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GLDD's Dodge Island dredging the Cape Fear entrance channel, June 2021.

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CONTENTS

EDITOR'S NOTE

This issue of WEDA's Journal of Dredging includes two manuscripts describing successful projects that should serve as useful examples of innovative management of dredged sediments. The first paper describes the use of maintenance dredging sediment in coastal New Jersey for a range of beneficial uses. It demonstrates how dredged sediment can add value to the local community and environment. The second manuscript describes a Brazilian project which dredged relatively clean sediment from an inlet adjacent to a critical shipping channel to form a CAD cell. Contaminated sediments from the shipping channel were placed in the CAD cell and capped to isolate them from the environment. This manuscript describes extensive environmental monitoring conducted during the placement of contaminated sediments into the CAD cell.

I pen this editorial with a heavy heart. My friend and colleague, Tim Welp, of ERDC passed away unexpectedly in late June 2021. Tim was an essential part of our dredging community. He was involved in many dredging-related professional activities, including WEDA. Tim was gregarious and forward thinking. He contributed positively to our community. He especially enjoyed "spit-balling" new ideas; nothing was too crazy to pass by Tim. I, and all of Tim's colleagues, will miss him. While Tim's passing saddens me, the many calls and emails I received as people heard the news reminded me how fortunate I am to be part of such a caring professional community. The relationships we enjoy extend beyond the professional realm to genuine concern for others' well-being. For me, this was a silver lining in an otherwise dark cloud.

At the time of his passing, Tim was working (with myself and others) on multiple manuscripts for the Journal related to sediment placement techniques. I hope to dedicate a special journal issue to Tim sometime in the near future, including those manuscripts and others. Please let me know if you are interested in contributing a manuscript in his honor.

Don Hayes
Editor, WEDA Journal of Dredging
August 2021

BENEFICIAL USE OF DREDGED MATERIAL FOR MARSH, DUNE AND BEACH ENHANCEMENT IN A COASTAL NEW JERSEY WILDLIFE REFUGE

W. Scott Douglas[1], Metthea Yepsen[2] and Sean Flanigan[3]

ABSTRACT

The New Jersey Department of Transportation, Office of Maritime Resources, manages over 200 nautical miles of navigable shallow draft waterways in the Atlantic shore and Delaware River regions. Historical dredged material management practices relied heavily on the placement of hydraulically dredged sediment into upland confined disposal facilities (CDFs). However, recent evaluations of marsh ecosystems in coastal NJ have revealed that many marshes are suffering from a lack of sediment input and that this may be in part due to the removal of sediment from the system as a result of dredging for navigation. Lack of sediment exacerbates the effects of climate change and sea level rise on marshes, causing marsh loss from shoreline erosion and drowning. One proposed solution is to develop and adopt strategies to keep the sediment within the coastal ecosystem, rather than removing it to an upland CDF. This strategy creates opportunities to manage dredged material in concert with natural processes to ensure that valuable sediment is retained where it is needed (e.g., marshes, beaches, mudflats) and kept out of places where it is not wanted (channels and berths). Not only would this potentially provide much needed management capacity for navigational dredged material, but it would also potentially increase the resiliency of natural and inhabited coastal areas to sea level rise.

In the fishing village of Fortescue, Cumberland County, New Jersey, routine maintenance dredging of the navigation channel that provides access from Delaware Bay to several marinas and emergency services had been hampered by a lack of dredged material management options. After extensive evaluations of the surrounding coastal ecosystem, it was determined by the project team that sediment from the channel could be used to enhance tidal marsh and beaches in the adjacent Fortescue Wildlife Management Area. The goals of the demonstration project were to dredge the navigation channel, increase marsh elevation and density of native vegetation, install a protective dune and thereby improve coastal resiliency, and replenish two beaches. Over the course of two dredging seasons 37,544 cubic yards (CY) of sediment were placed in four areas at a cost of $5.2 million: approximately 8,529 CY were placed onto two marsh sites, 7,565 CY was placed onto two beaches, and 21,045 CY was used to restore a protective dune. Adaptive management during construction ensured that the target dredged material placement elevations were not

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exceeded. Ongoing post-construction monitoring of the enhanced marsh has shown that some elements of the system were able to recover from the stress of placement activities, with readily apparent regrowth of vegetation; however, improvement in the health or resiliency of the ecosystem as a result of the project has yet to be observed.

Keywords: habitat restoration, coastal resiliency, dredged material management, salt marsh, sea level rise

INTRODUCTION

The coastal region of New Jersey (NJ) is a densely populated and heavily utilized shore ecosystem that contains diverse dune, beach, marsh and coastal forest habitats. This area also hosts a large and complex marine transportation system comprised of Federal, State and local engineered waterways, berths, marinas and private slips, supporting a $50 billion shore economy. Since 2014, the NJ Department of Transportation (NJDOT) has been charged with the operation and maintenance of over 200 nautical miles of waterway comprised of 216 marked channels that provide local access to the NJ Intracoastal Waterway (NJICWW), Raritan Bay, and the Delaware River. The US Army Corps of Engineers (USACE) operates and maintains the NJICWW, which runs for over 117 miles between the barrier islands and mainland NJ from Manasquan Inlet to Cape May. These two significant maritime assets have enabled the development of 400 marinas, 325 boat ramps, 235 commercial fishing slips, 57 recreational charters and 250 water-dependent businesses, as well as 40,000 private boat slips. Maintenance of this transportation system requires nearly continuous maintenance dredging to remove accumulated sediment, which has historically been placed on nearby beaches (sand) or in upland confined disposal facilities (CDFs). Since taking charge of Superstorm Sandy recovery and routine system maintenance, NJDOT's Office of Maritime Resources (OMR) has dredged over 1.2 million CY of sediment and placed it on beaches (20%) and in upland CDFs (50%), used it for habitat restoration (22%), or otherwise beneficially used the dredged material (8%).

The New Jersey Marine Transportation System (NJMTS) and the associated waterfront communities exist within a diverse matrix of sensitive coastal habitats, including approximately 1,800 miles of shoreline, 130 miles of beaches, and 289,000 acres of estuarine wetlands (USACE, 2014). Recently, wildlife and habitat managers have become increasingly concerned about losses of both tidal marsh and beach habitats due to the impacts from severe storm events and sea level rise (Bertness et al. 2002, Hartig et al. 2002, Church and White 2011, Partnership for the Delaware Estuary 2012, Watson et al. 2017, Weston 2014). Unfortunately, the rate of sea level rise, coupled with decreased sediment loads in tidal water from anthropogenic activities (e.g., engineered channels, dams, and bulkheads) has caused a dramatic increase in marsh and beach erosion and a reduction in acretion of mineral sediments (Cox et al. 2003, Boyd et al. 2017, Peteet et al. 2018). Since 1977, over 59,000 acres of marshland in NJ have been lost to erosion (Alex Ferencz, Stockton Coastal Research Center, *pers. comm.*). In 2019, the Rutgers University Center for Remote Sensing and Spatial Analysis modeled potential changes in tidal wetland acreage between 2000 and 2050 given a 2ft sea level rise scenario (Lathrop and Love, 2007); it was found that 74,000 acres of tidal wetlands were likely to convert to open water or mud flat due to erosion or drowning. Erosion is not only a problem for these natural areas, but it also increases dredging needs as the eroded material often is deposited into navigation channels.

Historically, a marsh surface was considered a suitable place to dispose of dredged material, with little consideration given to the resulting environmental impacts. As the value of wetlands became better understood and environmental regulations more restrictive in the 1970's, this practice evolved to be replaced with fully controlled upland CDFs. Today, while existing CDFs are allowed to operate, it has become extremely difficult to obtain, permit, and construct new CDFs. Since many CDFs are at or near capacity, there is a need to consider new approaches to managing dredged material or risk not being able to maintain safe navigation. Since healthy low marsh and high marsh habitats exist only at specific tidal elevation (between mean water levels and mean higher high water levels), it seems logical that dredged material be used to help marshes stay above the rising tides rather than being disposed of upland (Ford et al. 1999, Ray 2007, Graham and Mendelssohn 2013).

The rural community of Fortescue is a fishing village of some 400 residents in Downe Township, Cumberland County, New Jersey (Figure 1). The 3800ft long Fortescue navigation channel provides access to the Delaware Bay for two marinas, a small fleet of charter fishing boats, a US Coast Guard Search and Rescue station, a public boat access ramp, and a dock and dine restaurant. The channel is plagued by frequent shoaling, requiring many vessels to traverse the mouth of the Fortescue creek only at high tide. Other than the local beaches, there are no locations approved for the placement of dredged material in the vicinity, making it difficult to maintain safe navigation in the channel.

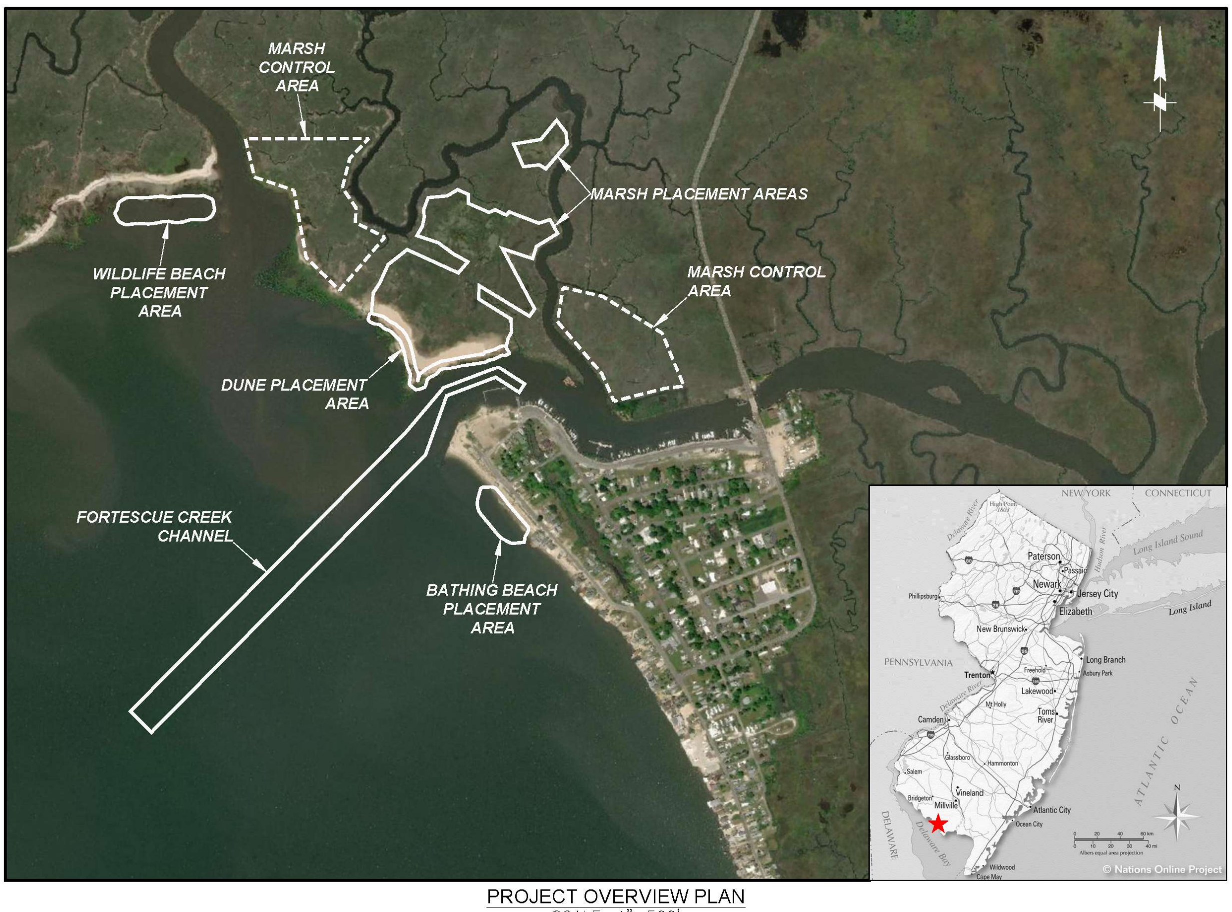

Figure 1. Location of dredging and placement sites in Fortescue, New Jersey

Fortescue village is located within the 1,300-acre NJ Fortescue Wildlife Management Area (WMA) and is surrounded on three sides by extensive salt marsh. The marsh has a tidal range of 6 feet, with typical salinities ranging from 14 to 20 parts per thousand. Vegetated habitats in the WMA include low marsh dominated by the high vigor form *Spartina alterniflora*, high marsh dominated by *Distichlis spicata* and *Spartina patens*, and a variety of native trees and shrubs, including *Iva frutescens* and *Juniperus virginiana*. Upland disturbed areas, including the remnants of man-made dunes, were dominated by the invasive reed *Phragmites australis*. It had been reported by the Partnership for the Delaware Estuary (PDE) that the Fortescue marshes were vulnerable to loss due to the marshes' elevation within the tidal range and recommended that dredged material be used to raise the marsh platform (Kreeger et al. 2015).

Several years ago, WMA managers approached the NJDOT to determine if dredged material from the navigation channel could be used to stabilize the marsh platform. The goals of the marsh enhancement project were to: (1) increase and maintain the optimal tidal elevation (hydroperiod) for native salt marsh species, (2) increase the cover and health of native salt marsh vegetation, and (3) return all other metrics to baseline (i.e., pre-implementation) conditions (unless they were expected to change due to habitat conversion). The ensuing demonstration project is described below.

PROJECT DESIGN

Navigation Channel

The Fortescue navigation channel had been historically maintained at a depth of 8 feet for about 3,800 linear feet. The channel was designed to be 200 feet wide at the Bay side and 60 feet wide inside the creek, with 3:1 side slopes. Condition surveys indicated that approximately 83,105 CY of mixed sand and fines would need to be dredged to return the channel to its authorized 9ft below mean low water (-9ft MLW) plus 1ft of over dredging (Figure 2). The sediment in the channel was primarily coarse-grained, but contained pockets of mixed sand and finer-grained material. Initial estimates of the material quantities were 22,536 CY of material with >90% sand (suitable for bathing beach placement), 32,742 CY of material between 75 and 90% sand (suitable for non-bathing beach placement), and 27,827 CY of finer-grained material (i.e., <75% sand) (suitable for marsh enhancement).

Marsh Enhancement

The next step in the design process was to define those areas in the marsh that needed enhancement with sediment, and what quantities and types of sediment would be required. Based on a reasonable hydraulic pumping distance, all marshes on State-owned land within a one-mile radius of Fortescue Creek were evaluated. Three types of initial site assessments were performed: desktop analyses, site visits, and marsh enhancement feasibility evaluations. The desktop analyses consisted of reviewing readily available information about the condition of the marshes. Specifically, LiDAR (Light Detection and Ranging) data were used to identify low- lying marsh areas (Figure 3) and historical aerial photographs available through Google Earth and the NJDEP Geographic Information System (GIS) were used to assess indicators of marsh stability over time, considering features such as expanding and contracting pools, shoreline erosion, tidal creeks, and the presence of mosquito control ditches. On-site visits were conducted to qualitatively and quantitatively assess vegetation, hydrology, faunal use, and marsh platform stability. Based on the outcomes of these evaluations, the list of potential enhancement areas was narrowed to those that exhibited

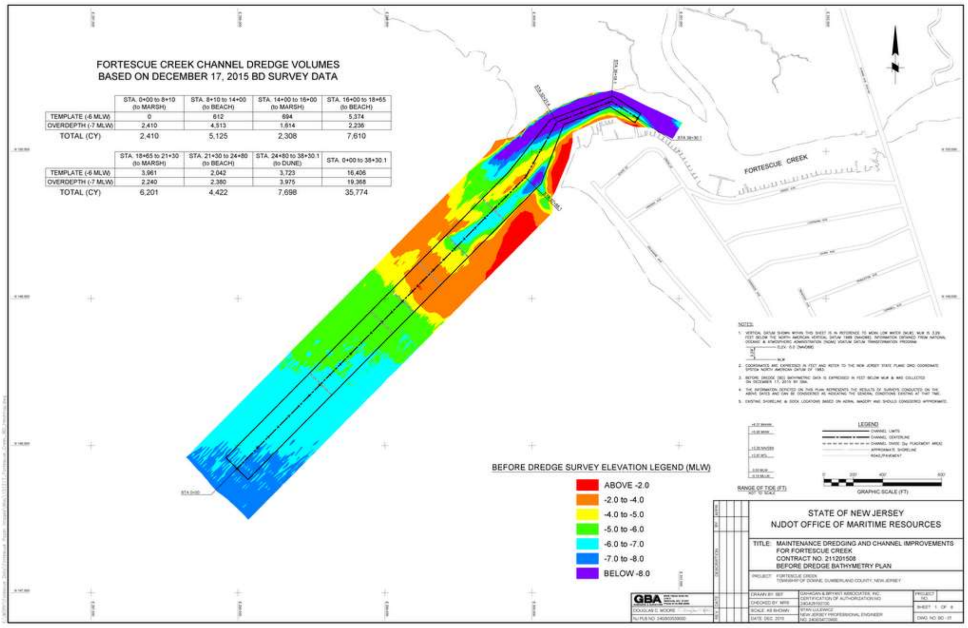

Figure 2. Initial conditions of Fortescue Creek channel in 2015.

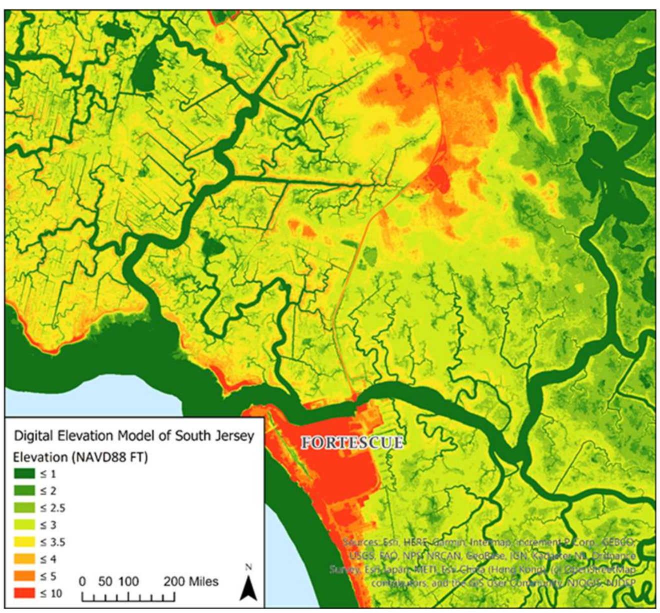

Figure 3. LiDAR based digital elevation model of the Fortescue WMA depicting the relative elevations of the marsh. This map was used to help preliminarily select areas of salt marsh that might benefit from the addition of sediment. Credit: NJDEP Bureau of GIS, NJ Office of GIS NJOIT, USGS, Sanborn Map Company, Inc.

multiple characteristics typical of stressed marshes, including undulating terrain, extensive mosquito control ditching, depressions, erosion, an unstable marsh platform (wobbly hummocks of *Spartina sp.* surrounded by unconsolidated mud), minimal faunal use, and sparse and stunted vegetation (Figure 4).

Finally, site-specific tide gauge data (Table 1) and topographic surveys were collected to further refine the locations suitable for dredged material placement. The final marsh enhancement areas were defined through a combination of marsh platform stability, plant cover and vigor, elevations, tidal range, and the location of natural marsh drainage pathways. Eventually, two target placement areas were identified, one 20.8 acres in size and the other 1.6 acres in size.

Target elevations for placement were determined by field observations of the elevation ranges of plants found on the marsh (Table 2). The maximum dredged material placement elevation was set at +3.3ft NAVD88, corresponding to a fill thickness of 0.0 – 4.0ft and an average depth of 9 in above the existing marsh platform (Figure 5a). It was expected that the dredged material would settle and consolidate, eventually resulting in a final depth of 4 to 6 in, and an elevation between 2.8 and 3.0ft NAVD88. It was hoped that limiting the project to these elevations would increase high marsh vegetation without encouraging further spread of *P. australis*.

The amount of sediment needed to achieve this elevation was estimated to be 16,013 CY (Table 3). Since the only placement site for fine- grained material was the marsh, the target depth for the dredging would

have to be limited to -7ft MLW (-6 ft + 1ft overdepth). This would ensure that there was adequate placement for the 11,350 CY of fine grained sediment to be dredged from the channel (based on initial condition surveys), with little chance that the site would be overfilled.

Figure 4. Examples of unstable marsh platform observed at Fortescue WMA during site visits. Portions of the marsh were characterized by low vegetation cover comprised of wobbly hummocks of *Spartina patens* and *Spartina alterniflora* surrounded by unconsolidated mud.

Table 1. Tidal Boundary Elevations. Tide range values were determined by on-site gauges and converted to NAVD88 to be referenced with NJ-DEP's Office of Engineering and Construction Bureau of Coastal Engineering Project 2155.

Tidal Boundary Elevation (ft)	Elevation (ft)
High Tide Level (HTL)	+4.53
Mean Higher High Water (MHHW)	+3.08
Mean High Water (MHW)	+2.66
0.00 NAVD88	0.00
Mean Tide Level (MTL)	-0.32
Mean Low Water (MLW)	-3.29
Mean Lower Low Water (MLLW)	-3.47
Mean Tide Range (MHW – MLW)	+5.95

Table 2: Biological Benchmark Range Summaries used to Select Target Elevations for the Fortescue project.

Plant Type	Elevation (feet NAVD88)
Iva frutescens (Bigleaf Marsh-Elder)	3.18 - 3.65
High Vigor *Spartina alterniflora* (Saltmarsh Cordgrass)	-0.2 - 3.69
Intermediate Vigor Spartina alterniflora	2.18 - 3.69
Low Vigor Spartina alterniflora	2.51 - 3.08
High Marsh	2.65 - 3.72
Phragmites australis (Common Reed)	2.98 - 3.72

Table 3. Summary of dredged material characteristics and placement site capacity.

Material Type	Placement Type	Placement Site Capacity CY	Dredged Material Volumes as a function of Target Depths and Material Types		
			-6 +1ft MLW (CY)	-7 +1ft MLW (CY)	-8 +1ft MLW (CY)
Sand, >90% coarse	Dune or bathing beach	17,160	7,800	14,906	22,536
Mixed sand and fines >75% coarse, <90% coarse	Wildlife beach	21,127	16,550	24,813	32,742
Fines, <75% coarse	Marsh	16,013	11,350	19,720	27,827
Total		54,300	35,700	59,439	83,105

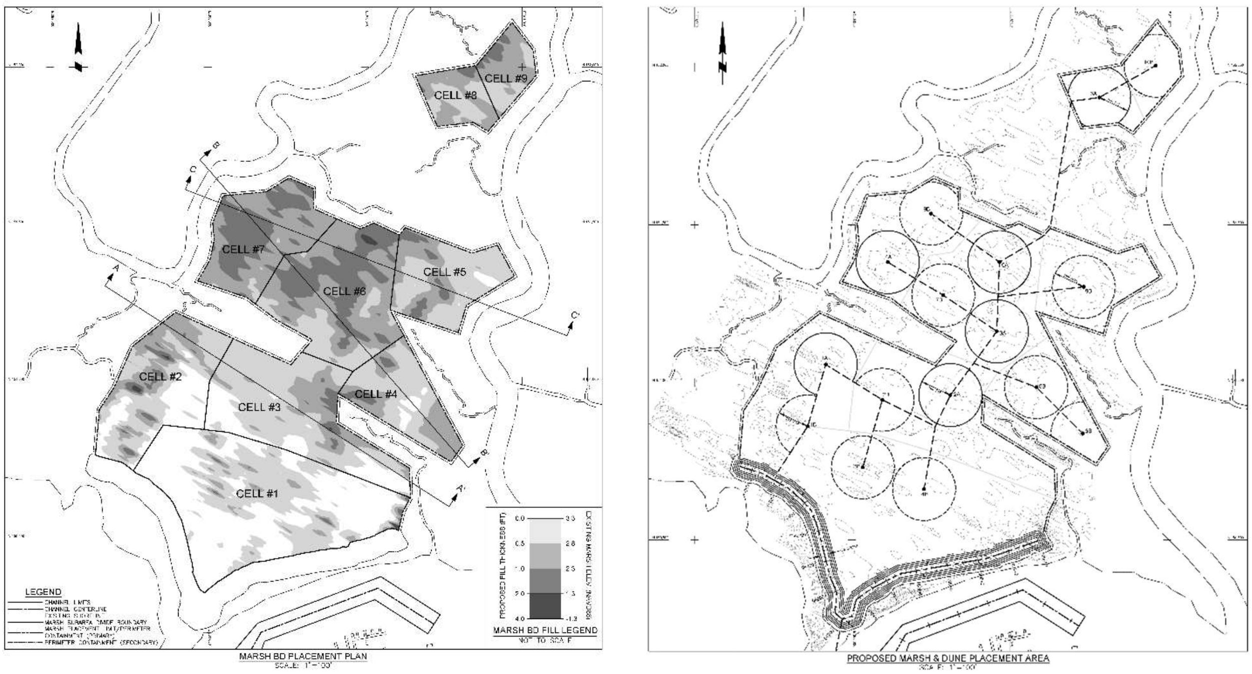

Figure 5. Targeted fill thickness (a) and engineered distribution array (b) for Fortescue marsh enhancement.

To deliver the sediment to the two target marsh areas, an array of inflow pipes and valves was designed (Figure 5b). Multiple pipe/valve pathways could be used at any given time, ensuring that the dredge could operate continuously even if parts of the enhancement site needed time for the dredged material to settle out and excess water drain out. Grade stakes marked at the maximum elevation of +3.3ft NAVD88 were placed throughout the placement areas prior to implementation to provide an easy visual reference for inspectors to ensure that the target placement elevations were not exceeded.

Due to the wide tide range, there was concern that fine-grained dredged material might not be retained on site and could potentially fill in natural drainage pathways. A 50 ft buffer was required around the largest streams, and a 10 ft buffer was required around smaller drainage pathways. To minimize dispersal of suspended sediment into these tidal creeks, both placement areas were to be entirely surrounded by a double ring of woodchip-filled photodegradable polypropylene tubes (Filtrexx®, Dover, OH). Twelve-inch diameter tubes were to be used for the primary containment and 6 inch tubes were to be used for the secondary containment. In low areas, the containment tubes could be stacked to provide the proper elevation as needed for retention of dredged material slurry. Containment tubes would be held in place with wooden stakes driven through the tubes into the marsh platform.

Dune Restoration

On the seaward boundary of the targeted marsh site there were the remnants of a man-made coastal dune. Environmental engineers determined that this dune was preventing erosion of the damaged marsh platform by reducing wave energy from the Bay. However, the structural integrity of the dune had been compromised by decreased elevation, reduced footprint, and breaches in two areas. In fact, the dune had been retreating at a rate of 0.5-1 meter/year since 1970 (Kreeger et al. 2015). The consensus of stakeholders was that without intervention the dune would eventually erode completely, leaving the marsh vulnerable to erosion and jeopardizing the success of the project. It was decided that coarse grained material from the channel could be used to restore the dune. Restoration would also provide an opportunity to replace the extensive stand of *P. australis* with native plants.

A 1,340ft long dune (3ft high, 25ft wide at the top and with 5:1 side slopes) was proposed on a 1.9 acre footprint using coarse-grained dredged material (>90% sand). Small trees and shrubs had stabilized the remnants of the old dune at its southerly point, and this area was utilized as a heron roost and would be retained. The restored dune would be planted with native grasses and shrubs. Should it become necessary, a beach area, owned by Downe Township for bathing, was identified to take any excess coarse-grained material. Between the dune and the beach there was capacity for 17,160 CY of >90% coarse.

Beach Replenishment

The beneficial use of dredged sand for beach replenishment has long been an accepted practice in New Jersey. Historically, most replenishment projects focused on bathing beaches, but recent efforts by agency land managers have been made to identify isolated natural beaches that can be utilized by wildlife, especially horseshoe crabs and shorebirds. During site assessments of the proposed natural beach restoration area, it was confirmed that it was both eroding and highly utilized by shorebirds and was, therefore, a good candidate for habitat restoration. A 650 ft long by 80 ft wide beach placement template, with a 15:1 slope, was designed for the site with capacity for 21,127 CY of material.

Final Design

Prior to seeking bids for dredging, a careful evaluation was performed comparing the volume and characteristics of the material in the channel to the amount of capacity available at each of the beneficial uses identified. It was decided that a target dredge depth of -7ft (-6ft MLW plus 1ft of over dredging) was appropriate. Adjustments were made to the plans to ensure that the contractor would be able to construct each of the desired features, while still accomplishing the navigation goals.

CONSTRUCTION

Wickberg Marine Contracting, Inc. of Belford, NJ was selected as the contractor for construction. Mobilization to the site began on January 27, 2016. Due to permit restrictions for protection of wildlife, construction had to halt on April 15, 2016. Unavoidable delays prevented the work from being completed in the first dredging season. The contractor remobilized to the site on December 9, 2016 and the dredging was completed on April 14, 2017.

The first step in construction was installation of the sediment enclosure. This required over 20,000 feet of Filtrexx® tubes and took four weeks to install (Figure 6a). During the installation, considerable damage was done to the marsh by vehicles. The second step was to install the distribution array. In an effort to reduce vehicle use, the sediment distribution array was constructed in phases, with the first phase going directly to the furthest area from the waterway with a backup line directed to the largest and deepest pool area in the center of the marsh. A "Y" valve was installed to allow the crew to switch between the two placement areas as needed (Figure 6b).

The dredge plant utilized was an AMMCO 12in x 12in diameter hydraulic cutterhead suction dredge with 900 horsepower (hp) pumping into a 12in diameter high-density polyethylene (HDPE) pipeline. The dredge was 90ft long with 70ft high stern spuds, and drafted 3ft. The dredge was equipped with Dredge Pack®, two global positioning system (GPS) antennas, and an inclinometer. The swing of the dredge was limited to 100ft, requiring two passes to dredge the entire channel width (Figure 7).

During marsh placement, the dredged material was pumped onto the site through the distribution array to the chosen placement area. The end of the pipe was moved about the placement area as needed using an excavator fitted with low pressure tracks (Figure 8a). When coarse-grained material built up around the discharge point, the pipe was redirected and/or the material smoothed out with the excavator bucket (Figure 8b).

While diffuser plates were available for use during the project, most of the time the free flow of the dredged material slurry provided acceptable results (no excessive mounding or loss of sediment).

Over the intervening time between the initial design and the start of dune construction, a number of severe storms caused considerable erosion to the front edge of the dune. In addition, sampling of the remaining material following season one dredging revealed that very little of the original amount of fine-grained

Figure 6. Perimeter containment installation (a) and contractor utilized distribution array (b)

Figure 7. AMMCO 12” Hydraulic Cutterhead dredge plant

Figure 8. Dredged slurry being pumped on marsh (a); distributed with long reach excavator (b)

material was still available in the navigation channel and in fact, this material had been replaced by coarser grained material that was unsuitable for marsh placement. It was decided to relocate and redesign the dune. The new dune would be 1,100ft long, 6ft high, 40ft wide at the top, with 4:1 side slopes on the inside and 5:1 side slopes on the outside, on a 2.3-acre footprint; at least 16,630 CY of >90% coarse-grained dredged material would be needed to construct the revised dune.

The required regulatory approvals for the revised dune design delayed the start of season two. The contractor did not remobilize to the site until December 9, 2016. During dune reconstruction, the dredged material slurry was pumped to a surge pit excavated into the marsh surface at the center of the dune footprint. The coarse-grained material settled out quickly, and the overflow was directed along the dune footprint and back to the bay, allowing sufficient time for fine-grained material to settle out over a small area of the marsh surface behind the dune (Figure 9a). The coarse-grained material was excavated continuously from the pit and bulldozed into place over the footprint to shape the dune (Figure 9b).

Once completed, the dune was planted with 16,000 plugs of 9 different native species.

During beach placement, the slurry was directed into a trench dug longitudinally along the target beach, with the overflow allowed to flow back toward the Bay (Figure 10a). Coarse-grained material was excavated from the trench and pushed into place with a bulldozer in the area demarcated by pre-placed and surveyed grade stakes (Figure 10b).

MONITORING

Monitoring of the marsh placement site was conducted from 2015 through 2017 under a grant from the National Fish and Wildlife Foundation, and from 2018 through 2021 using funds from a USEPA Wetland Program Development Grant. As a demonstration project, the monitoring plan was intentionally comprehensive to evaluate a broad range of the potential effects of placing dredged material on the marsh (Table 4). Most parameters were monitored following a before-after-control-impact (BACI) design. In addition to the formal monitoring plan, the dune and marsh placement areas were qualitatively inspected monthly during the growing season for two years to observe physical changes in the salt marsh and dredged material, and to document biological recovery. The perimeter and interior of each placement area were traversed, and qualitative observations were made. In 2016, these observations focused on documenting the status of vegetation recovery, identifying vegetation die-off areas, assessing containment integrity and impacts on marsh recovery and dredged material dynamics (e.g. dewatering, consolidation, erosion). In 2017, observations of planting success and failure were added to the list of marsh features being documented. These observations have continued on an annual basis and are planned through 2022.

Figure 9. Settling trench for dune construction (a) and shaping of dune with grade stake in foreground (b).

Figure 10. Settling trench for beach placement (a) and bulldozer grading sand to beach template (b).

Table 4. Long-term monitoring of marsh enhancement and control areas at the Fortescue site. Monitoring years are calendar years beginning with the first summer after dredging (2016).

Characteristic	Methodology	Location	Frequency
Sediment Thickness	Hand measurement	39 placement plots	Post-construction Years 1 and 2
Ground Elevation	RTK-GPS	Placement and control sites	Baseline, post-construction Years 1, 2, and 4
Water Level	Water level loggers in creek and wells	Placement and control sites	Continuous Feb-Dec, baseline through post-construction Year 2 and March-Oct post construction Year 4
Habitat Type	Drone flyover and GIS analysis	Placement and control sites	Post-construction Years 1, 3, 4, and 5
Bearing Capacity	Slide hammer	25 plots in placement and control sites	Post-construction Years 1, 2, 4, and 6
Sediment Characteristics	Sulfur, Potassium, Phosphorus, Carbon, % Organic Matter, Grain size	2 locations in placement and control sites	Multiple sampling events; post-construction Years 1, 2, and 4
Plant Cover, Height, and Composition	Visual assessment in $1 m^2$ plots	25 plots in both placement and control sites	Baseline, post-construction Years 1, 2, 3, 4, and 6
Benthic Infauna	Coring	10 cores each in placement and control site	Multiple sampling events; post-construction Years 1, 2, and 4
Epifaunal Macroinvertebrates	Visual assessments $0.25 m^2$ subplots	25 plots in placement and control sites	Baseline, post-construction Years 1, 2, 3, 4, and 6
Birds	Visual and song recording response	Placement and control sites	3 times per year, baseline, post-construction Years 1 and 2

RESULTS AND DISCUSSION

Approximately 37,544 CY of sediment was dredged over two dredging seasons, bringing the channel to a navigable depth of –6 (+1)ft MLW. Over the course of the project, 8,529 CY were placed on 6.6 acres of marsh, 7,005 CY were placed on 1.3 acres of natural beach, 21,045 CY were used to restore the 1,100ft long protective dune (2.3 acres), and 560 CY were placed on the municipal bathing beach (0.3 acres) (see Figure 11).

Dredging and Marsh Enhancement

A total of 8,529 CY of sediment was removed from the Fortescue channel and placed onto 6.6 acres of marsh over ten dredging days between March 6 and March 20, 2016 (Table 5). This utilized most of the available fine-grained material present in the channel. Since the remaining material was coarser than

Figure 11. Completed project areas, clockwise from left, marsh, dune, wildlife beach, bathing beach.

Table 5. Dredging summary.

Placement Site	Calendar Dates	Dredging Days	Volume (CY)	Acres	Cost (excluding engineering, oversight and monitoring)
Marsh enhancement	3/6/2016 to 3/20/2016	10	8,529	6.6	$893,100 (plus $583,106 for containment)
Habitat Beach Enhancement	3/26/2016 to 4/14/2016	8	7,005	1.3	$665,209
Dune Reconstruction	2/15/2017 to 4/10/2017	21	21,045	2.3 (1100 ft)	$1,085,565
Bathing beach replenishment	4/11/2017 to 4/12/2017	2	560	0.3	$56,804

originally expected and the effort needed to place it in the remaining mars areas would require the use of heavy equipment, it was decided to not place more material in the marsh and to focus on restoring the dune. Placement thickness on the marsh averaged 6.9 in (SD = 6.1in) based on thickness of sediment measured in at five points in 39 3.3ft^2 permanent monitoring plots. As-built elevations in the two lower marsh placement areas ranged from 2.0 to 4.0ft NAVD88, with an average of 3.0ft NAVD88 (Figure 12); this was below the maximum allowed elevation of 3.3ft NAVD88. Containment was allowed to remain in place until March 2018, when the tubes were cut open by hand. The wood chip filling was dispersed over the marsh, but the plastic Filtrexx® tubes were removed and disposed.

Schedule

Project mobilization, administrative delays, winter weather, and equipment difficulties reduced efficiency. Working in a coastal environment provided its usual challenges; including equipment becoming mired in marsh and potholes, resulting in 101.2 delay hours for equipment downtime. Conducting the project during the winter was required as a condition of the dredging windows specified in the permits issued for the project by the NJDEP and USACE. Over the course of the project, there were 34 weather delay days. Compounding matters, night operations could not be conducted out of concern for personnel safety and the large number of oversight personnel needed on-site. Overall, while only 41 dredging days were required to complete the project, it stretched over two dredging seasons from late January 2016 to April 2017.

Dredging and Beach Placement

Approximately 7,000 CY of sediment was removed from the Fortescue channel over the course of ten dredging days between March 26 and April 14, 2016, and the sand was placed onto the wildlife beach. A total of 560 CY was removed between April 11 and 12, 2017 and placed onto the Fortescue bathing beach (see Table 5). At both placement sites, fine-grained material was allowed overflow the trenches to return to the Bay, while coarse grained material was retained and then graded into place with a bulldozer to create 1.3 acres of wildlife beach and 0.3 acres of bathing beach (Figure 13).

Dredging and Dune Construction

A total of 21,045 CY of sediment was removed from the Fortescue channel over the course of 21 dredging days between February 15 and May 10, 2017 (Table 5). The coarse-grained material was excavated from

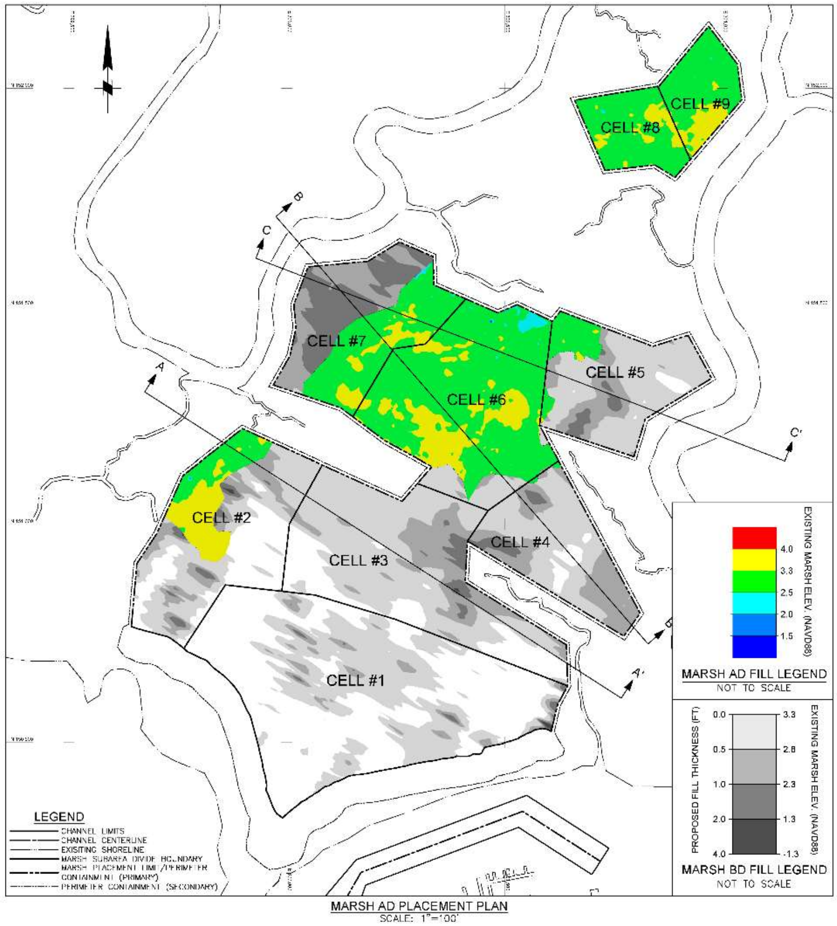

Figure 12. Final elevations for marsh placement sites

the slurry pit and bulldozed into a 1,100ft long dune that was 100ft wide at the base and 40ft wide at the top (Figure 13). The completed dune was planted with 16,000 plants representing 9 native species.

Cost

The total contractor cost, including mobilization and containment installation, was $3,430,128 for 37,544 CY of placed dredged material. The design, engineering, and oversight components of the project cost $1,152,224. The pre- and post-construction monitoring was performed by outside contractors and cost approximately $600,000. This brought the total project to $5,182,352, or $140 per cubic yard dredged.

Figure 13. Marsh damage caused by extensive vehicular traffic and a damaged area showing regrowth, but continued ponding between 2016 and 2019.

Adaptive Management During Construction

Multiple teams of inspectors monitored all aspects of the project during construction. Potential impacts to wildlife and historical structures/artifacts were carefully monitored as required by the permits; no impacts to wildlife or historical artifacts were observed over the two dredging seasons.

It was apparent during the installation of the dredged material containment that the marsh platform was not stable enough to support the marsh equipment used by the contractor. This resulted in rutting and damage to marsh grasses, and in some cases cutting of the marsh platform in softer areas (Figure 12). Rather than construct the full array of pipes and nozzles originally planned, it was decided to first place material in those areas of marsh requiring the most fill. Once those areas were filled, the discharge pipe was moved using an excavator to either fill the next closest area, or the slurry was directed out across the marsh. Regular observations were made of fill levels, and containment was checked to ensure it remained in place, was not overtopped by the dredge slurry, nor was dredged slurry observed to flow into the site drainage waterways. Movement of the dredge outflow pipe to direct placement where needed was adequate to avoid overfilling. In cases where coarse-grained material built up to a level higher than the target placement elevation, these areas were easily graded down with machinery to below the maximum elevations.

As previously mentioned, there was a loss of fine-grained material from the Fortescue channel over the course of the project and there was insufficient material available in season two to fill the ruts and holes created by equipment in season one. To speed recovery, areas that were devoid of vegetation were staked out in the following elevation zones and planted with 27,765 plants:

- **2.0 – 3.0’ NAVD88**: *Spartina. alterniflora* (100%)
- **3.0 – 4.0’ NAVD88:** *Spartina. patens, Distichlis spicata, Juncus gerardii, Spartina cynosuroides and Solidago sempervirens* (each at 20%)
- **3.5 – 4.0’ NAVD88**: *Iva frutescens* (33%) and *Baccharis halimifolia* (67%)

Those areas not able to be planted due to deep water were allowed to revert to open water habitat.

Post Construction Monitoring

Depth of Placed Sediment, Elevation, and Water Level

Increasing the elevation of the marsh to optimize the flooding regime for native salt marsh plant species was the most important goal for this demonstration project but it is also the most difficult result to evaluate. As-built surveys in the placement sites showed an average elevation gain of 0.5ft, from just under mean high water (MHW; 2.5ft NAVD88; Standard Deviation [SD] 0.41ft) to just under mean higher high water (MHHW; mean of 3.02ft NAVD88, SD 0.27ft). But by 2019, the gain in elevation had decreased to a mean of 0.27ft in the enhancement area. At the same time, the control sites had gained an average 0.39ft. Despite this mathematical difference, the average elevations at both sites were still between MHW and MHHW which is typically considered to be elevation range for high marsh habitat (Bertness 1991).

It is possible that average elevation is an inappropriate metric to characterize a diverse site. Looking at it a different way, prior to placement, only 17 percent of the enhancement area was within the target elevation (between 2.8 and 3.0ft NAVD88), but after four years, that had increased to 33 percent. Unfortunately, at the same time other areas of the enhanced marsh site decreased over time while the majority of areas in the control site increased over the same time. Analysis of changes in marsh elevation over time are ongoing.

Bearing Capacity

Bearing Capacity was three-fold higher at the Fortescue placement sites compared to the control sites (Faircloth and Zito-Livingston 2020). In a natural marsh, bearing capacity is used as a proxy for the density of roots and rhizomes, with higher density associated with better condition and less inundation (Twohig and Stolt 2011). However, in marshes enhanced with sediment, the higher bearing capacity is not an indicator of belowground biomass but is likely correlated with the lack of organic matter in the soil, compaction of sediment, and the presences of thick algal and bacterial mats – all of which may also make it more difficult for vegetation and the benthos to recover. It is noted however, that in this case, recovery appears to have taken place.

Sediment Properties

Properties of sediment sampled in the enhanced marsh were different than the properties of sediment found in the control site. Enhancement area surficial sediments were sandier (90% sand vs. 90% silt in control) and had far lower concentrations of total phosphorus (10%), total nitrogen (8%), sulfur (21%) and organic matter (4%) of the natural marsh control sites based on 2017 data collection (Taghon 2017). The lower carbon, nitrogen, phosphorus, and organic matter contents in the upper layer of the enhanced marsh sediment are likely to change over time now that the vegetation has recolonized the site and as the tides bring in nutrients and sediments. The grain size of the sediment also may change over time as the placed dredged material is integrated into the existing marsh sediment (Croft et al. 2006).

Vegetation

Overall vegetative cover significantly decreased in the placement areas one-year post-construction, with a return to baseline and matching control site conditions by the third year after construction (Figure 14). As

Figure 14. Time series of marsh placement area at Fortescue site over three growing seasons.

of four years post-construction, native vegetation has completely recovered, but plot-based monitoring has not shown a statistically significant increase in cover when compared to baseline conditions or the control site.

The project was primarily designed to establish high marsh habitat, but the expected shift in dominant plant species from *S. alterniflora* to *S. patens* and *D. spicata* was not observed in the permanent monitoring plots; *S. alterniflora* remained the dominant species (Faircloth and Zito-Livingston 2020). It is possible that more time is needed for high marsh plants to establish, or that the elevation gained was not sufficient to create high marsh habitat. Monitoring of vegetative cover in the marshes using drone photography is ongoing.

Benthic Infauna

The first year after sediment was placed on the marsh, very few benthic infauna were found in the top 0.1in of the marsh sediment. The following year, there was some recovery, but the density and species composition of the benthic infauna were still statistically different than that at the control sites (Taghon 2017). While the initial loss of benthic infauna was expected, the lack of recovery over the first-year post-construction was not expected. At least one other study of benthic infauna recovery in beneficial use of dredged material projects found rapid recovery of some species (Myszewski and Alber 2017). Taxa well-suited to disturbed environments began to recolonize the sediment after two years. As noted above, the placed sediment differed from natural marsh sediment, and this may have slowed recolonization (Minello and Zimmerman 1993, Bolam et al. 2006). It is expected that as sediment properties continue to change, so will the benthic infauna community.

Epifaunal Macroinvertebrates (EMI)

The three species of EMI observed at Fortescue were the salt marsh snail (*Melampus bidentatus*), ribbed mussel (*Geukensia demissa*), and burrowing crabs (using burrows as a proxy for crab abundance). EMI richness and density were much lower in the placement area monitoring plots compared to the control plots immediately post-placement; this was anticipated due to the low mobility of these species (Moritzen et al. 2017). EMI richness increased steadily from year 1 to year 4. Abundance of *M. bidentatus* and crab burrows also increased from year 1 to year 4, and now matches that seen in control plots. However, abundance of *G. demissa* remains much lower in placement plots versus control plots in year 4 (A. Zito-Livingston pers. comm. April 2021). Crabs, snails, and ribbed mussels are dependent on sediment characteristics, vegetation, and flooding. Thus, changes in the EMI post-placement were expected. Additionally, some of these species, especially ribbed mussels, are less mobile than crabs, snails, birds and fish, and may take additional time to recolonize.

Nekton

Because the goal of the project was to elevate the marsh platform, decreases in nekton were expected. All the fish species present in 2017 were found in greater numbers at the control sites compared to the enhancement sites (Kwityn and George 2017). It is not expected that nekton density will ever return to baseline conditions at the enhancement site.

Birds

Avian guilds represented at the sites were gulls, rails, passerines, wading birds, and shore bids. The proportion of individuals belonging to different guilds shifted between years in both the control and placement areas. There were no differences in bird abundance or species richness found between the enhanced marsh and control marsh as of Year Two post-construction, however the species composition did change dramatically year to year. The most notable changes in birds between the pre-construction and post-construction surveys seen in both the control and enhanced marsh in Year 2 were a precipitous drop in clapper rail (*Rallus crepitans*) sightings and an increase in Passerines and shorebirds (Princeton Hydro LLC 2017). It is not known if this was due to the project or other factors. If the clapper rails do not return to the site, further study will be needed.

SUMMARY

The total cost of the project was high relative to historical costs in the region; over $140 per CY including permitting, oversight, and monitoring. However, the demonstration nature of the project, as well as its relatively small volume, use of multiple placement areas (requiring multiple mobilizations,) and highly conservative permit conditions (dredging windows and containment requirements), contributed significantly to this cost. It is believed that the lessons learned from this demonstration project will enable future projects to be constructed at a much lower unit price.

While more monitoring is needed, this study begins to support the idea that dredged material from navigation projects can be safely used to enhance coastal ecosystems, including marshes, provided the material is of suitable grain size, not contaminated at levels of concern, and placed on sites that have been shown to be degraded due to low elevation. The per cubic yard costs of marsh enhancement projects using these placement techniques are likely to be higher than traditional dredge material management practices; however, additional benefits to coastal communities and ecosystems can potentially offset or justify these higher costs. In addition, in areas without alternatives, marsh enhancement and shore stabilization projects may be the only viable dredged material management alternative.

The initial adverse impacts of this dredged material placement, at least to marsh ecosystems, are significant and full recovery of such sites is on the scale of years, if not decades. Based on studies of created, restored, and enhanced marshes the goal to have all other ecological metrics return to baseline condition may not have been realistic, especially in the initial two-years of monitoring the project (Moreno-Mateos et al. 2012). Therefore, this technique should be avoided in marsh systems that are functioning normally or are not under threat from sea level rise. Additional study is warranted to determine the long-term effects of this practice and the impacts of repeated applications of sediment before applying the technique to large-scale resource management in coastal ecosystems.

Of particular note are these lessons learned from this demonstration project:

- Evaluate the current condition and needs of potential placement areas and establish control sites
- Define success criteria prior to the start of the project
- Identify multiple placement options and backup capacity
- Develop an adaptive management plan prior to the start of construction
- Include both dredging and habitat stakeholders in project development from the beginning
- Minimize containment to what is essential
- Minimize the use of machinery on the marsh
- Plan for more than two years of post-construction monitoring

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CONFINED AQUATIC DISPOSAL (CAD) AS A SOLUTION FOR SEDIMENT MANAGEMENT IN THE PIAÇAGUERA CHANNEL CLEAN-UP – SANTOS – SP - BRAZIL

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Patrícia F. Silvério[4] and Michael R. Palermo [5]

ABSTRACT

This article presents the history, criteria and planning that supported decision making for the use of a Confined Aquatic Disposal (CAD) cell in the Santos Estuary, São Paulo, Brazil, for contaminated sediments management during the clean-up of the Piaçaguera Channel. The methodology used in CAD implementation phases, the CAD capping design, and beneficial use of dredging material from Santos Port channel are described. Finally, aspects of construction management, environmental monitoring, and the clean-up results to date are presented.

Keywords: Confined Aquatic Disposal; Contaminated Sediments; Capping; Dredging; Beneficial Use, Density Profiles.

INTRODUCTION

The Piaçaguera Channel, located in the Santos Estuary, São Paulo, Brazil, is an important navigation route linking the Terminal Integrador Portuário Luiz Antônio Mesquita - TIPLAM and USIMINAS terminal to the navigation channel of the Port of Santos, often considered the most important port of South America (Figure 1).

Santos Estuary and particularly the Piaçaguera Channel were severely anthropized during the industrialization processes occurring since the 1950s (Silva et al. 2008). Fortunately, with increasing regulatory control in the last decades, the regional water and sediment quality are better, but on the Piaçaguera Channel, depth profiles from environmental surveys found sediment contamination mainly from metals and PAHs.

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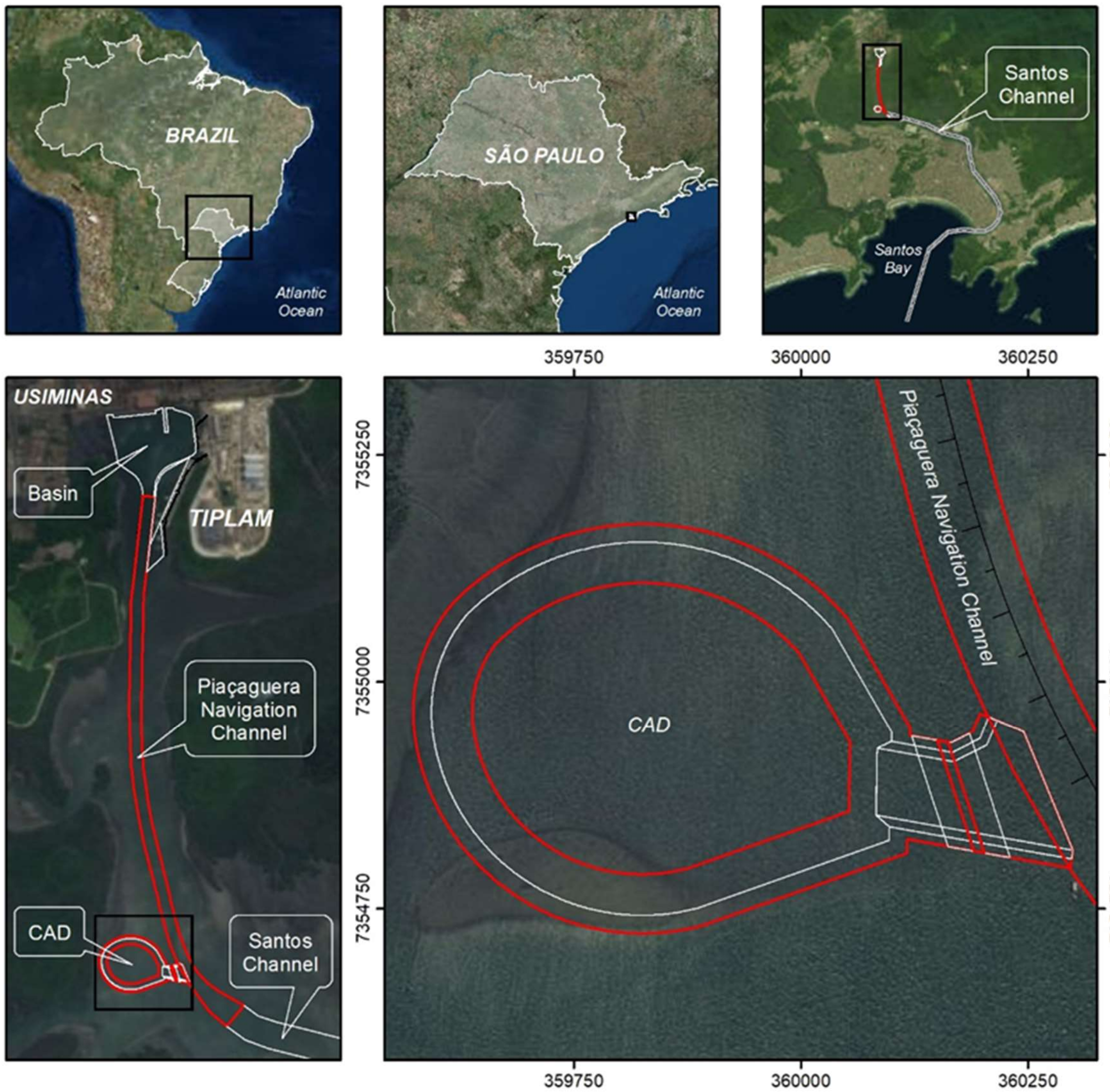


Figure 1. Study area. Piaçaguera channel, Santos, São Paulo, Brazil.

Since dredging is essential to maintain depth for a navigation channel and the terminals, several sediment characterization studies have been carried out to evaluate the concentrations of PAHs and other contaminants in the channel sediments throughout the project area to determine layers for dredging and to define a clean-up project. Hundreds of sediment samples collected from the top 4 meters of sediment along the entire Piaçaguera channel were analyzed. Those samples showed some hot spots along the channel with the higher contaminant concentrations reaching up to 100 ppm of total PAH.

The sediment quality evaluation was carried out using a Screening Level Risk Assessment during the planning of the channel dredging. The risk assessment results were used to define clean-up dredging limits for the Piaçaguera Channel. Based on the results, dredging the channel to -14.5 m depth was defined as an adequate clean-up action.

Due to the significant volume of material that needed to be dredged for clean-up of the Piaçaguera Channel, around 2.8 million cubic meters, it was necessary to find a solution for contaminated sediments management and final disposal. The total volume (2.8 M) included good quality material as well and was considered a conservative estimate to meet both dredging technical considerations and environmental agency requirements. Several engineering and environmental studies were carried out in the search for a technical, economic, and environmental solution that would allow for the safe handling and disposal of the contaminated sediments, which are not suitable for oceanic disposal. The decision matrix indicated the best alternative would be the implementation at an underwater Confined Aquatic Disposal (CAD) cell located in the interior of the Santos Estuary, near the Piaçaguera Channel. The selected site was in an area duly licensed and authorized by the Brazilian and São Paulo State authorities based on rigorous and complex environmental and modeling studies carried out to obtain necessary permits.

The purpose of a CAD is to isolate contaminated dredged material inside a subaquatic cell which is then capped with better quality, essentially uncontaminated, material. According to Vogt (2009), a CAD can be created in natural depressions in the seafloor, in borrow pits in the seafloor from mining operations (e.g., beach nourishment), or in specifically designed and constructed cells to contain the contaminated dredged material, which is exactly the case of the Piaçaguera Channel.

During the years 2016 and 2017, a CAD cell was excavated using different dredging methodologies and following strict technical and environmental control and monitoring standards, with the CAD opening phase completed in June 2017.

Once the CAD was opened, filling with dredged material from the Piaçaguera Channel was initiated. The CAD´s filling was strategically executed in two steps between December 2017 and November 2019 to allow time for the dredging material to consolidate. Following the initial filling step, deposited sediments inside CAD were allowed to consolidate by its own weight until the CAD was capped in August 2020 with suitable material dredged from Santos Port channel to isolate the contaminated material.

Clean sediments in the seabed of Santos Port channel were used for the capping material. The re-use of these sediments was proposed as a beneficial solution for the dredged material that usually is disposed in the ocean in front of Santos Estuary inlet at the Oceanic Disposal Polygon (ODP). The clean-up dredging in the Piaçaguera Channel resulted in the removal of a large mass of contaminants (PAHs and metals) from the area and their disposal into permanent confinement in a CAD cell.

DESIGN CRITERIA AND PLANNING FOR CAD IMPLEMENTATION

The CAD´s implementation was planned as three distinct phases: i) opening, ii) filling (2 steps) and iii) capping. All phases were completed.

The CAD was designed to contain all material not suitable for oceanic disposal from Piaçaguera Channel, including an additional volume based on the conservative scenario as defined by the environmental agency. The first stage of filling was equivalent to a volume of approximately 2.3 million cubic meters and the second stage was estimated at 500 thousand cubic meters, totaling 2.8 million cubic meters.

Considering recommendations from USACE (1998), PIANC (2002) USACE (2004) and the environmental agency, the CAD design called for a cap thickness of at least 1.5 meters. Considering the cap thickness as well as the bulking process during placement, the CAD was designed to hold an excavation/dredging volume of approximately 3.5 million cubic meters. Figure 2 shows a typical section of the CAD.

To open the CAD, because the site was very shallow, less than 2.0 meters deep (Figure 3), the excavations were initially carried out using a mechanical clamshell operating with a bucket of 20 cubic meters capacity and two barges of 2,800 cubic meters each. Monthly, about 200 thousand cubic meters of material were dredged with disposal in the open sea in the ODP where uncontaminated dredged material from the Santos Port channel is usually disposed. This mechanical CAD excavation was completed in approximately 4 months with 800 thousand cubic meters dredged. The new CAD cell depth was approximately 25 m.

CAD OPENING

The mechanical clamshell was then replaced by two Trailing Suction Hopper Dredgers (TSHD) with approximately 10,000 cubic meters of hopper volume, which alternately excavated the CAD to a maximum depth of 25.0 meters and removed approximately 2.7 million cubic meters during six months. Altogether,

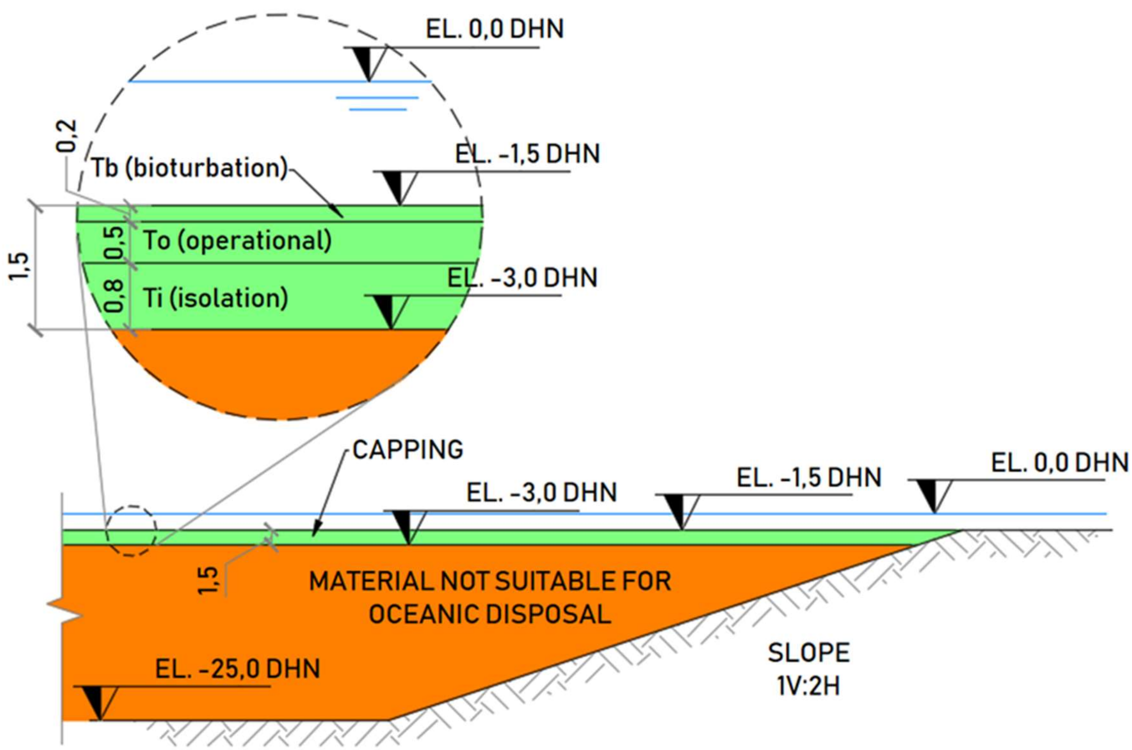


Figure 2. Typical section of the CAD.

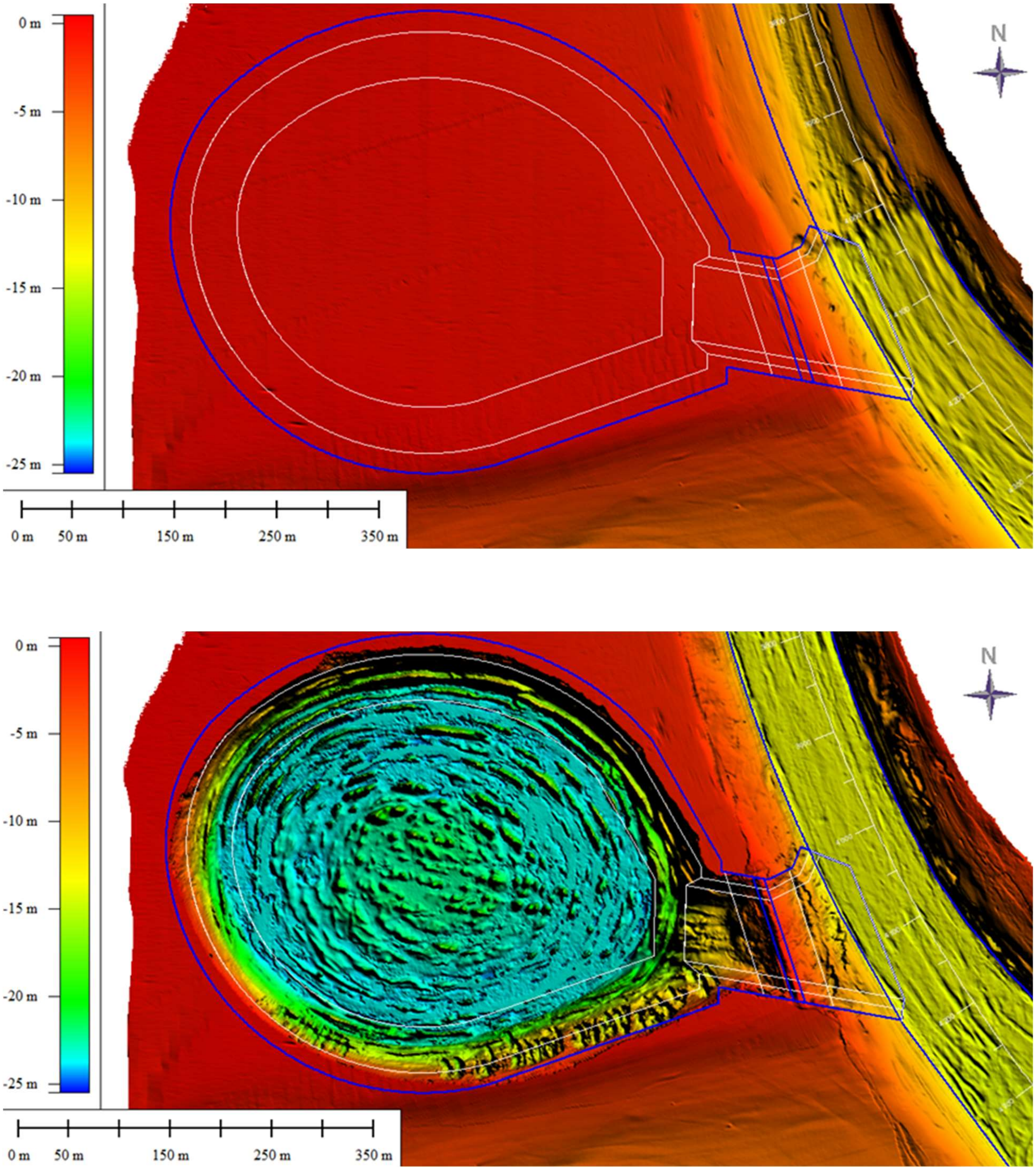


Figure 3. Bathymetric conditions before (above) and after (below) CAD total opening (after mechanical and hydraulic dredging).

approximately 3.5 million cubic meters were dredged in the CAD opening phase. Figure 4 shows images of the equipment used during the CAD opening.

CAD FILLING

The total opening of the CAD was completed in June 2017 and soon after that the first step of filling began. Prior to the disposal, a silt curtain was deployed around the entire perimeter of the CAD to control the dispersion of suspended solids (Figure 5).

Silt curtains are flexible floating barriers that partially block the plumes of suspended solids during dredged material placement, reducing the dispersion of these solids beyond the perimeter created by the curtain. Such curtains are widely used in dredging operations and the effectiveness of their use has been demonstrated by various laboratory and field studies, especially when the barrier is not open and when there

Clamshell

Barge

TSHD Geopotes 15

TSHD Ham 316

Figure 4. Equipment used during the CAD opening.

is “adaptive handling” in the positioning and dimensions (Radermacher et al. 2013). This approach was applied in the Piaçaguera Channel dredging, where a specialized technical team was dedicated to installation, handling, and maintaining the floating barrier. A silt curtain was deployed in shallow water depths surrounding the entire CAD cell, extending from the surface to the bed. To facilitate the anchoring and mooring of the barrier, steel piles were also implanted around the entire CAD as shown in Figure 5.

For the dredging of the Piaçaguera Channel and CAD filling, one of the two TSHD used during the opening step was used. The TSHD excavated from the channel and pumped through a high-density polyethylene (HDPE) piping into the CAD (Figures 6 and 7).

A submerged diffuser was installed at the end of the tube with the objective of directing the fluidized material to the bottom by reducing the transport velocity. Its position was controlled through anchors by the crew. The objective of the diffuser was to minimize the effects of turbulence during the descent and dispersion of the sediment plume upon impact on the bottom of the CAD cell.

Silt curtain around the CAD

Maintenance of the barrier

Silt curtain details installation

Silt curtain details

Figure 5. Silt curtain implemented around the entire perimeter of the CAD to control the dispersion of suspended solids.

Figure 6. Illustrative image of the material disposal method within CAD and detail (right) of connection between TSHD and floating piping.

Figure 7. TSHD performing pumping through HDPE piping to fill the CAD.

The diffuser equipment has a conical shape, increasing the cross-sectional area near the end, which significantly decreases the velocity of the fluid, helping to dissipate the turbulence and minimize the dispersion of sediment during disposal. In addition, the diffuser released the flow within a geotextile skirt supported by a steel frame to guide the boom to a depth of approximately 10 meters, preventing the sediment from spreading on the CAD surface (Figures 8 and 9). This skirt had its depth adjusted as the level was raised during the filling of the CAD. From the environmental point of view, the use of the diffuser together with silt curtains helped in the reducing the suspended sediment plume.

The first step of filling of the CAD and dredging of the Piaçaguera Channel ended in December 2017, lasting 5.5 months and dredging about 2.5 million cubic meters, including placement inside the CAD. This step was done to remove as much material as possible for the clean-up (80% of the total) and to establish a water depth of around 13.5 meters along the entire channel to improve navigability. Some time later, additional dredging was conducted in the channel to remove contamination in the hot spots as explained below.

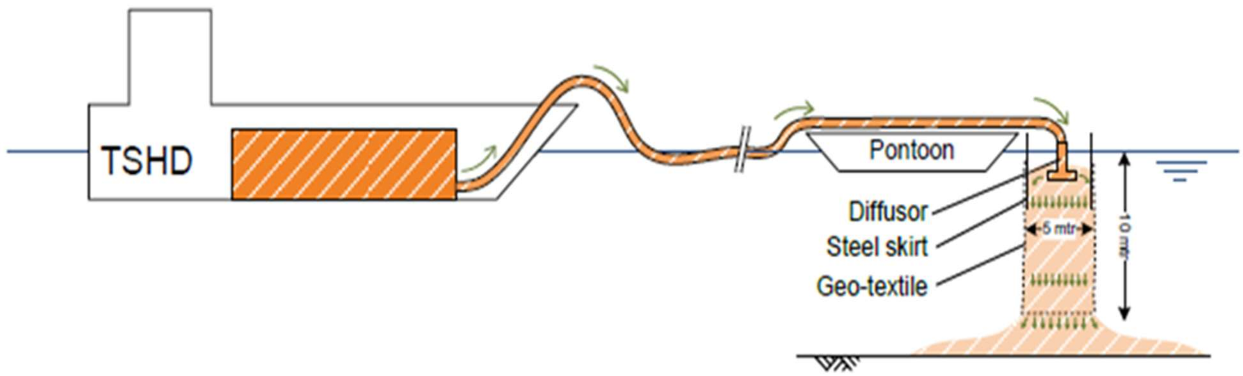


Figure 8. Schematic of the TSHD operating in combination with a diffuser.

Figure 9. Pontoon and diffusor.

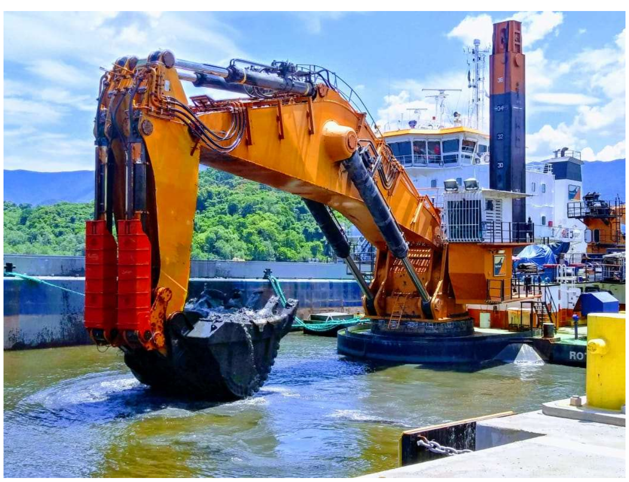
The second step of filling occurred irregularly during 2018 and 2019, using mechanical dredges and split barges (Figure 10) for the more precise excavation of hot spots (isolated points with higher contamination). During this step, around 500 thousand cubic meters was removed from hot spots in the Piaçaguera Channel, just 20% of the total amount dredged for the Piaçaguera Channel clean-up project. These sediments were placed by opening the split-hull barges inside the CAD. Some sectors of the channel were dredged until a depth of 14.5 meters was attained. Filling ended in November 2019.

CAPPING AND THE REUSE OF DREDGING MATERIAL

Between the first filling step ending in December 2017 and August 2020, the material inside the CAD was allowed to consolidate by its own weight for a period of approximately 32 months. A lot of bathymetric and density surveys were executed with the objective of monitoring the consolidation process before the placement of the capping material to insure proper isolation of the material (Figures 11, 12 and 13).

The density survey was conducted using a dual frequency bathymetric sensor (24 and 200 kHz) and an in-situ density profiler manufactured by the Stemma Systems (https://stema-systems.nl/equipment/). In parallel, several environmental monitoring campaigns were executed, to confirm that safe environmental conditions were maintained around the CAD area during the stand-by time for the material consolidation.

The CAD capping occurred between July and September 2020 and was the final stage of the CAD´s implementation, aiming at the permanent physical-chemical isolation of the material contained within it. For this purpose, a uniform layer composed of contaminant-free material with a minimum thickness of 1.5 meters was provided over its entire surface (Figure 2). The choice to use existing material from Port of Santos navigation channel was deemed appropriate for capping of the CAD based on the following technical criteria:



Backhoe Clamshell

Figure 10. Equipment used during the second step of CAD filling.

Figure 11. Inside CAD material density survey monitoring using DensiTune equipment.

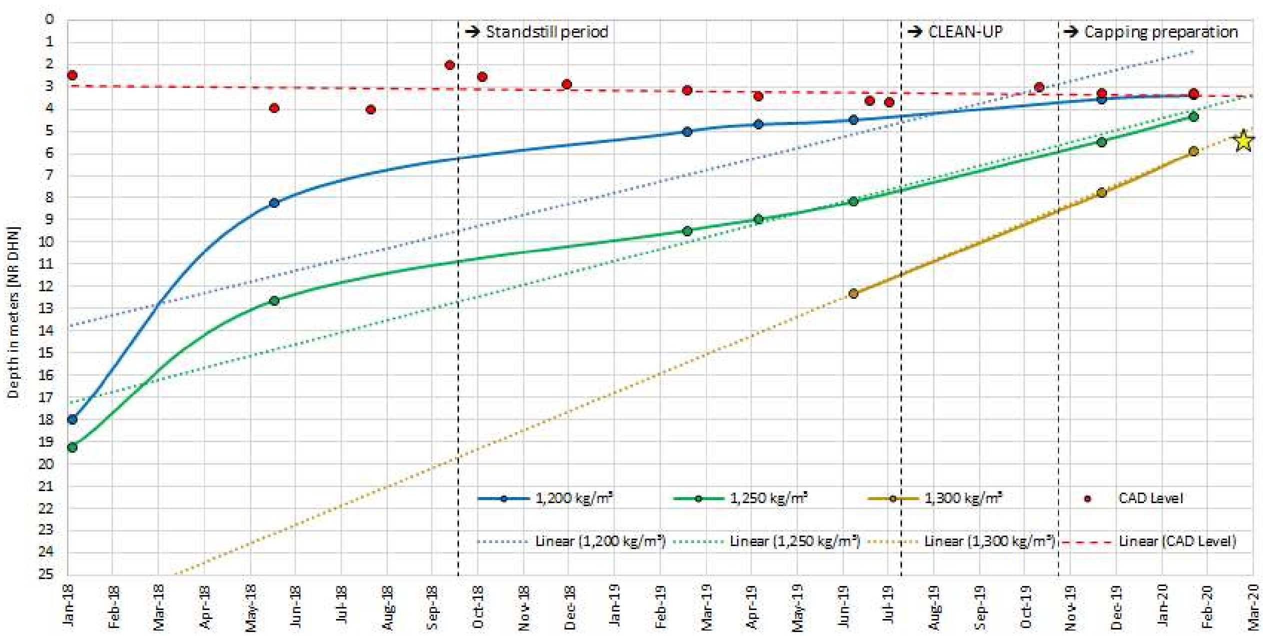


Figure 12. Projection of the density gain curve along time, based on the average density measured on the profiles, used to determine the best timeframe or capping placement.

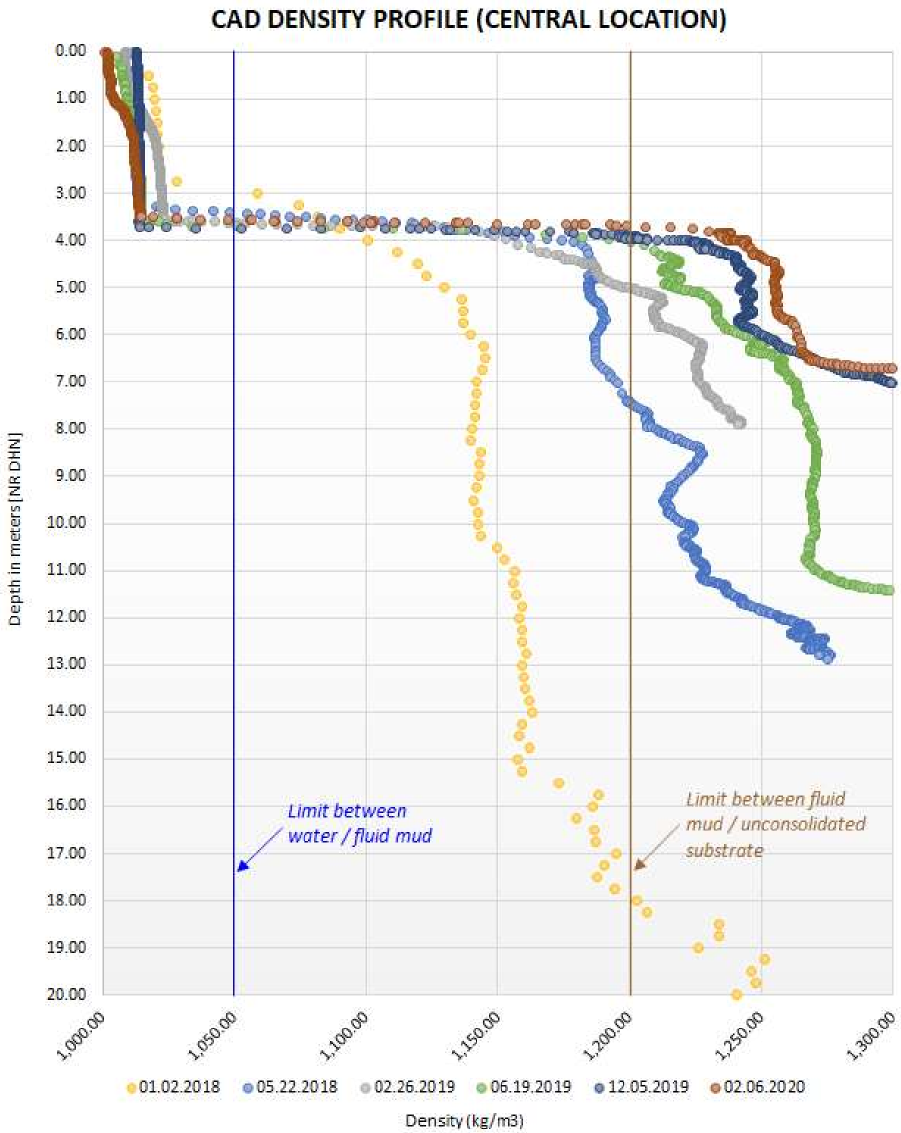


Figure 13. Evolution of density profiles measured at the central monitoring point of the CAD over time. The different colored profiles show the distinct density monitoring campaigns.

- Must be free of contamination.
- Must be available nearby and with the quantity required.
- Must have an adequate density.
- Must promote effective chemical isolation.

- Must be erosion resistant.
- Must have particle size characteristics as similar as possible to the surroundings to promote the colonization of the benthic community.
- Must allow for monitoring.
- Priority should be given to materials that meet the concept of beneficial use of dredged material.

The criteria definition was mainly based on recommendations as described in USACE (1998), PIANC (2002) and Palermo (2015), as well as the Brazilian regulations. The sediments from the Port of Santos channel fully fills the 8 technical criteria established above and allowed for the "beneficial use of dredged material", which as defined by Resolution 454/12 of CONAMA (Brazilian National Environment Council, 2012) consists of the use of dredged material, in whole or in part, as a resource in production processes that result in environmental, economic or social benefits, therefore without generating environmental degradation as an alternative to their mere disposal in the soil or water. The referred Resolution recommends that the owner considers, prior to the decision on disposal, the possibility of beneficial use of the dredged material, according to its characterization and classification, as well as the environmental assessment and the analysis of economic feasibility and disposal options. In addition to the above, it should be added that the beneficial use of dredged material is a widespread and established practice around the world and its adoption brings Brazil in line with the international vanguard regarding the handling of dredged material and port environmental sustainability (PIANC, 1992; PIANC, 2009, USACE, 2015 and USACE, 2018).

For the execution of the capping, it was established that:

- Material within the CAD should already be consolidated (density material inside CAD more than 1,250 kg/m^3 - less than this value was considered fluid mud).
- Method of cap placement shall be mandatorily hydraulic.
- Disposal must occur uniformly on the surface capped.
- Disposal should be gradual into thin and uniform thin layers.
- Bulking potential must be considered.
- Turbidity plumes should be minimized.

In September 2020 the CAD´s capping operations were completed with the use of approximately 300 thousand cubic meters of sediments extracted from stretch 1 of the Santos Port channel (Figure 14), using a very similar strategy applied during the filling phase. The excavation and transport of capping material was executed with a 4,750 cubic meters TSHD dredge (Figure 15) which pumped the material through a high-density polyethylene (HDPE) tube piping over the CAD surfaces. The same submerged diffuser was used with the pipeline to control the flow reducing the turbidity plumes and to control the amount of material for a gradual and uniform placement.

Figure 14: Sediments extraction area (red) located in the entrance of the Santos Port channel.

CONSTRUCTION MANAGEMENT AND ENVIRONMENTAL MONITORING

The construction management effort was performed to ensure that CAD implementation as well as dredging for the channel clean-up were executed as designed in the engineering project, obeying the contractual deadlines and prices and in accordance with the environmental permitting and governmental authorizations.

Figure 15: THSD dredge used during the CAD capping.

During the entire period of the CAD implementation, a technical team including engineers, oceanographers, surveyors, HSE technicians, environmental experts and managers checked and registered all the activities carried out both on land and on board, ensuring that dredging and placement of material were carried out as authorized, with the highest HSE standards.

Among the technical controls established during the work, it is worth mentioning the online continuous registration by satellite navigation and positioning of the equipment allocated, time record and place of the beginning and end of the dredging and material placements, the frequent monitoring of the bathymetric conditions on dredging/excavation areas (CAD, Piaçaguera channel and Santos Port channel) and the placement sites (ODP and CAD), as well as continuous geotechnical monitoring of CAD slopes.

As explained above, during all stand-by time for material consolidation, bathymetric surveys, sample collection and analysis, as well as *in situ* measurements of density were monitored (Figure 12).

A silt curtain barrier was implemented during CAD filling and capping phases, which helped to reduce the dispersion of suspended solids and turbidity plumes control.

In relation to environmental monitoring, an extensive program was implemented for sampling and analysis of sediments and water in the Piaçaguera Channel, CAD, and adjacent region, as well as fish bioaccumulation monitoring, birdlife monitoring and monitoring of vessel traffic.

The results of the environmental monitoring programs during CAD implementation were compared to historical monitoring data collected since 2006 in the Piaçaguera Channel (14 years of monitoring) and did not indicate any negative changes in sediment, water and bioaccumulation data that could be associated with dredging and disposal activities for the channel clean-up.

During CAD opening, filling and capping phases, intensive monitoring was carried out in water and sediment, to assess PAHs, metals, and physical-chemical parameters. The main results showed:

- No significant variations between sampling location and sampling time for all parameters.
- Trend of higher turbidity values in bottom samples as compared to near surface samples.
- The turbidity control showed only some outliers caused by adverse weather conditions, due to the CAD's location close to the sediment bank, an area of natural resuspension of sediments.
- No significant changes in water quality were observed during the environmental monitoring. The most relevant compounds in the sediments (PHAs and metals) were not made available to the water column during the execution of the works.
- The clean-up resulted in a significant recovery in sediment quality in the Piacaguera Channel (Figure 16).

CLEAN-UP RESULTS AND FINAL CONSIDERATIONS

The case of the Piaçaguera Channel broke local paradigms. Substantial volumes of contaminated sediments not suitable for oceanic disposal were managed in a safe way allowing for the establishment of better environmental quality of exposed sediment in the channel, overall reduction of the presence of contaminated sediments in the site, implementation of more favorable and safety navigation conditions along the Piaçaguera Channel, and a more rational use of Santos Port dredged material for a beneficial use concept.

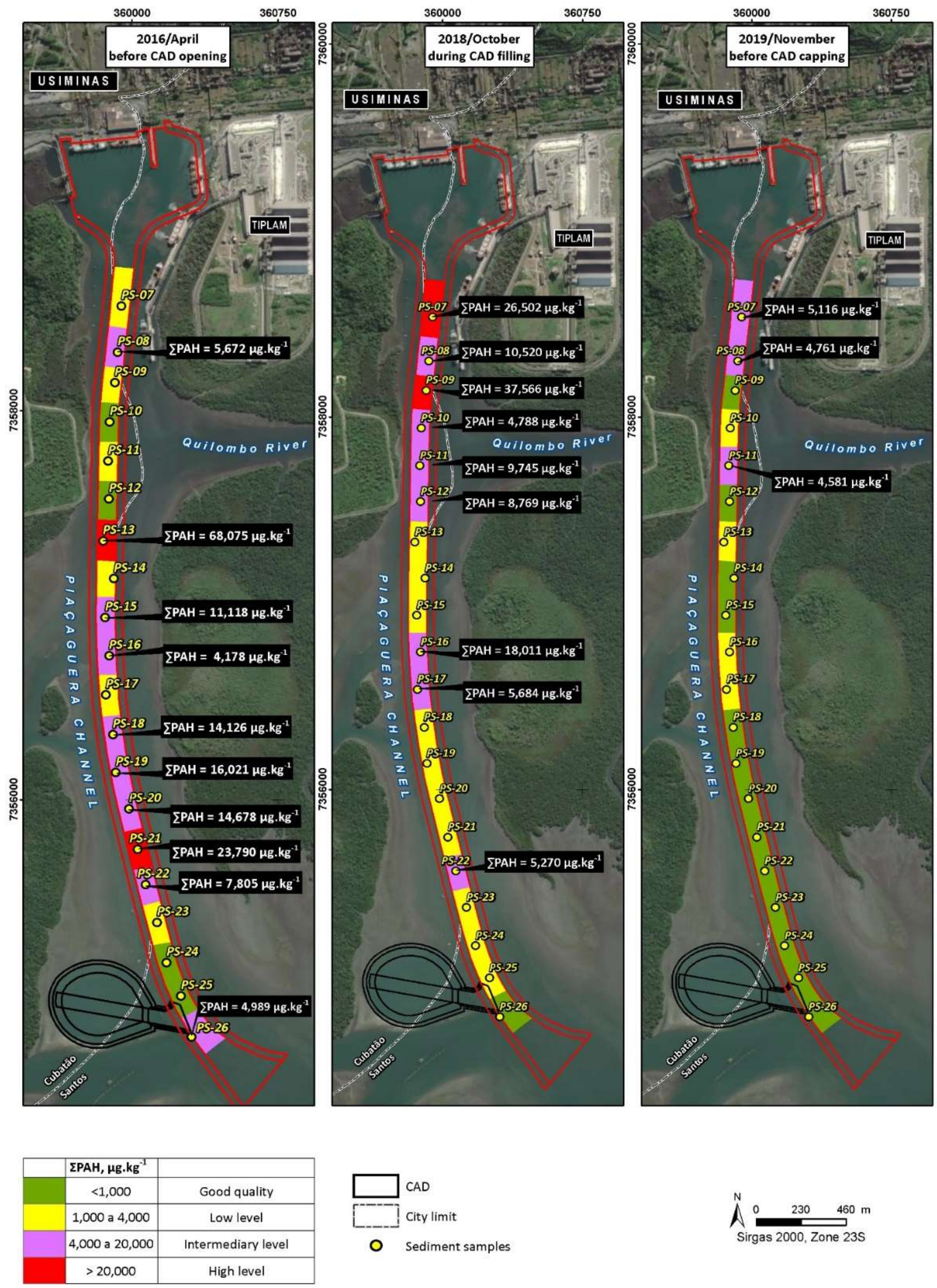


Figure 16: Sediment monitoring results during the cleanup showing a significant recovery in the sediment quality at the Piacaguera Channel.

Based on surficial exposed sediment in the Piaçaguera Channel floor, the clean-up resulted in a significant recovery in sediment quality, with a reduction on PAHs along the entire channel, with median PAHs concentration less than 4.0 ppm.

It is expected a natural improvement of surficial sediment quality will occur once the contaminant sources are much more controlled as compared to historical data in the Piacaguera Channel. This evidence baseline will continue to be monitored through the Sediment Quality Monitoring Program.

Finally, with channel clean-up concluded, it is expected that future maintenance dredging will involve only sediments accumulating from natural channel silting which will be suitable for ocean disposal, but this will depend on if all contaminant sources be full controlled until there.

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