# RESILIENCE & ANTI-FRAGILITY OF THE NEW JERSEY STATE-MAINTAINED MARINE TRANSPORTATION SYSTEM

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## ABSTRACT

Following Superstorm Sandy, responsibility for maintenance and recovery of New Jersey's state-maintained navigation channels shifted to the New Jersey Department of Transportation's Office of Maritime Resources (NJDOT OMR). Immediately following the storm, NJDOT OMR implemented a system-wide data collection and prioritization program to restore the state-maintained marine transportation system's (MTS) channels and dredged material storage facilities to a state of good repair. In addition to the Port of New York & New Jersey, a multi-billion-dollar fishing industry, and hundreds of marinas, the NJ MTS consists of over 370 nautical kilometers of state-maintained channels and nearly 70 dredged material confined disposal facilities (CDFs). Bathymetric surveys and over 5,000 sediment cores were collected from 209 of NJ's 216 state-maintained channels within 5 months. To assist coordination of these surveys and sampling, OMR solicited the participation of numerous stakeholders, including the US Army Corps of Engineers, US Coast Guard, NJ State Police, and design consultants from WSP and Gahagan & Bryant Associates (GBA). To establish a sequential recovery plan for the NJ MTS, the state-maintained channels were prioritized based on economics, social importance, and other factors. After 5 years, the MTS recovery is still on-going, though significant progress has been made. The extent of impacts to navigation within the channels and dredged material storage capacity have been computed for pre-storm, post-storm, and current conditions using post-storm damage assessments, sediment core sample analysis, and bathymetric surveys. Analysis of these values for channels both singularly and system-wide, and for individual CDFs and system-wide dredged material storage capacity, portray not only the resilience but also the anti-fragility of the NJ MTS, as values have improved to better than pre-storm levels. The recovery efforts have also demonstrated a feasible link between resilience and sustainability by focusing on beneficial use of dredged material to restore damaged CDFs, restoration of habitat degraded from underwater borrow pits and restoration of degraded coastal marsh via placement of dredged material. A case study of a multi-agency cooperative marsh restoration pilot program in Fortescue, New Jersey is provided, which demonstrates significant additional potential for enhancing the resilience of the NJ MTS. As a result of the post-storm prioritization and recovery planning, a shift in public sentiment regarding dredging, OMR's focus on establishing a sustainable dredging program, and availability of recovery funding, the NJ state-maintained MTS is on pace to not simply recover to pre-storm conditions, but to recover to a higher level of resilience than before the storm.

**Keywords:** Recovery planning, dredged material, beneficial use, marsh enhancement, thin-layer placement, confined disposal facility.

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## INTRODUCTION

New Jersey is a maritime state, surrounded by water on three sides. A significant portion of New Jersey's economy is dependent on its maritime infrastructure. New Jersey's Marine Transportation System can be divided into three major regions: the NY/NJ Harbor, the Delaware River, and the Atlantic Shore. Within these three regions are over 930 km of engineered waterway, thousands of berths, docks and ramps, as well as two internationally significant port complexes with associated terminals and goods handling facilities. Overall, New Jersey's MTS supports an economic engine worth over US$50 billion annually ranging in activity from tourism and recreation to commercial fishing to international trade. Millions of cubic meters of sand, silt and gravel are transported into this channel network by Mother Nature every year and must be removed by maintenance dredging.

On the evening of October 29, 2012, a post tropical cyclone made landfall in Brigantine, NJ, just north of Atlantic City. This storm, named by the media "Superstorm Sandy", was the largest Atlantic storm on record with winds extending over 1800 kilometers. Superstorm Sandy brought unprecedented storm surge (4.23 meters), waves (9.9 meters) and winds in excess of 125 kilometers per hour to the mid-Atlantic region, causing significant damage to homes, businesses and infrastructure. At the peak of the storm, 2.6 million NJ customers were without power and twelve New Jerseyans lost their lives. Over 160 kilometers of shoreline were severely eroded, most of it in New Jersey and Long Island, New York. In New Jersey alone, damage exceeded US$36 billion, making Superstorm Sandy the costliest storm in New Jersey history.

Resilience is defined by the National Academy of Science as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. PIANC Task Group 193 follows a similar definition of "the capacity to anticipate and plan for disruptions, resist loss in operations and/or absorb the impact of disturbances, rapidly recover afterwards, and adapt to short- and long-term stressors, changing conditions and constraints". Essentially, resilience is an iterative process with four distinct stages: pre-planning before a disturbance, resisting loss during a disturbance, recovery after a disturbance, and adapting for the next occurrence. In certain circumstances, a system may exhibit anti-fragility, or the ability to recover stronger and more resilient than pre-disturbance levels.

This paper highlights the NJ state-maintained MTS (NJ MTS) recovery and adaptation phases as well as recovery planning conducted during the initial stages of the recovery. In their recovery efforts, the New Jersey Department of Transportation's Office of Maritime Resources (OMR) has begun the iterative resilience process, resulting in a NJ MTS exhibiting anti-fragility and growing resilience.

## RECOVERY PLANNING & PRIORITIZATION

Immediately following the storm, significant efforts were undertaken to evaluate the damage and begin recovery efforts. While damage to the ports on the Delaware River and in the NY/NJ Harbor was handled by their respective Port Authorities, damage to the Atlantic Shore infrastructure fell to the State's Departments of Environmental Protection (NJDEP) and Transportation (NJDOT). Historically, the NJDEP's Bureau of Coastal Engineering was responsible for maintenance dredging of the state navigation channels. However, the extent of the damage from the storm and the need for rapid deployment of multiple contractors led the administration to ask for the NJDOT's Office of Maritime Resources (OMR) to take charge of the channel recovery effort. NJDOT immediately initiated a cooperative interagency workgroup to perform the necessary condition surveys and associated evaluation needed to permit and procure dredging and debris removal contracts. Representatives of multiple State and Federal agencies were partners in the process including the NJDEP, NJ Office of Emergency Management, US Army Corps of Engineers, US Coast Guard, as well as engineers from Parsons Brinckerhoff (now WSP), Gahagan and Bryant Associates, and Dewberry Engineers.

Field reconnaissance and side scan sonar was used to locate, and eventually remove, large debris and wreckage in the channels, but the greatest impact was from sediment washed into the navigation channels. In order to define this, an unprecedented system-wide bathymetric survey was undertaken. Using single beam sonar technology, over 370 kilometers of shallow draft navigation channels (209 individual channels) were surveyed in 4 months.

### Debris Removal

As side scan survey data was processed, a detailed review of each channel-specific dataset was performed. The number of identified targets in each channel was documented and sorted by channel, type, and NJDOT Region. Geo-referenced mosaics were generated, and identified debris targets were geocoded to their coordinate position and used to generate a statewide database of storm-related channel data. To assist the debris removal efforts, each target reference included a series of attributes, including width, height, length, shadow, and a classification/description based on a visual review of the target area. These data were documented as part of a GIS-ready shapefile as well as a channel-specific summary document that included overall channel scan imagery, a summary table of targets, and a target-specific summary table.

The resultant survey provided data for what ultimately became the largest waterway debris removal project in United States history. Nearly 5000 pieces of debris, including 36 vessels and 20 dock sections, were identified and located for NJDEP debris removal contractors. Over 450 of these pieces of debris were large enough to create a hazard to navigation and were either removed or marked for later removal.

**Channel Prioritization**

In addition to the debris, approximately 2.3 million cubic meters of sediment were identified within the state-maintained channels above the design depth. To derive this quantity, single beam bathymetric surveys were performed to confirm channel depths and ultimately identify shoal locations and material quantities. Survey lines consisted of cross-sectional transects run perpendicular to the channel centerlines at 30-meter intervals, as well as two longitudinal tracks run parallel to the channel centerlines at a 7.6-meter offset either side.

After acquisition, data was post-processed and presented on plan sheets to show preliminary alignment and depths. These bathymetric plans were reviewed by State engineers to determine the best centerline location to maximize navigability and minimize dredging requirements. This strategy is believed to have reduced the number and/or extent of shoals by as much as 10%.

The evaluation also served multiple other purposes: to review the physical condition of the channels, including shoals and debris targets; to prioritize remediation efforts through an evaluation of the economic value and usage of specific channels, and; to repair the channels in order to protect the public from hazardous conditions resulting from the storm.

Once the final alignments were determined, the data was imported to engineering and modeling software. Design template alignments, illustrated in Figure 1, were constructed in Terramodel, a product of Trimble, and average end area shoal quantities were calculated between the templates and surveyed existing ground surfaces. This graphic represents the dredge envelope (green) and allowable overdredge (blue). The dredge envelope represents the channel design depth for its entire width, plus 3H:1V side slopes extended upward from the outer extents until they intercept the existing bathymetry. Overdredge represents the allowable area that can be dredged beyond the proposed depth (for this project, 0.3 meters) to ensure that at a minimum, the proposed depth is met throughout the entire channel. In addition, surface-to-surface DTM quantities were calculated for comparison as quality control.

Shoaling calculations were performed and reported for each 30-meter section of channel, separated into left and right quadrants in an Excel spreadsheet. Shoaling in each channel was reported using both a graphical display for the entire channel that showed the location of each shoaled quadrant and with a summary report that totaled the volume in each quadrant by both minimum and maximum dredge depth (design depth plus 0.3 meters).

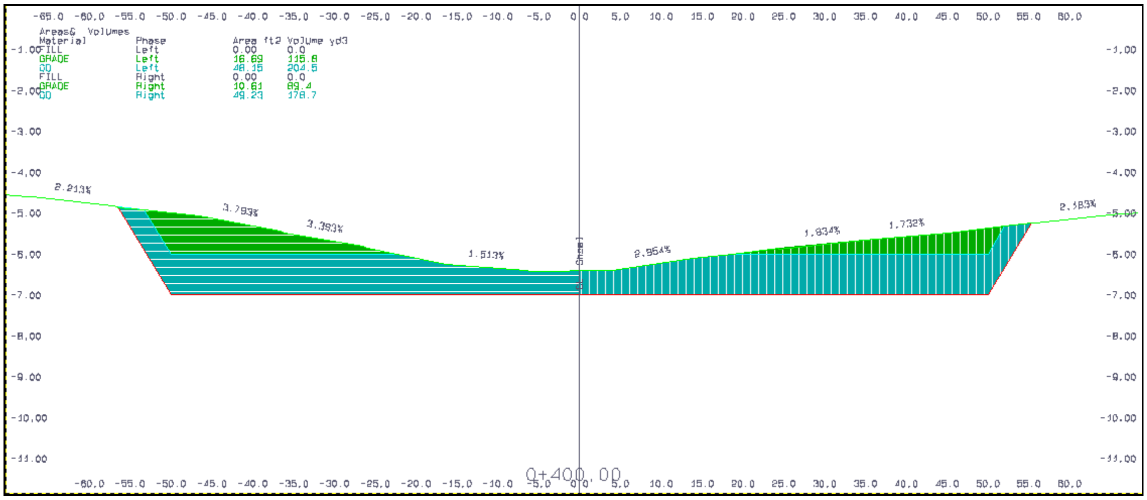


**Figure 1 – Typical cross section of data and design template during average end area calculations showing grade and overdepth regions**

To further define the status of each channel, the team also made a determination of navigability through each shoaled area. Each shoal was "ranked" as follows:

> Minor: Reasonably navigable (at or near authorized depth.)
>
> Moderate: Navigable, but with caution; may be impassable for some vessels at low tide.
>
> Severe: Navigability is severely impaired for many vessels even at high tide; dangerous conditions may be present at some tide stages for some vessels.

An overall rank was given to each channel based on the location of the shoals within the channel relative to the location of users and the orientation of the channel to the entire channel network.

Once the debris was removed and each shoal that was considered a hazard to navigation marked, the massive task of removing the 2.3 million cubic meters of sediment was initiated. In order to prioritize this task, OMR initially evaluated projects based on their readiness to proceed and dredged material disposal availability in the following order of precedence:

1) Shovel-ready projects already permitted from the pre-Storm program
2) Projects with existing dredged material disposal sites with capacity available
3) Projects with dredged material disposal potential
4) No dredged material disposal options

To rank projects within the above groupings, OMR considered the economic benefit and severity of shoaling of specific channels to provide a form of cost-benefit and need assessments. A series of Economic Value and Channel Usage Ratings were developed to aid in the assessment of the impact of each channel on the local economy as well as the importance of each channel on statewide navigational/travel patterns. These need-based and cost-benefit assessments were especially useful where more time and effort was required to initiate a project, such as channels requiring development of dredged material disposal options and/or purchasing property for disposal sites.

### Assessing Storm Impacts

Using the final approved channel centerline and limits, a team of maritime professionals (engineers, marine scientists and coastal planners) from the NJDOT Office of Maritime Resources and the NJDEP Bureau of Coastal Engineering reviewed available data to evaluate whether shoaling might be attributable to Sandy. Where possible, the determination of channel impacts was made based on comparison of pre-storm and post-storm bathymetry. However, as this channel bathymetry was only available for 49 channels at the time of the storm, OMR and their team reviewed approximately 5,000 core samples taken from within 116 channels after the storm. The cores were inspected for debris, composition, and other characteristics to assess storm-produced sediment versus pre-storm sediment. Where both pre- and post-storm bathymetry and core sampling data was not available, a determination based on best professional judgment was made, including the following considerations:

- Input from local boaters
- Location of the waterway and its orientation relative to the storm path
- Surrounding landforms
- Fetch (amount of open water near the channel)
- Proximity of the channel to ocean inlets
- Bathymetry of surrounding area (evidence of sand waves)
- Direct field observations of storm damage (e.g. landward sand deposition, wave damage)
- Navigation incident reports from boaters, marina owners, local governments, and the Marine Services Bureau of the New Jersey State Police
- Storm surge mapping
- Historical channel maintenance records

For simplicity, channels with similar impacts were grouped by the geographic regional clusters. This regional assessment, along with available channel specific information allowed the team to label each channel as “yes”, “no” or “maybe” with respect to Sandy impacts. This information was used to prioritize storm recovery work, negotiate for FEMA reimbursement, and to prioritize future dredging efforts statewide.

### Multi-Party Coordination

Critical to the recovery was clearing or marking all channels before boating season was in full swing (May 2013). A response of this magnitude required a multitude of agencies to be engaged on a variety of levels and times. To achieve this massive task in an aggressively set timeframe, NJDOT and NJDEP created a multidisciplinary team of consultants and state and local agencies, each with defined roles in the recovery process. The consultant team developed a schedule for collection, processing and reporting of sidescan sonar data and bathymetric survey data. The team also utilized a series of management tools, including daily coordination conference calls and ProjectSolve2: an Internet-based file sharing tool where project staff could access and review the numerous files generated for each channel.

In order to clear and/or mark hazards to navigation quickly and manage the massive data collection and reporting, the team developed a series of processes and tools for effective and efficient communication. Each channel was given a unique identifier and a database for reporting was created. This database included channel name and number, date of sidescan survey, date of sidescan processing, number of targets identified, date the sidescan data was uploaded to the ProjectSolve2 site, date of hydrographic survey, date of hydrographic processing, date of shoaling reports uploaded to ProjectSolve2, and number of shoals identified.

Each day, data was collected, processed, and reported for marking and/or clearing debris. The team held daily calls with the NJDEP (debris removal team), NJDOT OMR, NJ State Police, NJ Office of Emergency Management (OEM), FEMA, and US Coast Guard. On these calls, the team reported on:

- Which channels were completed that day and where they would be the next day
- Progress on debris identification,
- Progress on debris marking or removal

Data was uploaded to ProjectSolve2 and available for NJDEP to utilize for debris removal, ATON and OEM for marking hazards to navigation and US Coast Guard and State Police for notice to mariners. The constant communication amongst project team members and timely response of all project team members allowed the project to be completed on time in only 4 months.

## RESILIENCE & ANTI-FRAGILITY OF THE STATE-MAINTAINED MARINE TRANSPORTATION SYSTEM

As a result of the recovery planning, multi-agency coordination, and integration of team members, the OMR team quickly utilized the collected data to begin the process of restoring the state-maintained navigable channels and to restore or identify dredged material storage options. The effective planning prior to the start of recovery efforts has resulted in anti-fragility and increased resilience of the NJ MTS for the navigable channels and dredged material storage capacity, both of which contribute directly to the rate of system recovery.

**Navigable Channels**

From analysis of collected survey data, over 2.3 million cubic meters of sediment were identified above the design depth across the state-maintained MTS. Over half of the 209 channels were significantly shoaled, and 34 percent were severely shoaled or impassable. Comparison to recent bathymetry taken prior to the storm showed that the storm had deposited a significant amount of material in some places. Unfortunately, pre-storm bathymetry was available for only 49 channels. In order to determine the storm's impact on the rest of the system, over 5000 cores were taken in shoaled areas down to authorized depth. Geologists examined the cores for signs of recent deposition in the form of vegetative debris, marine organisms and consolidation (or lack thereof). In the final analysis, as presented by Marano, M. et al. (2017), about 27 percent of the sediment could be attributed to Superstorm Sandy, or 610,000 cubic meters.

It is important to note that this analysis is limited to the State channel network, and does not include the needs of the myriad of local access channels, marinas, lagoon communities and private berths. Although there is no published study that defines the private and local need for dredging, our experience tells us that the numbers are even higher, mostly due to long neglect of maintenance. Nor are we including the more than 200 kilometers of Federal channels and inlets that serve the Atlantic coast of New Jersey, or the Port of New York & New Jersey for which resilience was previously reported by Wakeman, T.H. & Miller, J. (2013) and Wakeman, T.H. et al. (2015).

Based on review of bathymetric surveys performed in 2013 and 2015, natural sedimentation results in approximately 2 channels dropping out of a state of good repair each year and in two channels going from moderate to severe impacts to navigability. This natural diminishing of MTS operability is indicated by the baseline in red in Figure 2. When comparing to the post-Sandy baseline of MTS impacts to navigation in Figure 2, the number of channels in a state of good repair (i.e. minor to no impact) has exceeded pre-storm levels as of January 2018, demonstrating anti-fragility of the system.

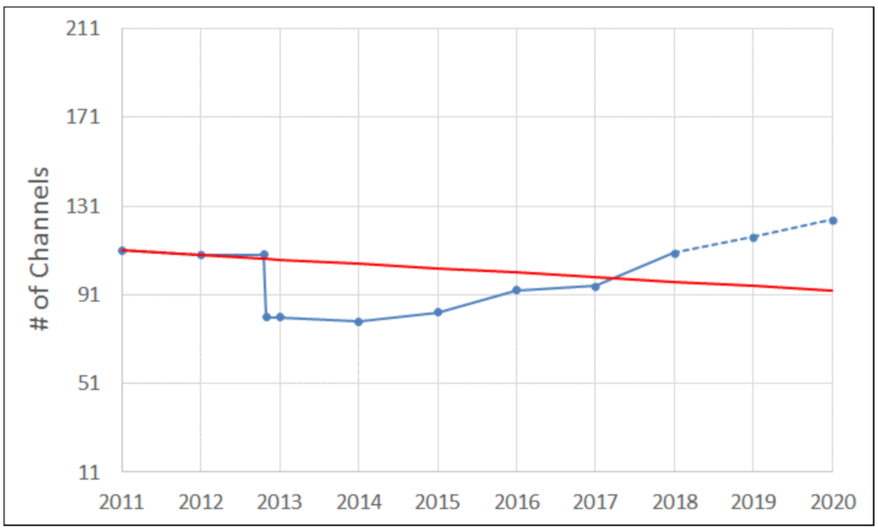


**Figure 2 – Number of Channels in Good Repair with Baseline Post-Storm Trend (in red)**

As noted in Figure 2, planned projects or those currently on-going will continue to improve the state-maintained MTS and the anti-fragile response hints at a higher rate of resilience expected following the next storm. Due to the recovery program and post-storm planning, 35 shoaled channels have been restored to a state of good repair as of January 2018. In all, 52 percent of channels are now in a state of good repair (up from 38% post-storm), with only 20 percent of channels experiencing severe impacts to navigability (down from 34% post-storm). OMR's recovery efforts to date have provided improved navigability to approximately 58 marinas, 69 businesses, 1 ferry terminal, nearly 200 commercial vessels, and over 2,000 residential docks.

While the loss in functionality shown in Figure 2 indicates a low to moderate risk and low resilience based on characteristic relationships presented by Linkov, I. et al. (2014), the measured resilience is reflective of the pre-storm funding levels and lack of available storage capacity for fine-grained sediments in the storm's aftermath. To combat this low resilience and improve recovery speeds following the next storm, OMR has focused on several dredged material management strategies as part of the on-going recovery efforts.

## Dredged Material Storage

Equally critical to the restoration of storm-impacted navigable channels, dredged material storage of the NJ MTS was significantly impacted as a result of past-use and storm damage. In an ideally resilient system, sufficient storage capacity would be available to accommodate projected dredging needs following a storm in addition to maintenance dredging needs. In such a system, channel restoration could begin immediately following the storm and result in a quicker recovery and increased system resilience. As such, a direct correlation exists between the amount of available dredged material storage capacity and the resilience of marine transportation systems.

### *Confined Disposal Facilities*

Historically, coastal New Jersey navigational dredging is performed with small (0.25 m to 0.45 m) cutterhead pipeline dredges. While dredged material processing and other dewatering methods, e.g. filter press, are available in New Jersey, dredged material has predominantly been managed in upland disposal sites or on beaches, depending on grain size. Material that is greater than 90 percent sand is suitable for bathing beaches, while material greater than 75 percent sand is potentially useable on non-bathing beaches. On a systemwide basis, about 20 percent of the maintenance material is coarse-grained (75% sand or greater), and 80 percent is fine-grained.

A recent survey of the state by NJDOT revealed over 45 historical dredged material placement sites along the east coast of NJ (not including beaches) ranging from free pump unconfined disposal to fully engineered confined disposal facilities (CDFs) with engineered level control structures. Many of these CDFs are small, with potential air capacities of less than 75,000 cubic meters. This is probably not an exhaustive list since many upland sites have been developed or have become unrecognizable over time. Regardless, not all of the sites are permitted for use due either to environmental regulations or having passed into private ownership. At the time of the storm, there were 25 useable CDFs along the state's east coast, with approximately 1.4 million cubic meters of air capacity. This would not be close to enough to manage the 2.3 million cubic meters of sediment within the MTS let alone the 610,000 cubic meters of sediment from the storm when accounting for operating capacity and applying swell factors to these in-situ sediment volumes. To compound matters, at least some of the capacity would need to be reserved for the Federal Intracoastal Waterway (ICWW), due to a long-standing agreement between the US Army Corps of Engineers (USACE) and the State.

Figure 3 shows the locations of these CDFs broken out by region.

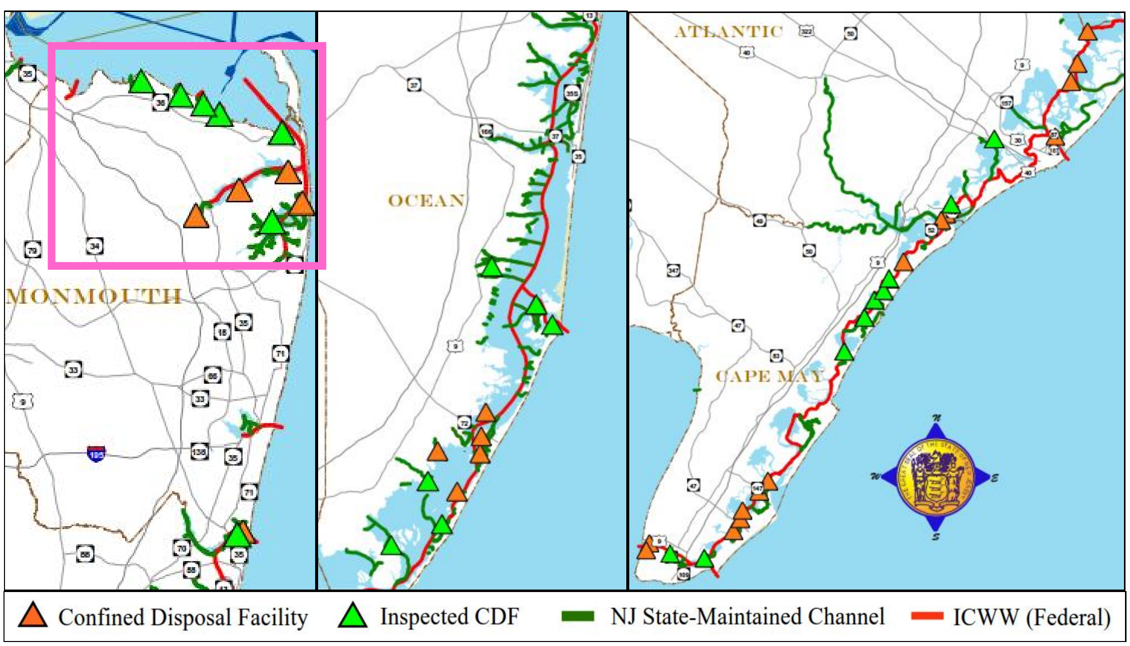


**Figure 3. Locations of Inspected CDFs along Raritan Bay & ICWW: Raritan Bayshore (boxed) and Monmouth Rivers (Left), Barnegat Bay (Center), and Atlantic & Cape May Counties (Right).**

To begin the rebuilding of the state channel network, considerable efforts were put into restoring capacity in CDFs. This included evaluating remaining capacity as well as identifying those facilities damaged by the storm and making appropriate repairs. These efforts included on-site damage assessments of 22 CDFs in the system, revealing significant damage at 11 of these CDFs which could not be used without likely breaching the confining dikes.

Based on computed estimates of available CDF capacities systemwide, the CDFs in the NJ MTS had approximately 1.4 million cubic meters of air capacity available before the storm, dropping to 1.2 million cubic meters of air capacity following the storm due to CDF damage.

Through a continuous program of emergency and maintenance dredging and CDF rehabilitation, a significant restoration in available CDF air capacity has been achieved with planned projects in 2018 projected to exceed pre-storm capacity levels systemwide, as shown in Figure 4 (left). In general, CDFs have been restored only when needed for dredging, as the priority has been on restoring navigability in the channels, resulting in the relatively flat trend indicated in Figure 4 (left) until planned CDF repairs are carried out in 2018. However, as indicated in Figure 4 (right), CDF dikes have continued to be raised systemwide resulting in an increased potential air capacity after removal of stored dredged material. While not all damaged CDFs have been repaired, potential CDF air capacity is expected to reach and exceed pre-storm levels in 2018. Taking the system as a whole, potential CDF air capacity has exhibited a low to moderate risk and low to moderate resilience based on the conceptual resilience relationships published by Linkov, I. et al. (2014), as indicated by Figure 4 (right). The storm-induced loss of functionality was sharp but a low percentage of the overall system capacity, with a variable recovery rate.

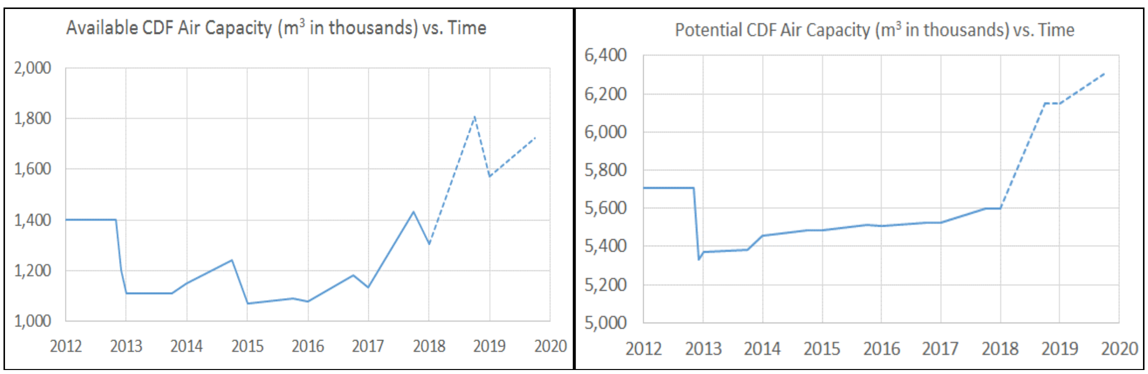


**Figure 4 – Available CDF Air Capacity (left) and Potential CDF Air Capacity (right) over Time for the New Jersey State-Maintained MTS**

Looking at all CDFs shown in Figure 3, a total air capacity of approximately 6.5 million cubic meters could theoretically be achieved if all accessible CDFs were repaired and rehabilitated using all on-site dredged material, without consideration for elevating the confining dikes. Roughly 1 million cubic meters of additional capacity could be achieved by elevating all confining dikes by 0.6 meters. However, while useful, the systemwide capacity can be deceiving, as the sharp but low percentage drop in overall potential air capacity averages out impacts across both low impacted and high impacted areas and is not indicative of severe regional impacts. In the case of the NJ MTS, the potential CDF air capacity in Figure 4 (right) was skewed higher due to the large percentage of total available capacity in Cape May County, which was less severely impacted by the storm than the Raritan Bayshore region. As a result, looking at storage capacity on a regional level returns a more representative assessment of the system resilience, as dredging in NJ is typically restricted to regional dredged material storage options.

This capacity loss from Superstorm Sandy was especially apparent in the Raritan Bayshore region of the state, which was hit the hardest from the storm and experienced a storm surge more than 2.8 meters above mean high water elevation.

*Raritan Bayshore Region*

Along the Raritan Bayshore (boxed in Figure 3), 4 CDFs were in locations that could be utilized for recovery efforts immediately following the storm; however, one was severely damaged by the storm, two were nearly full, and one had no available capacity. As such, only 14,500 cubic meters of air capacity was available immediately after the storm. The Raritan Bayshore region received a high priority from OMR following the storm, and air capacity was improved via elevating and emptying of 4 existing CDFs and construction of a new CDF at Leonardo. All increases in CDF dike heights were accomplished using dredged material on-site or from nearby CDFs. In the case of the N61 CDF, additional material to raise and repair the dikes was obtained via excavation and transport of roughly 38,000 cubic meters of dredged material from the Atlantic Highlands CDF and the Monmouth Cove Marina CDF, increasing capacity of 3 CDFs at one time. These projects not only supported dredging of 8 severely impacted channels, but also resulted in improvement to CDF air capacity that well exceeded the pre-storm levels, as indicated in Figure 5. Accounting for current available CDF air capacity (Figure 5 left), the post-use available air capacity has leveled off at around 100,000 cubic meters. Assuming future storage potential after removal of dredged material, the potential air capacity in the region has increased by roughly 80 percent from pre-storm levels as indicated in Figure 5 (right). Both measures of dredged material storage capacity show anti-fragility of the system directly resulting from the beneficial use of on-site dredged material to increase CDF dike heights. Unlike the navigable channels, the potential dredged material storage capacity in the Raritan Bayshore region demonstrated high risk and high resilience based on the relationships published by Linkov, I. et al. (2014) with a sharp, significant loss of functionality followed by rapid recovery. This higher resilience and anti-fragility is a direct result of OMR's prioritization of this region during recovery planning.

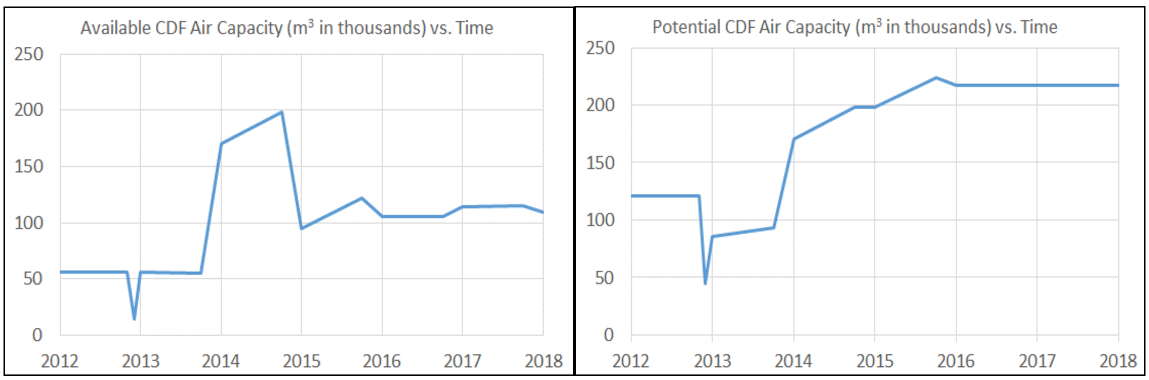


**Figure 5 – Available CDF Air Capacity (left) and Potential CDF Air Capacity (right) over Time for the Raritan Bayshore Region**

This increased capacity also allowed a Federal channel providing access for an interstate Ferry service to be dredged. To date, approximately 145,000 cubic meters of sediment has been dredged and placed into these CDFs from 7 channels. Currently, negotiations are underway to restore a historical CDF on private property in the Raritan Bayshore region. This CDF will provide support for a second Federal channel and 23 State channels (23.6 km total length), including one 3.4-km-long channel providing access for 5 marinas.

With additional CDF rehabilitation projects planned for the next several years, further improvement in dredged material storage capacity is expected. In many cases, hazard mitigation in the form of revetments or dike placement above the anticipated storm surge elevation will work to lessen damage and improve recovery time following the next major storm. As a result, increased resilience can be expected of the NJ MTS following the next major storm, and the data presented herein may be used as a benchmark upon which to measure the effectiveness of resilience improvements and anti-fragility of the NJ MTS.

Going forward, plans are underway to construct more CDFs along the beachfront in Keansburg, NJ where the CDFs will be integrated into the existing dune system to improve coastal resilience and combat sea level rise, providing a win-win by boosting resilience of both coastal communities and the NJ MTS.

***Case Study: Dredging of Waackaack Creek & Thorns Creek and Keansburg CDF***

The biggest challenge with dredging in New Jersey is the availability of placement sites. The placement of sand on the beach and/or restoring or creating protective dunes is an excellent example of the dual benefits of dredging and coastline resiliency provided by this project. The channels were cleared to their permitted depth and the dredged material was used to protect the coastline from tidal surges and flooding.

Another concept that serves this dual purpose is the construction of CDFs along a linear alignment parallel to the coastline (see Figure 6). This concept allows for the placement of more fine-grained material adjacent to the existing beaches. After placement, a filled CDF will provide more stability to the shoreline than the existing beaches which are more susceptible to erosion during storm events. A dune made on top of a CDF filled with fine-grained material would be more stable than a dune made solely of sand, since fine-grained material has more natural cohesion. The CDF constructed in the borough of Keansburg in Monmouth County, NJ is precisely this application (see Section A-A in Figure 7).

**Figure 6 - Construction of beach-fill berm**

The borough of Keansburg in the Raritan Bayshore region of New Jersey was severely impacted by Superstorm Sandy. In Keansburg, the US Army Corps of Engineers created a flood protection levee and installed a floodgate on Waackaack (pronounced Way cake) Creek in the late 1960's. The floodgate separated the inland portion of Waackaack Creek and Thorns Creek from the outer segment of Waackaack Creek that extends from the floodgate to the NJ Intracoastal Waterway (see Figure 7). The nature of the material to be dredged consisted of predominantly beach-quality sand in the outer channel and fine-grained material inside the floodgate.


**Figure 7 – Project Map with Section A-A of the Keansburg CDF**

An upland CDF already existed less than 60 meters from the mean high water line, but it was already filled to capacity with dredged material from the previous maintenance cycle. NJDOT approached the borough with the prospect of removing the dredged material for the construction of another coastal CDF in a nearby Monmouth County town. The borough did not accept this proposal and viewed this coastal CDF and the material in it as an added protection to their town from the next storm event.

The design team accepted this constraint as a positive and built upon it. The CDF was designed to remain within the original permitted footprint, while using the existing interior material to raise the confining berms, thereby creating capacity. This allowed for the placement of the fine-grained dredged material into the raised portion of the CDF and provided the town with an even larger natural barrier to Raritan Bay storm surges. The coarse-grained material from outside the floodgate was designed into a dune-like feature simply by extending the top of the confining berm elevation waterward and transitioning to the lower existing beach grade at a 3:1 horizontal to vertical slope. The slope met the existing beach grade well upland of the mean high water elevation line.

The dual benefits of the long-awaited dredging of Waackaack and Thorns Creeks, combined with a naturally hardened section of coastline, was deemed such a success that the borough requested the State construct additional, similar CDFs along the coastline adjacent to the existing Keansburg CDF.

Based on possible footprints for two additional CDFs built into the dune system, an additional 85,000 to 115,000 cubic meters of storage capacity could be gained for the Raritan Bayshore region. With such an increase in capacity, the MTS recovery in the region following a future storm would be greatly accelerated, and the CDF dune system would provide additional protection to the near-shore properties behind the CDFs. OMR's collaboration with local stakeholders and planning for future storms has directly resulted in increased MTS resilience and provides a win-win for both OMR and Keansburg. Coordination with state regulatory agencies has opened other opportunities for dredged material management, including confined aquatic disposal to restore or enhance underwater habitat.

### *Confined Aquatic Disposal – Dredged Holes*

Confined aquatic disposal (CAD) facilities are defined as below water depressions in the existing ground that serve as open water dredged material placement areas. A CAD pit, or cell, may be formed from either natural events or intentional subaqueous construction. Suitable below water depressions, termed "dredged holes" or "borrow pits" exist throughout the bay and estuary system in New Jersey and have the potential to be used as a dredged material management solution to combat shoaling within the New Jersey state-maintained channels.

CAD facilities satisfy the same need as upland confined disposal facilities (CDF) in terms of storing dredged material. However, the two types of disposal facilities differ in several categories such as habitat, site accessibility, and material placement methodology. Like upland sites, CAD facilities are able to accept unsuitable, or contaminated material by use of a controlled cover, or cap. The cap consists of coarse-grained material and serves to ensure minimal loss of material from within the hole after the placement has occurred. A major advantage to the use of an existing cell as a CAD facility is that minimal to no construction is required upfront. Further advantages over other conventional placement methods are that these sites allow for either hydraulic pipeline discharge or mechanical placement, require minimal equipment needs, and are often located near dredging sites. A specific disadvantage to a CAD facility stems from the need of the cap when placing fine and contaminated sediments. In order to reduce the risk of resuspension and loss of dredged material from within the hole, the cap may be required immediately following a placement event, thus dictating the potential need for an interim cap in the event of a disruption of placement, such as a seasonal dredging permit restriction. Further disadvantages of these sites include the need to prevent loss of sediments during transport and placement, and potential difficulty obtaining agency approval.

A number of these CAD facilities were inadvertently created in New Jersey waterways when sand was excavated for upland construction in the early to mid-1900s. A January 2015 study titled 'State Channel Maintenance Capacity' performed by NJDOT-OMR, Richard Stockton College of New Jersey Coastal Research Center (CRC), and Ocean and Coastal Consultants (OCC) investigated the presence of potential facilities and identified a total of 122 dredged hole features along the NJ MTS. Amongst these 122 features, 10 were identified as candidate sites after field personnel measured depths greater than 5.5 meters below the surface. Upon establishing these candidate sites, hydrographic surveys were performed and yielded volumes for dredged material containment of over 1,720,000 cubic meters to elevations at or below -3.7 meters mean low water (MLW).

Amongst these identified candidate sites, is a feature shown in Figure 8, located in Brick Township, Ocean County denoted as Dredged Hole #18 (DH18). Water quality samples retrieved by CRC in 2013-2014 indicated that the benthic habitat within this feature is azoic due to extended periods of hypoxic conditions (dissolved oxygen levels of less than 2 mg/L). In its present state, DH18 is considered degraded and offers limited ecological value. DH18 is a viable candidate to receive dredged material due to its potential for habitat restoration and its proximity to several state channels in need of maintenance dredging. Within a 5-kilometer radius of DH18, there are 18 state-maintained channels totaling over 20 kilometers in length. The placement of dredged material from local channels is expected to eliminate the stratification of the water column resulting in the reduction of stagnation and hypoxia within DH18. The existing ground surrounding the feature ranges in elevations from approximately -1.8 m to -1.2 m MLW allowing for a high quality shallow water habitat containing beds of submerged aquatic vegetation (SAV) to thrive. Furthermore, the aforementioned CRC water quality samples show that the dissolved oxygen content is significantly greater within the adjacent shallow water.


**Figure 8 – Google Earth imagery from 2002 (left) and 2016 (right) clearly depicts the defined depression of Dredged Hole #18**

Hydrographic surveys conducted by Gahagan & Bryant Associates in June 2017 show depths as deep as -7 m MLW within the hole and yielded a storage volume of approximately 130,000 cubic meters up to elevation -1.2 m MLW. Dredged material can be placed within DH18 to restore the hole to the surrounding natural elevation between -1.8 m and -1.2 m MLW with an approximate 0.6-m layer of coarse sand to serve as the final cover. Contract documents are currently being developed for a construction project that would result in the dredging of 7 to 9 state channels and placement of approximately 130,000 cubic meters of dredged material into DH18. The construction of this project is anticipated to begin in June 2018. Several measures and best managements practices will take place over the course of construction to ensure minimum adverse effects during dredged material placement. Among these measures are the utilization of a turbidity barrier; monitoring of turbidity, water quality, settlement, compaction, and SAV; and periodic hydrographic surveys.

Given a successful DH18 project, several other CAD site candidates within the New Jersey intracoastal waters are expected to develop into additional dredging construction projects and will result in further restoration of degraded habitat while alleviating the shoaling within New Jersey state maintained channels. The identification of these sites has also greatly enhanced the state-maintained MTS storage capacity potential, and thereby the NJ MTS resilience.

## SUSTAINABILITY IN RECOVERY METHODS AND INCREASED RESILIENCE

Based on the example of the NJ MTS, the link between resilience and sustainability is exemplified via economic, operational, and environmental sustainability. Viewing dredged material as a valuable resource, rather than a hindrance, has been critical to envisioning projects that seek to promote more resilient and more sustainable systems through cost effective management of funding sources and use of dredged material to promote marsh health, mitigate coastal erosion, enhance coastal protection and restore habitat.

### Economic Sustainability

For many years prior to Superstorm Sandy, funding for maintenance of the Atlantic Shore portion of the NJ MTS was unreliable and not commensurate with maintaining the system in a state of good repair. Following the storm, considerable funds were released to initiate recovery efforts. In addition, FEMA reimbursed the NJDOT for the cost associated with removing sediment that could be attributed to Superstorm Sandy. The improvement in MTS navigability shown in Figure 2 would not have been possible without the corresponding infusion of funds, and the system's resilience would have been greatly reduced. Compared to Figures 2 and 4 (right), an inverse relationship to funding over time could easily represent the funding received by OMR and its impact on the MTS recovery.

OMR has utilized a number of management tools to increase the efficiency of the design, permitting and procurement of dredging projects. These include bundling channels in close geographic proximity to achieve economy of scale, actively soliciting dredging industry awareness in the Department's efforts through public outreach, and working with resource agencies to increase the number of options available for management of dredged materials, particularly beneficial use. OMR is in the process of developing a management plan for existing CDFs in order to ensure that capacity is maintained for future maintenance needs. Rather than considering CDFs to be for permanent storage, CDFs are considered to be temporary dewatering facilities, and the sites on which they are located to be management facilities for the processing and staging of sediment for beneficial use. As a permanent facility, it is easier to justify the expense of mitigation efforts such as relocation above storm surge elevation, hardening of dikes against waves, or other similar strategies.

OMR is utilizing modern transportation system tools to improve the management of the Atlantic shore MTS. Asset management tools in the form of public facing electronic databases and crowd sourcing of condition reports will enable OMR to better allocate limited funds to the parts of the system with the greatest need. In addition, a strong marketing plan is being implemented for the beneficial use of dredged material that will encourage its use in construction and development. This effort includes a continued partnership with the NJDEP to streamline permitting of projects that utilize dredged material for remediation. Finally, OMR is funding research and pilot projects to evaluate and develop new (or new to NJ) strategies for the beneficial use of dredged material in habitat restoration and recovery efforts. The combination of these initiatives should directly reduce the costs of dredging and dredged material management by increasing competition.

However, none of these efforts will bear fruit without continued state funding at meaningful levels. In fact, the recovery of the NJ MTS will be halted, if not reversed, and MTS resilience dampened if funding levels are dropped back to pre-storm levels. OMR continues to analyze system data to provide the information needed to determine the proper level of funding needed to ensure that this does not happen. At a minimum, the efforts undertaken to date increases the likelihood of a more rapid recovery and a similar anti-fragile response following the next storm

### Operational Sustainability

If a CDF is simply used once and filled to capacity, the storage capacity of a MTS would constantly be at a deficit to the system's dredging needs. However, by beneficially using dredged material, the dredged material capacity of the MTS can be continually renewed without having to find, purchase, permit and construct new facilities. Such is the case with the NJ MTS, where dredged material is viewed as a resource rather than a hindrance. As evidenced by the recovery along the Raritan Bayshore region, stored dredged material is often used to elevate existing CDF confining dikes, providing a double benefit of emptying the CDF while also increasing the site's maximum capacity. Rather than only implementing a closure plan for each CDF, increased operational sustainability of the MTS could be achieved through preparing operations and maintenance programs for each site. Coupled with a robust beneficial use program, such as described by Marano, M. et al (2016), such programs would allow for perpetual use of a CDF even after achieving its maximum dike height. In doing so, the potential air capacity of the NJ MTS can be maintained at the improved level indefinitely and allow for enhanced resilience by getting dredges in the water quicker following the next storm.

Likewise, the time between excavation events could be lengthened by reducing the amount of sediment entering the channels. Significant stretches of the NJ coastline are eroding each year and adding to the sediment load within the NJ MTS. Several efforts are underway to reduce dredging needs, including realigning channels to better avoid areas of high sedimentation and making use of natural processes such as tidal scour. The concept of soft armoring via living shorelines and marsh restoration has also been advanced in NJ to reduce erosion rates in the face of sea level rise.

### Environmental Sustainability

Several benefits can present themselves when dredged material is used to enhance habitat. Not only does the project facilitate restoration of a navigable waterway but it also promotes a healthier aquatic ecosystem necessary for coastal communities and fishing to thrive. Using dredged material to enhance degraded benthic habitat provides a solution to an age-old problem of dredged material disposal, but because there are a finite number of dredged holes available, this option is not nearly as attractive as marsh restoration.

Around the world, many coastal marshes are disappearing at an alarming rate, including Louisiana, New Jersey, and the U.S. East Coast in general as shown by Barras, J.A. (2006) and Leatherman, S.P. et al. (2000). Combined with subsidence, sea level rise unbalances the marshes health by shifting the intertidal zone and drowning marsh vegetation. The resulting loss of vegetation reduces the associated root mat and contributes to erosion of these critical coastal ecosystems, often depositing the eroded material into navigable channels and increasing the need to dredge. As such, the stabilization of these marshes via thin-layer placement (TLP) of dredged material would not only restore critical habitat; but, in doing so, could potentially reduce the need for maintenance dredging in adjacent channels. Application of TLP to degraded marshes could be performed on a cyclical basis to keep up with sea level rise while fulfilling the dredged material storage needs of a channel maintenance program. Additional benefit is provided via increased resilience to coastal communities behind these coastal marshes, as a marsh buffer has been shown by Lunemann, M. et al. (2017) to reduce damage beginning at buffer widths of 45 meters. Building on two pilot projects by the US Army Corps of Engineers at Stone Harbor, NJ and Avalon, NJ, OMR sought to expand on these examples with a joint pilot project for TLP using dredged material to enhance marsh health at Fortescue, NJ.

**Case Study: Thin-Layer Placement – Fortescue, New Jersey**

Between the winter of 2016 and spring of 2017, maintenance dredging was performed in Fortescue Creek located in Downe Township, Cumberland County, New Jersey. The project consisted of over 27,500 cubic meters of material that was dredged and placed at 4 different sites. Fill methods consisted of thin-layer placement as marsh fill, non-bathing beach fill, shoreline restoration dune fill, and bathing beach fill. Material was designated to a placement site after extensive material sampling and analysis of the shoal volumes within Fortescue Creek. Portions of the channel containing the most fine-grained sediment (silts and clays) were designated most suitable for marsh fill. Portions of the channel consisting of coarse grained material greater than 90% sand were designated for either dune fill or bathing beach fill, while material containing between 75% and 90% of sand content was designated for non-bathing beach fill. Aside from being unique for utilizing four separate placement areas, this project was a pilot test of thin layer marsh enhancement sponsored by the New Jersey Department of Environmental (NJDEP) on 8 hectares of degraded coastal marsh. Collaboration between multiple entities, including NJDOT-OMR, USACE, and NJDEP was required during the planning phase to establish goals and success criteria. Extensive studies of the marsh were performed by the NJDEP's environmental consultant to determine a range of target fill elevations that would restore areas of low and high marsh habitat without creating new uplands. Upland habitat in marsh areas of this part of New Jersey are prone to domination by *Phragmites australis*, an invasive weed with little habitat value.

As with any pilot project, challenges were presented throughout both the design and construction processes. Given the geography of the project location, the adjacent Delaware Bay plays a major role in dictating tidal fluctuation at this site. Tidal ranges varied from approximately -0.152 m to +2.124 m MLW in the most severe instances. One challenge associated with a large tidal range at a degraded marsh site is that portions of the marsh fill area can become completely inundated during the peak of a high tide event. For this reason, specialized equipment was utilized to transport materials and personnel across the work site. Equipment used during the marsh fill events included pontoon excavators, marsh buggies, an amphibious tracked vehicle, and a low ground pressure bulldozer. Dredging was performed using a 0.3-m discharge pipe diameter cutter suction dredge and material was conveyed through a 0.3-m diameter high density-polyethylene (HDPE) pipeline. The pipeline from the stern of the dredge was landed ashore of the marsh and connected to a network of additional shore pipeline featuring a "trunk" with several "branches" that spanned across the entire marsh fill area. Each branch had the ability to be opened and closed by means of a valve system at its intersection with the trunk. This methodology was chosen for a variety of reasons, such as allowing for a rapid response to divert the flow in the event of insufficient control of the inflow point, and to allow for simultaneous inflow at multiple locations. The use of HDPE pipeline allows for additional maneuverability of the inflow points given its flexible and lightweight nature as indicated in Figure 9.

**Figure 9 – Pumping Dredged Material onto the Marsh during Fortescue TLP**

To further control inflow material, multiple layers of sediment control/filtration (SiltSoxx), were placed along the perimeter of the placement site as shown in Figure 10. The SiltSoxx played an important role in capturing fine-grained dredged material that failed to separate from the slurry upon discharge, which prevented sediment from reaching natural drainage features outside the placement area and being reintroduced into the surrounding waterways.

**Figure 10 – Aerial View of Fortescue TLP Site and Outer Rows of Sediment Control**

After all thin-layer placement operations had been completed; approximately 5,350 cubic meters was placed across the site. As of January 2018, after one full growing season, the marsh had already established desirable vegetation and was on its way to environmental success.

Over the course of placement operations, the design team discussed several ways to improve thin-layer placement methods going forward. One major challenge associated with this concept is maximum fill elevation restrictions. In the event that the target fill elevation is exceeded, the potential for invasive plant species, such as *Phragmites australis* or Common Reed, increases. In cases where a single inflow point is used to discharge for an excessive amount of time, the inflow location is susceptible to accumulate too much material and form mounds above the target elevations. Appropriating the amount of time spent at a single discharge point is dependent on the thickness of fill, characteristics of the dredged material, and volume of slurry. In order to combat mounding, either the discharge point must be moved frequently, or the slurry inflow rate must be reduced. This was experimented with in Fortescue by utilizing amphibious excavators and marsh buggies to physically adjust the discharge point in a lateral manner, moving the pipeline from side to side to encourage dredged material to disperse.

Another method associated with thin-layer placement is referred to as spray dredging. Spray dredging is conducted by discharging the slurry through a narrow opening, such as a nozzle, with the end of pipeline oriented in an upward fashion. This results in an increase in discharge velocity and therefore will spray dredged material allowing for a more controlled filling over a greater coverage area. A disadvantage to this technique is that additional risks are associated with transportation of heavy equipment across sensitive marsh grasses, as was experienced during the Fortescue project. Excessive movement of the equipment on soft soils, especially excavators mounted on pontoon tracks, would occasionally lead to bogging. Furthermore, reducing the discharge diameter by use of a nozzle can result in losses of dredge productivity and a greater propensity for clogging, leading to increased project costs and longer project durations.

Another notable conclusion taken from the Fortescue project was that the high tide events served to further distribute dredged material in a uniform manner. These tides combined with wind and precipitation were beneficial in achieving more acreage of fill as well as reducing the height of undesired mounds. Further consideration should be given to the use of natural processes to “smooth out” the final elevations in future TLP projects.

Given the vast acreage of similar ecosystems along New Jersey’s coastline, there are many additional opportunities for thin-layer placement. Applying innovative strategies built upon lessons learned from pilot projects such as Fortescue is an important part of developing a more sustainable and resilient process.

**Mutual Improvement to Sustainability and Resilience via TLP**

The approaches described by the Keansburg CDF (i.e. CDFs used for coastal protection) and Fortescue TLP (i.e. dredged material for enhancing marsh health) provide an unorthodox approach to managing dredged material in New Jersey, but one that seeks to achieve a win-win situation out of singular projects and promote public perception of dredged material as a resource. The potential MTS resilience gained from the sustainable TLP approach is especially promising.

The application of the TLP approach to the coastal marshes around the state’s upland CDFs would provide enhanced protection to the confining berms as noted by Lunemann, M. et al. (2017), thereby boosting MTS resilience while maintaining the health of the critical marsh habitat. However, New Jersey contains a significant amount of coastal marshes along the eastern back bays. Using TLP on these marshes would provide dredged material as a sustainable resource to promote marsh health in the face of sea level rise along roughly 145 kilometers of New Jersey’s coastline from Bay Head to Cape May, while also providing valuable dredged material storage capacity on a regular basis.

Looking at the Barnegat Bay region alone (Figure 11), Barone, D.A. et al. (2014) have identified TLP as an alternative at three locations to restore wetlands eroded from Superstorm Sandy directly seaward of structures, which would require nearly 145,000 cubic meters of dredged material. On a wider scale, based on the Barnegat Bay Partnership’s 2016 State of the Bay Report by Baldwin-Brown, A., et al. (2016), TLP could be used to restore roughly 2.75 square kilometers of tidal marsh lost to erosion since 1995. Assuming an average of only 0.15 to 0.3 meters placed to restore these eroded wetlands, a potential dredged material storage capacity of approximately 400,000 to 800,000 cubic meters could be gained.

While these potential applications deal with restoring already-lost tidal marshes, degraded marshland could also benefit from TLP of dredged material. Based on mapping of confirmed stressed marshland within the Barnegat Bay by Baldwin-Brown, A. et al. (2016), these stressed marshland areas total approximately 19 square kilometers. By using TLP to restore this marshland, an estimated additional

1.45 million cubic meters of storage capacity could be gained, assuming TLP at a conservatively low average application thickness of 7.5 centimeters for the magenta-shaded areas of coastal marsh in Figure 11. Only areas of marsh confirmed as stressed via sampling and testing are provided in Figure 11, and additional areas of degraded marsh are likely present.

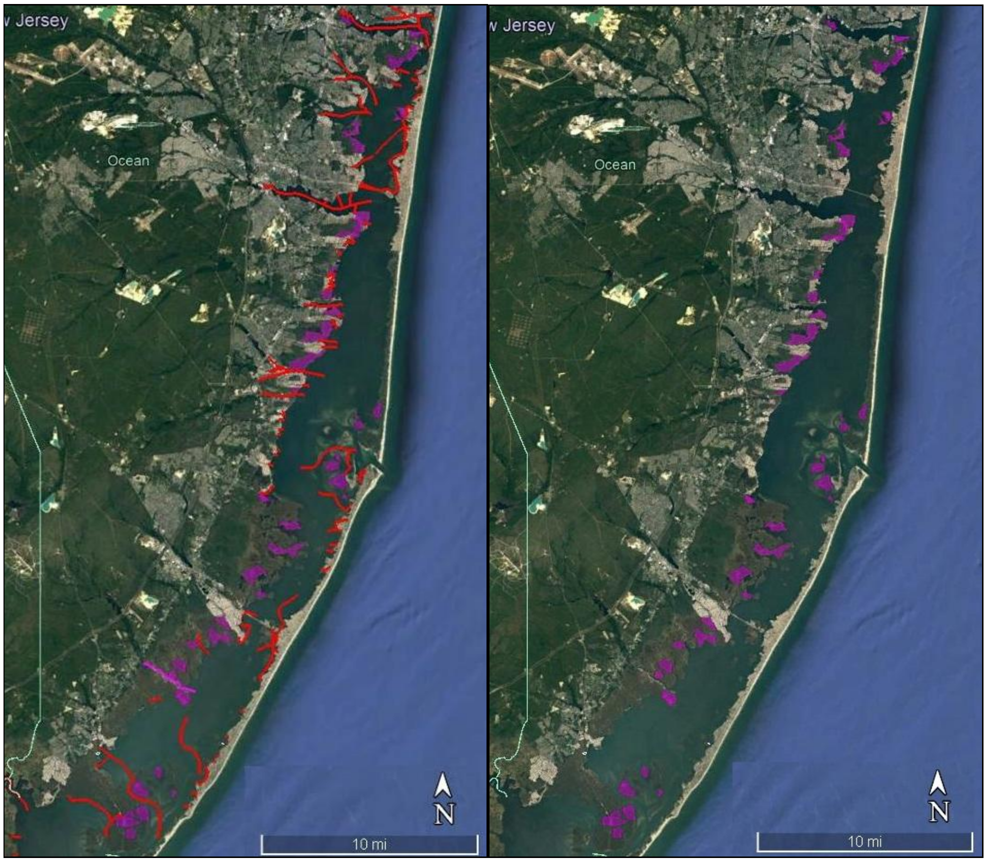


**Figure 11 – Areas of Stressed Marsh in Barnegat Bay Region (shaded magenta), with Channels (in red, left) and without Channels (right)**

As a result, TLP use in just the Barnegat Bay region could provide as much as 2 million cubic meters of dredged material storage capacity, effectively quadrupling dredged material storage capacity in this region. Providing a beneficial use alternative in the northern Barnegat Bay where no CDFs exist, and promoting a healthy marsh habitat and coastal buffer along 65 kilometers of coastline, enhances both sustainability of the region and resilience of the MTS. The availability of these degraded marshes for dredged material storage could significantly increase the rate of recovery systemwide following the next storm and shift the channel navigability to a higher level of resilience.

The state is currently in discussions with the US Fish and Wildlife Service to restore numerous degraded coastal marshes in Barnegat Bay via TLP using material dredged from the NJ MTS. Considering the success of the Fortescue TLP project and that these marshlands are all within an 8-kilometer radius of state-maintained channels, the potential for TLP to play an increased role in the state channel dredging program is high.

However, while the agency mindset toward dredged material use and TLP may be optimistic in New Jersey, the current cost of TLP (US$150/cubic meter) is approximately double that of CDF-use, making TLP less attractive economically. Increased frequency of these projects, as well as increasing the scope and scale of TLP projects, is hoped to result in reduced costs or more innovative methods that would make TLP more economically sustainable. One option to recoup TLP costs could be the formation of a state-owned wetlands bank. Under this setup, the state would gain regulatory credits for restoring wetlands using TLP that could then be sold to private developers, or used by NJDOT, to offset impacts to wetlands on other projects. Depending on location, wetlands bank credits have been sold for as high as US$150,000 per credit in New Jersey with an average in-state value of approximately US$50,000 per credit based on the NJ In-Lieu Fee Mitigation Program, Final

Instrument (2015). While not likely to fully fund NJ MTS projects, the value of these credits could seek to offset some of the costs associated with TLP and make TLP more economically sustainable.

## CONCLUSIONS

Superstorm Sandy has provided a daunting recovery challenge to the region that has sparked discussions on resilience and sustainability in the storm's aftermath. Numerous challenges faced the recovery process, including extensive debris removal, severe shoaling of navigation channels, and a change in channel management agencies. Though these challenges dampened the resilience of the NJ MTS following the storm, OMR's prioritization and pre-recovery planning contributed to higher resilience on the regional level, as demonstrated by the Raritan Bayshore region. OMR's efforts to restore the state-maintained marine transportation system, as well as their commitment toward enhancing sustainability and resilience as part of their recovery efforts to reduce future damage and improve dredged material storage capacity, have yielded an anti-fragile response as indicated by Figures 2, 4 (right), & 5. As such, OMR has demonstrated that resilience planning, even if performed during the initial stages of recovery, provides a more effective and resilient recovery which can lead to anti-fragility of a system.

A direct link between sustainability and resilience was also highlighted by the NJ MTS following Superstorm Sandy. With post-storm funding levels significantly exceeding pre-storm levels, the funding stream made available following the storm also contributed to the anti-fragile response. However, failure to maintain a sustainable, adequate funding source would result in undoing or reversing the gains in resilience and hamper future recovery efforts as a direct result of the lower economic sustainability of the system.

However, in addition to economic sustainability, a more resilient MTS requires a comprehensive approach to dredged material management to maintain dredged material disposal capacity. By viewing CDFs as temporary dewatering facilities, using CAD to improve degraded aquatic habitat, and by applying TLP of dredged material to enhance degraded coastal marshes, win-win situations are developed via gains in both operational and environmental sustainability. The success of the Fortescue TLP project demonstrates the efficacy, challenges, and potential of this approach to enhance NJ MTS resilience on a wider scale. The increased potential storage capacity directly leads to improved resilience, as dredging projects could begin more rapidly following the next event, while additional economic sustainability could be gained by establishing wetlands banks to partially offset the costs of TLP projects.

The importance of multi-party coordination and stakeholder engagement during recovery processes was indicated by the Keansburg CDF case study. Via stakeholder engagement, a unique situation of locals wanting more dredged material opened the door to the creation of additional storage capacity by creating a hybrid CDF-dune system to enhance coastal protection through the beneficial use of dredged material. The debris removal phase of the NJ MTS recovery provided further correlation between multi-party coordination and the effectiveness and speed of recovery.

As such, with a little foresight and commitment to resilience, extreme events or other stressors can result in an improved system compared to the pre-stressor conditions, i.e. anti-fragility, due to a refocus of political priorities, availability of improved funding, and changes in public perception. As the OMR program continues to advance and grow, the resilience of the NJ MTS grows as well. The continued improvement of the state-maintained channels to a state of good repair and continued efforts to increase available dredged material storage capacity, will find the NJ MTS in a better condition when the next storm impacts the state and in a position to better resist damage and more rapidly recover.

## ACKNOWLEDGEMENTS

The authors would like to recognize the following people for their involvement and contribution to the work that formed the basis of this paper: Sean Flanigan & John Drake from Gahagan & Bryant Associates (GBA); Jerry Chen, Steve Chiaramonte, Kristen Maloney, & Dave Wysocki from WSP; Kelly Rosofsky from Dewberry Engineers; and Bill Henderson & Joselyn Wall from NJDOT OMR.

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