly contaminated sediments could be disposed and covered by relatively uncontaminated sediments, thus isolating the contaminants from the environment. The first carefully monitored project entailed capping sediment from Stamford Harbor at two separate disposal points within the Central Long Island Sound Disposal Site. Caps were comprised of fine-grained sediment from inner and outer New Haven Harbor. DAMOS monitoring of the first and subsequent capping activities resulted in the development of the following capping management procedures: (1) use of taut-wire buoys to confine contaminated material, (2) bathymetric and SPI surveys to determine sediment distribution and to design cap placement, and (3) follow-up monitoring to assure capping success and benthic community recovery (Fredette et al., 1993).

Comprehensive monitoring has demonstrated the effectiveness of caps in isolating contaminated sediment from the marine environment. In Long Island Sound, for instance, cores were collected from capped mounds created 7 and 11 years prior to sampling. Cap material was generally clearly distinguishable, both visually and chemically, from mound material (Fig. 4). There was no conclusive evidence of physical disturbance or chemical migration, although chemical heterogeneity of the cap and mound sediments and the 20 cm homogenates made the interface less distinct in some cores (Fredette et al., 1992). Geotechnical analysis has shown that although mound elevation can decrease over time, this decrease is due to consolidation rather than erosion, and the fluid expelled from the consolidated contaminated material is contained within the cap materials (Bokuniewicz, 1989; Silva et al., 1994). Further evidence of contaminant containment is provided by Feng (1982), who found that mussels deployed at capped sites one year after capping showed no higher contaminant tissue concentrations than those at reference sites.

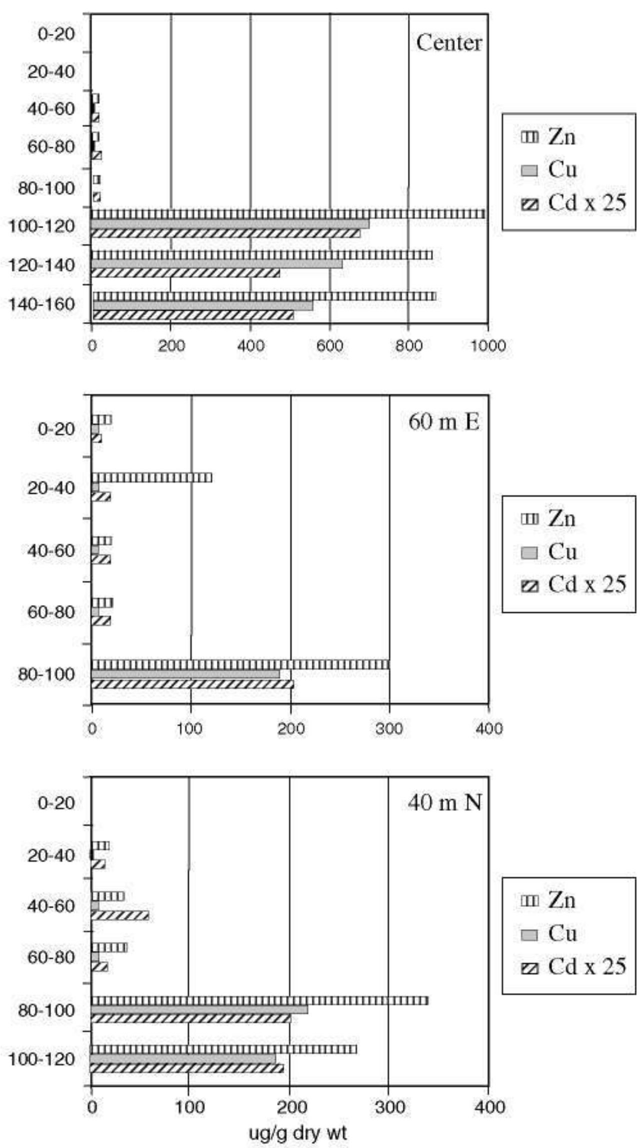

Fig. 4. Chemical profiles of zinc, copper, and cadmium (×25) from 20 cm core sections at the Stamford–New Haven capped mound 11 years after capping. Cores shown are from the mound center, 60 m east of center, and 40 m north of center. Core sections with no data shown were not analyzed. Top of core is set at 0 cm. Based on data in Sumeri et al. (1991).

DAMOS is now assessing the feasibility of capping in deeper waters. Two pilot projects have been conducted recently. For the purpose of these demonstrations, uncontaminated sediment was used as the "unacceptable" dredged material in both projects. In 1995 to 1997 a capping demonstration project was conducted at the Portland Disposal Site in 64 m of water (Morris et al., 1998). Prior to this project, capping has generally occurred in waters 14–24 m deep. A combination of survey techniques revealed a discrete disposal mound with a distinct cap. More recently, investigations have begun at an even deeper site, the Massachusetts Bay Disposal Site at 90 m depth, with sediment from Cohasset Harbor, Cohasset, MA. A postcap survey has been conducted, and feasibility of future capping is being assessed.

Another technique related to capping that has benefited from DAMOS monitoring is the creation of "rings" of mounds at disposal sites to create basins to contain dredged material (Morris et al., 1996). DAMOS bathymetry studies have assisted in guiding scows to dispose of sediment in such a way as to create a ring. Sediment unsuitable for unconfined disposal may then be placed in the rings and then capped. This technique impedes the lateral spread of unsuitable material.

5.2. CAD cells

The DAMOS program has also been instrumental in the development of confined aquatic disposal (CAD) cell techniques. CAD cells are used to contain contaminated sediment in-place. The first large scale use of CAD cells was at Boston Harbor. When the Harbor needed deepening, an environmental impact statement (EIS) determined that the use of CAD cells would have the least environmental impact for sediment unsuitable for unconfined ocean disposal. DAMOS assisted in the development, monitoring, and refinement of techniques for this burgeoning technology. A pilot study for construction of one CAD cell in 1997 was conducted first, and applying lessons learned, techniques were modified for Phase II in 1998 and 1999. Sediment was excavated in cells beneath the shipping channel to well below maximum channel depth, and the top layer of unsuitable material was stored on a barge. The deeper, clean sediment was transported for offshore disposal. Cell excavation continued into Boston Blue Clay, a homogeneous, high strength greenish gray clay with low water content and low permeability (CDM, 1991). The unsuitable material from that pit and surrounding areas was placed in the pit, and clean sandy sediment from the Cape Cod

Canal was placed on top. CAD cells were dredged and filled using clamshell dredges and bottom dumping barges, whereas capping involved slow release from hopper dredge equipment to minimize resuspension of contaminated sediment. Sand cap effectiveness was intensively evaluated using several different techniques, including multibeam bathymetry, sub-bottom profiling, coring, and side-scan sonar. Placement and capping operations successfully minimized the potential for exposure of contaminants to the environment. From Phases I and II the following recommendations for future construction were developed: (1) use a moving barge or vessel to slowly dispose the sand over the silt material; (2) increase the time between silt disposal and capping to allow greater consolidation to increase the bearing capacity of the dredged material; (3) continue to use multiple methods to assess cap coverage, including sub-bottom acoustic profiling and coring; (4) use an open clamshell bucket for dredging the silts to minimize the amount of water mixed into the barge. In addition, many recommendations were made for improvements in monitoring techniques (Fredette et al., 1999).

6. Related work

The scientific investigations conducted in New England represent only one part of the enormous body of literature that has been amassed over the last four decades. Considerable work has been done throughout the world to address these same issues. This includes work exceeding $200 million conducted under the Corps of Engineers sponsored research programs (Table 2). Internationally, several countries have made substantial contributions (e.g. The Netherlands, Great Britain, Canada, Germany) (Steeghs et al., 1989; Beckwith et al., 1995; Kothe, 1995; Ridden, 1995). In addition, global oversight is provided under the international London Convention treaty. The convention provides a consistent framework that both member and non-member coastal countries can apply to their individual programs and regulations.

Table 2
Major US Army Corps of Engineers dredged material research programs

Program	Years conducted
Dredged Material Research Program (DMRP)	1973–1978
Field Verification Program (FVP)	1982–1988
Long-term Effects of Dredging (LEDO)	1981–present
Dredging Research Program (DRP)	1988–1995
Dredging Operations Environmental Research Program (DOER)	1998–present

7. Discussion

Dredging and sediment disposal acquired an ignoble reputation that has become almost indisputable. This reputation, while originally based on truth of historic practices, needs to be reconsidered and challenged in light of the tremendous changes that have been made in both the scientific knowledge and the environmentally conscious approach that is now taken for such projects. This is not to say that environmental damage cannot nor will not occur from dredging projects, but the days of large-scale impacts and ignorant decision-making are gone. It is time that the popular opinion surrounding dredging projects change to reflect the existing practices and capabilities. We have learned to evaluate, consider, and balance the impacts from dredging activities. The research effort devoted to environmental impacts of dredging is vast. We have developed methods to make dredging projects result in positive gains for the environment through the isolation of contamination and the restoration and creation of habitats. We have developed methods to monitor environmental consequences and take remedial actions where warranted. Evidence of severe and large-scale unexpected consequences of dredging projects is rare. Monitoring conducted at scores of sites around the world has shown that impacts are typically near-field and short-term.

However changes in public perception come about slowly and will not occur from technical publications. Industry and government need to reach out to the public through multiple communication channels. We believe that steps we have taken in New England to produce brochures and videos (US Army Corps of Engineers, 1999), provide presentations and exhibits, talk one-on-one, and develop web content (www.nae.usace.army.mil/environm/damos/splash_page.htm) have helped to shape New England regional perspectives. The reality of dredging and disposal project management has undergone significant change. The positive and balanced role that dredging now plays in our society's welfare deserves greater recognition.

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