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FROM THE EDITOR'S DESK:

Adapting to sea level rise, one layer at a time

By

Lesley C. Ewing, Ph.D., editor

On 9 August 2021, the Intergovernmental Panel on Climate Change (IPCC) released the Sixth Assessment Report, Climate Change 2021: The Physical Science Basis, the first of three major reports. Second and third reports on Adaptation/Vulnerability and Mitigation are scheduled to be released in the spring of 2022. The Physical Science report provides updates on climate trends and one of the sobering projections is that even if greenhouse gas (GHG) emissions are limited to keep global temperature increases to a 1.5 °C., sea level will continue to rise through the 21st century and beyond. Even with negative GHG emissions, a reversal of sea level rise will take centuries to millennia to happen. One consequence of this trend is that many coastal areas will be confronting erosion and flooding for the foreseeable future.

My reason for raising these global and long-term (and unfortunately depressing) IPCC projections is that coastal areas will need a broad range of adaptation tools for resilience to rising sea level. Beach nourishment and dune restoration are two well-recognized options for using sediment for shoreline enhancement and adaptation to rising sea level. Marsh enhancement and thin layer placement provide a third option for beneficial reuse of sediment. Marsh and wetland areas can provide coastal communities with flood protection, habitat and water quality values, and support for long-term resilience. Like other beneficial uses, thin layer placement is not appropriate for all sites and all conditions, but it has been used successfully at several locations in the U.S. and there is potential to use it for many other areas.

I’m really pleased that Shore & Beach has this special issue on this process and am thankful to Candice Piercy and Ram Mohan for suggesting the issue and developing the broad geographic and topical coverage of marsh enhancement. I hope everyone enjoys this issue.
IN MEMORIAM:

Timothy Lee Welp
(1957-2021)

Tim Welp, a long-time industry researcher who contributed in many ways to the dredging, coastal, and marine industry, passed away on 18 June 2021. Tim served in the U.S. Navy and earned engineering degrees from the University of Wisconsin and the Florida Institute of Technology. Since 1990, he worked as a Research Hydraulic Engineer at the U.S. Army Engineer Research and Development Center (ERDC), contributing to many programs including the Dredging Operations Technical Support (DOTS), Dredging Operations and Environmental Research (DOER), Engineering with Nature (EWN) and many others. Tim’s career at ERDC spanned three decades and he was one of the world’s premier experts on innovative dredging practices and sediment management. He had an almost childlike enthusiasm for dredges and dredging equipment and was passionate about his work. More importantly, Tim’s spirit and kindness made him a wonderful colleague, mentor, and friend to all those who worked with him. Tim was a loving husband and father, who was also an avid scuba diver, metal detector, ice fisherman, and a third-degree black belt. It seems fitting to remember Tim and his contributions to our industry as a part of this dedicated issue on marsh enhancement.
Thin layer placement for marsh enhancement: Planning, design, construction, and monitoring considerations

By

Ram Mohan, Ph.D., P.E., F.ASCE,¹ Candice Piercy, Ph.D., P.E.,² and Timothy Welp³

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ABSTRACT

Thin layer placement (TLP) is the purposeful placement of thin layers of sediment in an environmentally acceptable manner to achieve a target elevation or thickness. TLP is used for a variety of purposes, such as sediment management, beneficial use of dredged material (DM), and ecological enhancement. The term “thin” is used to distinguish TLP from other methods of sediment placement in which sediments are applied in layers on the order of several meters thick. In this paper, DM disposal refers to the deposition of sediment in a location and manner where no beneficial use is attained; with DM placement the sediment is used to benefit society and the environment. The application of thin layers of sediment has advantages over more traditional, thicker sediment applications in environments where these thicker layers pose potential challenges to natural resources, infrastructure, navigation, or other assets. Although TLP projects are most often conducted in wetlands, there are open-water applications as well. But because TLP is relatively early in its development, there is a dearth of design and construction information and guidance available to practitioners. This paper provides a high-level summary of pending national TLP guidance being developed by the authors on behalf of the U.S. Army Corps of Engineers’ Engineer Research and Development Center (USACE ERDC).

Sediment has historically been excavated in one location and placed in another in a particular way to achieve benefits. Thin layer placement (TLP) is increasingly used for projects in wetlands and open water because the methodology has displayed ecological and resiliency benefits over more traditional, thicker sediment placement processes. As its name implies, TLP is the purposeful placement of thin layers of sediment in an environmentally acceptable manner to achieve a target elevation or thickness. This definition is intentionally broad so it can be applied to placement in a variety of habitats and for various purposes: wetlands, open water, and capping. TLP projects can include efforts to support infrastructure and to create, maintain, enhance, or restore ecological function, and commonly occurs in open water and wetlands.

Recent interest in TLP has mostly concerned applications in coastal wetlands. (Figure 1 shows a cutterhead dredge conducting wetland TLP in Chesapeake Bay, Maryland; Figure 2 shows a platform-based nozzle spray used at Seal Beach, California. Both configurations use high-pressure spray.) Various reports have documented the benefits of wetland TLP, including increased marsh elevation, improved soil stability, and enhanced wetland functions while maintaining characteristic plant communities (DeLaune et al. 1990; Mendelsohn and Kuhn 2003; Mohan et al. 2016). Several studies document the benefits of TLP applications to marsh vegetation, with common wetland plants (e.g., Spartina alterniflora) displaying the capacity for recovery following the deposition of a layer of sediment 0.1 ft (0.30 cm) thick, depending on wetland characteristics (Ray 2007; Mohan et al. 2016; VanZomeren and Piercy 2020).

In 2008, the Louisiana Coastal Protection and Restoration Authority (CPRA) referenced the LaPeyre et al. (2006) definition of marsh nourishment, a subcategory of TLP as “a restoration technique that can refer to either the direct placement of a thin-layer of sediment through spray or hydraulic dredging or from the ‘spilling’ of a thin-layer of sediment over marsh that is adjacent to an uncontained restoration project” (CPRA 2008). At the time, it was reported that “marsh nourishment is a relatively new restoration strategy that provides an opportunity for further research” and that a marsh nourishment component had been included in several marsh creation projects in coastal Louisiana. Marsh nourishment is currently defined by CPRA as “typically accomplished by the placement of hydraulically dredged material into unconfined or confined vegetated marsh area(s), to the elevation (typically lower than MC [marsh creation]) required to achieve the project intertidal marsh objectives for the project design life” (CPRA 2017).

Open water TLP has been used as a management tool to maintain littoral sediment supply in coastal and estuarine settings. Examples include placing a 0.5-ft (15-cm) thick layer of dredged material (DM) in shallow water (10 ft [3 m]) to reduce impacts to the benthic communities in Mississippi Sound (Wilbur et al. 2007) and to maintain sediment supplies within the Mobile Bay, Alabama, system while enhancing benthic communities with a 1-ft (30-cm) thick sediment layer (Parson et al. 2015). Figure 3 shows an example from a 2012 Mobile Bay TLP project in which a spill barge was used to place DM from a cutterhead dredge. A deeper (40-55 ft [12-16.8 m]) open water TLP project at the mouth of the Columbia River in Or-
egon provided supplementary sediment in support of existing infrastructure to address littoral sediment needs by placing sediments with a hopper dredge to reduce scour along jetties, while avoiding potential negative impacts to navigation safety (e.g. mound elevations) and smothering of biological resources, such as fish and crabs (Norton et al. 2015).

Thin layer capping or covers (TLC), a modified TLP approach, has also been used to restore environmentally degraded sediments like those at legacy contaminated sites. A summary of case studies of open water TLC is presented in Merritt et al. (2010), and elsewhere in this issue of Shore & Beach, Mohan et al. (2021) summarize considerations for the first successful field-scale pilot TLC application to restore a legacy contaminated wetland site in Brunswick, Georgia (see Figure 4). Regardless of the method of application or the ecosystem uplift goal, similar principles apply to the successful planning, design, and implementation of TLC and TLP projects.

More examples of TLP projects are available on the website (https://tlp.el.erdc.dren.mil/) developed by the Dredging Operations and Environmental Research program and the U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) Dredging Operations Technical Support program to highlight TLP concepts, case studies of pilot and full-scale projects, and associated literature (USACE ERDC 2021).

PLANNING CONSIDERATIONS
A process framework for initiating, planning, designing, constructing, monitoring, and managing a TLP project is shown in Figure 5. TLP projects are complex, not only due to the difficulty of designing for the creation, maintenance, enhancement, or restoration of ecological function, but also due to the regulations that govern wetlands and open water. The need to identify and acquire a suitable sediment source within the project timeline and to coordinate schedules with the dredging project may also make a TLP project even more complex. Project delays can be mitigated through diligence in the planning and initial design phases to address logistical issues associated with project planning and sediment acquisition.

Adaptive management should be used throughout planning, design, construction, and postconstruction project phases. A good definition of adaptive management, slightly modified from the Natural and Nature-Based Features (NNBF) Guidelines document (Bridges et al. 2021) and Craig and Ruhl (2014), is the following: “Adaptive management is a structured decision-making method, the core of which is a multi-step, iterative process for adjusting management actions to changing circumstances or new information about the effectiveness of prior TLP projects or the system being managed.”

Planning stages require significant engagement with groups of key stakeholders and should focus on team building and developing consensus on key project aspects, such as goals and objectives, constraints, and success criteria. Because TLP projects frequently involve groups with distinct goals, this stage is critical to ensuring clear communication among all parties at project outset. Successful TLP projects require a balancing, or harmonization, of all stakeholder perspectives to achieve a win/win situation. This harmonization is facilitated when all sides have a “clear and common understanding of the overall project goals” (TNC and NJDEP 2020). The stakeholder group should include not only the project lead, which often is the landowner, but also other groups or universities that may be involved in project monitoring; regional restoration programs; federal, state, and local government agencies; and regional or local groups interested in conservation or waterway management (e.g. bird watchers, shellfish lease owners, ports, and local residents). Early stakeholder engagement often informs project goals and objectives, so key stakeholders should be approached before project goals and objectives are formalized. Early stakeholder group formation also allows relationships (and, in some cases, trust)
Figure 3. A spill barge facilitates TLP in Mobile Bay, Alabama. (Source: U.S. Army Corps of Engineers, Mobile District.)

to develop over time; however, not all potential stakeholders need to be assembled immediately. Not all stakeholders are immediately apparent at the outset of a TLP project, and peripheral stakeholders may be better engaged once the project enters the design phase. Understanding a project’s social and regulatory context will help identify the key stakeholders and provide guidance on when they should be engaged.

Before the start of a TLP project — or any project that includes habitat restoration or management — the entire project team should have a good understanding of how the receiving habitat functions and how TLP may improve overall habitat functioning. In the early phases of a TLP project, the project team should work with local experts to examine the region of interest, whether it is a particular embayment, river reach, or navigation channel, and develop or communicate to the project team a rough conceptual understanding of how that system functions, including how water, sediment, and biota move.

During planning, all TLP projects should establish how TLP will achieve project objectives. TLP is one of many beneficial-use tools and should be clearly distinguished from traditional DM placement methods. The primary purpose of TLP is not DM disposal, but rather the achievement of a specific target elevation or depth, often for an ecological purpose. TLP should be considered only if it is suited to the placement location, and all projects should establish the suitability of the site for the technique before proceeding. The choice to use TLP should be considered carefully because of the limitations and tradeoffs involved in using the technique. Most TLP projects have been implemented to address degradation in the landscape, such as loss of wetland elevation or coastal erosion, although some projects are designed simply to keep sediment within the coastal or riverine system while minimizing potential negative ecological and navigational impacts.

A major consideration for TLP projects is how well sediment acquisition and sediment placement align. Sediment must be acquired and placed in ways that minimize damage to the surrounding and receiving habitats, and the placement design must be compatible with not only the sediment type, but also the source location, quantity, and method of conveyance. Because the sediment properties will drive many aspects of the design, the sediment source should be identified early in the process.

Existing data and information should be thoroughly investigated and reviewed to optimize resources and help inform the data gap analyses to determine how much and what kinds of additional data will be required. Table 1 lists planning considerations for TLP projects that are generally applicable to most projects.

**Table 1.**

TLP project planning considerations check list.

- Define TLP project goals
- Identify potential sites (dredging and TLP)
  - Perform logistics analysis (transport mode, distance)
- Define habitat zones and success criteria
- Identify development timeframe
  - Decide on placement cells, lift thickness, wetland establishment timesframes
- Preliminary site screening
  - Are sites compatible with TLP project goals?
  - Are there regulatory constraints?
- Gather relevant site data
- Large-scale topography and bathymetry
- Generic soil/sediment types
- General descriptors of vegetation zones and types
- Benthic characteristics (species, abundance)
- Hydrodynamic conditions
- Tidal ranges
- Cultural and archaeological resources
- Land rights (easements, right-of-way)
- Infrastructure (pipelines, cables, etc.)
- Determine preliminary sizing of TLP project
- Develop alternatives analysis and cost estimates
- Identify potential funding sources
- Select preferred alternative

**DESIGN CONSIDERATIONS**

Once the TLP project team decides to proceed, the development schedule should be established. This will include not only the design schedule and placement timeframe but also the expected time required for the wetland or subaqueous bottom to recover after sediment placement. Once the schedule is known, it can be matched with existing and future DM sourcing from nearby projects, or another sediment source can be identified. Early identification of the sediment source is critical to ensuring the project proceeds. Although the design process for TLP projects is similar to those for any other earthwork project, a project that relies on...
DM for sediment is essentially two projects: a TLP project and a dredging project. The engineering phases for dredging and placement should align as much as possible so that both projects are ready for implementation at the same time. This design process requires a multidisciplinary approach that can involve a wide variety of professionals, including biologists and geotechnical, civil, and environmental engineers, all working to produce documentation (including technical specifications, engineering drawing, cost estimates, and measurement and payment clauses) that enable the contractor(s) to bid and construct the project.

**Design phases**

In general, the following are the typical phases of engineering design for TLP projects:

**Conceptual (15%) design:** This is mostly equivalent to a master plan to implement the project and focuses on overall design goals, success criteria, and the path to get there. Key conceptual project features — and often a conceptual-level cost estimate — are developed at this stage. These design documents are used to evaluate the technical and cost feasibility of different alternatives. Sources of funding for project implementation are also often evaluated during this phase.

**Preliminary (30%) design:** In this phase, site-specific data are incorporated into the engineering analysis and the design is developed further. A data gap analysis is conducted to identify any critical data that may be missing so they can be collected in the field. Preliminary plans, a list of technical specifications, and an updated construction cost estimate, which should indicate a reduced contingency factor, are also developed. Project permit applications often are submitted during this phase.

**Intermediate (60%) design:** This is an optional design phase in which the plans and specifications are advanced much further along with the engineering design. During this phase, regulatory agency and stakeholder input, as well as any permit conditions, are incorporated into the design documents. Typically, at the completion of this design phase, processes such as value engineering (to identify high-cost items with a view to reducing costs) and a constructability review (to identify costly or infeasible construction elements that can then be optimized) are implemented.

**Pre-final/final (90%/100%) design:** In this design phase, inputs from value engineering and the constructability review are incorporated to finalize the engineering design. Final estimated quantities, design specifications such as pipeline corridors and marsh access, staging areas, restoration plan and other relevant details are developed during this phase. Contingencies at this stage should be minimal and should reflect uncertainties such as market factors, material variability in the field, etc. Project certifications and permits are appended to the design document during this phase. Plans and specifications are also finalized and stamped/sealed at this time.

The conceptual and preliminary designs should assess which elements require further development to bring the project design to a constructable phase (i.e. the final design stage). Common key design elements are summarized in Table 2. Not all projects will require all these design elements.

Depending on the project, other design elements may also be required.

### Table 2. Common key design elements for wetland and open-water TLP projects.

<table>
<thead>
<tr>
<th>Placement area layout</th>
<th>Construction access and staging areas</th>
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<td>Erosion and sediment control</td>
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<td>Project area (limits of work)</td>
<td>Equipment type</td>
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<td>Target elevations/depths</td>
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<td>Channel/borrow DM volumes vs. placement capacity</td>
<td>Placement area topography/bathymetry</td>
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<tr>
<td>Placement tolerances</td>
<td>Access corridors for pipelines and/or vehicles</td>
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<td>Source material for TLP (dredge site)</td>
<td>Sequence of work</td>
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<tr>
<td>Desired DM composition (grain size)</td>
<td>DM elevation (consolidation, settling, etc.)</td>
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<tr>
<td>Sediment transport (during and after TLP)</td>
<td>Measurement and payment methods</td>
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<tr>
<td>Flood/scour protection</td>
<td>Permit conditions</td>
</tr>
<tr>
<td>Sediment biogeochemistry (i.e. nutrients, sulfides)</td>
<td>Planting/restoration</td>
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<tr>
<td>Environmental impacts</td>
<td>Long-term monitoring</td>
</tr>
<tr>
<td>Containment structures (if any)</td>
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</tbody>
</table>
Table 3. Checklist for engineering design of TLP projects.

- Define project goals/success criteria
- Obtain site data
  - Topography and bathymetry, including channels, marsh pannes and other features
  - Vegetation density and types
  - Geotechnical information for dredge and native (surface and subsurface) sediments
  - Tidal flow regimes, ranges and velocities
- Determine site area for placement and target elevations and/or lift thickness (including tolerances)
- Site access and staging area plans
- Material sourcing (for TLP)
- Develop regulatory permitting strategy and incorporate regulatory constraints into design
- Decide on dredge type and specifications (depending on contracting mechanism)
- Determine optimal placement method (spray, baffles, etc.)
- Determine DM volume relationships (in situ volume vs. placement bulking)
- Determine DM consolidation/subsurface settlement impact on elevation over time
- Decide on lateral containment if any
- Protect natural channels and drainage features?
- Determine requirements for site drainage and turbidity control
- Develop engineering design – plans, specifications, and cost estimate
- Determine means and methods for placement tracking (volumes and lift thickness)
- Develop procurement strategy
- Long-term monitoring plan
- Adaptive management plan and identify entity who will execute the plan

Not all design elements will require the same level of detail to execute a project successfully, and the project team should determine the appropriate level of detail depending on the project objectives and the regulatory environment. Projects that involve or are near especially sensitive habitats or protected ecological resources, such as shellfish, may require a greater level of design detail than projects in or near degraded habitats. A generic checklist for developing engineering designs for TLP projects is presented in Table 3.

Cost estimate

The final construction cost estimate should be developed based on plan quantities and pricing estimates once the design nears finalization. It should detail the critical construction steps depicted in the bid sheet and project schedule. Typical elements for wetland TLP projects include mobilization and demobilization, dredging and placement site surveys (including material costs [e.g. grade stakes or settlement plates]), access and staging areas, containment structures, dredging (if applicable), placement, site restoration, and temporary warning signs. Vegetative plantings may be added based on landowner preference and risk tolerance related to concerns with re-colonization of existing vegetation, seed stock, and potential for colonization by invasive species. It is important to include uncertainties and appropriate contingency factors for each phase of the engineering design, as depicted in Table 4.

Construction considerations

Construction considerations, equipment, and methods for dredging and DM placement are discussed in the USACE manual Dredging and Dredged Material Management (USACE 2015) and in CPRA engineering guidance pertaining to construction of marsh creation and wetland nourishment projects (CPRA 2017). Lessons learned from implementing the Ring Island, Avalon, and Fortescue TLP projects in New Jersey are presented in TNC and NJDOT (2020). We therefore present here additional information on construction considerations, equipment, and methods specific to wetland and open water TLP projects to emphasize or augment the information in these other three references.

Generally, the following should be evaluated during the construction phase:

- **Safety:** An assessment of potential job hazards and mitigation protocols, including worker training, should be developed.
- **Equipment and methods:** A survey of appropriate and available equipment and methods must be conducted, specific to the nature and goals of the TLP project. Considerations may include dredge type, transport methods, and placement modes including low- or high-pressure discharge (Cahoon and Cowan 1987):
  - “Low pressure discharge” consists
of either an open-ended pipe without any attachment, or a pipe equipped with a spreader plate to slow the slurry and provide better control over its placement and reduce impacts to wetland surfaces or the water column.

- “High pressure discharge” involves the use of a contraction section (typically a nozzle) at the end of a pipe to propel the slurry in an arc-shaped pattern.

- Place a checklist for the construction phase considerations is presented in Table 5.

**MONITORING CONSIDERATIONS**

TLP project monitoring includes monitoring during and immediately after construction to determine whether the construction activities meet specifications and comply with regulatory requirements. Baseline and post-construction monitoring are designed to evaluate site recovery and enhancement after placement. Monitoring plans should focus primarily on monitoring metrics that are easily measured and actionable from an adaptive management standpoint. Collecting a wealth of “nice-to-know” information with no clear plan for how to use those data to manage the TLP site can raise project costs without increasing benefits. Instead, a few thoughtfully selected monitoring metrics are recommended; additional metrics can be added if the site does not function as expected. This caution does not apply to biologic resource utilization monitoring, which should more appropriately track with ongoing resource management plans.

Monitoring during construction typically includes some measure of placement depth or elevation throughout the TLP site, through the use of simple grade stakes to visually assess the elevation or depth of slurry or through hydrographic surveys. Some dredges are equipped with flow meters that can determine the volume of slurry moved to the site and can estimate how much sediment has been pumped on the site.

Other monitoring during construction is designed to assess whether construction is affecting ecological resources in the area. Turbidity is frequently monitored near TLP sites to determine whether sediments are quickly leaving the site or moving into ecologically sensitive areas. No hard rules specify the turbidity levels permitted near a TLP site, which vary from project to project and state to state. However, turbidity from TLP decreases rapidly with distance from the site, especially if the site is in relatively shallow water. Photographic and video documentation of TLP projects has also been used to assess ecological impacts qualitatively and quantitatively.

Once construction is completed, monitoring plans shift their focus to site recovery and function. The post-construction monitoring plan should be informed by the TLP project objectives and developed as part of an adaptive management plan. There is no standard array of recommended monitoring metrics that will work for every TLP project. TLP projects designed for marsh restoration will use a

<table>
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<th>Table 4. Typical marsh creation project design phases.</th>
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<td><strong>Project design phase</strong></td>
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<td>Preliminary design (30%)</td>
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<td>Intermediate design (60%)</td>
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<tr>
<td>Pre-final (95%) and final (100%) design</td>
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Note: 1) The level of contingency is shown for informational purposes and does not replace the judgment of the design professional.
Table 5. Construction checklist for TLP projects.

- Align goals and obtain cooperation between owner, contractor and key stakeholders
- Check if value engineering or constructability review performed?
- Prequalify contractors, or review key experience criteria as part of bid requirements
- Perform bid neutralization analysis, if possible, to compare bids more fairly
- Review best management practices and conformance to regulatory stipulations to minimize environmental impacts on wetlands
- Check if placement accuracies are reasonable
- Do not over-prescribe means and methods
- Are preconstruction measurements complete?
  - Contour mapping, surveys and construction staking
- Access for construction personnel, equipment and pipeline transportation corridors marked?
- Encourage innovation with respect to field equipment
  - Use of high pressure and low pressure (traditional end-of-pipe spreader) spray
  - On board versus end-of-pipe nozzles
  - Optimize slurry placement (place sands using natural hydraulic sorting)
  - Shaker screens to screen off debris?
  - Single versus multiple discharge points
  - Single versus multiple placement areas on site
  - Use of low-ground-pressure equipment (amphibious equipment, swamp buggies, etc.)
  - Shoreline and bank stabilization construction techniques/operations
- What kind and how much lateral containment should be used?
- Provisions to work 24/7 (including night-time operation)?
- Time of year restrictions (also known as environmental windows)
- Contingencies for weather delays
- Construction monitoring plan
- Conduct field review after completing construction
- Incorporate adaptive management into long-term monitoring strategy

very different set of monitoring metrics than projects designed to disperse sediment into the nearshore environment. Consequently, the project team should use best practices to develop a monitoring plan that is compatible with the project objectives and budget.

Monitoring plans should be designed to inform site management, and metrics ideally should be tied to prospective site management decisions and adaptive actions. Metrics for TLP projects typically fall into one of four categories: 1) placement site geometry; 2) hydrodynamic function; 3) sediment and soil properties; and 4) ecological properties. Placement site geometry includes both topography and bathymetry of the site, as well as the planform size and shape, and is commonly monitored in some way for all TLP projects. Typical site survey methods are used for site geometry monitoring. Depending on site characteristics and required resolution, they may include land surveying techniques such as total station or real-time kinematic global positioning systems, bathymetric surveying techniques using side-scan or multibeam sonar, or remote sensing techniques using Light Detection and Ranging (LiDAR) or structure-from-motion photogrammetry. For TLP projects where sediment is meant to be dispersed, repeated surveys can determine how quickly sediments are being removed from the site. For sites where sediment is meant to be retained, repeated surveys can be used to ensure sediment is not being lost or to determine consolidation rates. Surveys can be repeated over many years to measure site erosion or accretion rates, which may be especially important for wetland TLP projects. Finer scale measures of accretion and elevation change may use marker horizons, settling plates, or surface elevation tables.

Hydrodynamic process monitoring is not necessary for all TLP projects, but when it is, specific hydrodynamic metrics will depend on project characteristics. Hydrodynamic metrics that may be relevant to wetland TLP projects include water level and the duration of inundation on the wetland platform, waves over the wetland platform or at the wetland edge, and tidal currents in creeks. Currents, waves, and water levels may all be appropriate for open-water TLP projects, depending on project purpose and concerns about placement. For instance, current was monitored as part of the Mobile Bay TLP project to determine the conditions under which bottom currents in the placement area were strong enough to mobilize the sediment.

Sediment and soil properties should be monitored if stakeholders are concerned with consolidation or soil development processes. Typically, sediment and soil properties are only monitored during site recovery for fine or mixed sediments because sandy sediments consolidate very little and are unlikely to show much change in biochemical properties. For consolidation processes, metrics such as bulk density can determine how the sediment is self-compacting. For projects with mixed grain size, additional sediment grain size sampling may be helpful to determine the degree of hydraulic sorting that occurred during placement and to identify areas that are likely to consolidate more than others. Soil development metrics typically focus on biochemical properties. At wetland TLP sites, sediment salinity will often rise immediately after placement as sediments dewater and evaporation concentrates salts in the pore space. Monitoring salinity can help determine when planting can occur without salt-induced plant mortality.

Other biochemical properties that may be useful in projects where ecological function fails to increase as quickly as expected include pH, soil carbon, and nutrients. Special screening methods for the presence of acid-volatile sulfides may be indicated if soil conditions appear to inhibit ecological recovery. Ideally, these site-specific characteristics are identified during the design phase so that appropriate management tools (such as soil amendments like lime) can be
<table>
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<tr>
<th>Metric type</th>
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<th>Method</th>
<th>Purpose</th>
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<tbody>
<tr>
<td>Geometry</td>
<td>Elevation</td>
<td>RTK survey</td>
<td>Determine rate of elevation change after TLP</td>
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<td>Ground-based LiDAR</td>
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<td>Surface elevation table</td>
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<tr>
<td>Hydrodynamic properties</td>
<td>Wave conditions</td>
<td>Wave gages</td>
<td>Determine if wave conditions have changed due to TLP</td>
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<td>Water levels</td>
<td>Water level loggers</td>
<td>Determine if inundation duration of marsh surface has decreased</td>
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<tr>
<td>Sediment/soil properties</td>
<td>Salinity</td>
<td>Conductivity probe</td>
<td>Determine if sediment has consolidated enough to support plant roots</td>
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<tr>
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<td>Bulk density</td>
<td>Soil cores</td>
<td>(alternatively also to confirm that planting can be done before the</td>
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<td></td>
<td>pH</td>
<td>pH/EC probe of soil/sediment slurry</td>
<td>substrate gets too dense for the roots to penetrate)</td>
</tr>
<tr>
<td>Ecological properties</td>
<td>Vegetation</td>
<td>Percent cover</td>
<td>Determine if vegetation recovery is occurring, determine if planting</td>
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<tr>
<td></td>
<td>abundance</td>
<td>Above-ground biomass</td>
<td>is necessary</td>
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<td></td>
<td>Below-ground biomass</td>
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<td></td>
<td>Macroinvertebrate</td>
<td>Benthic invertebrate sampling</td>
<td>Determine if TLP caused invertebrate mortality, determine if benthic</td>
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<td>abundance</td>
<td>Acoustic tagging</td>
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<td>Vegetative surveys</td>
<td>Determine if invasives are present, and document type, for site</td>
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<td>management plan</td>
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considered. These factors often change or improve over time, so patience may indeed be a virtue as a field planning consideration.

Ecological metrics are monitored frequently for all TLP projects. Ecological monitoring for wetland TLP projects often focuses on vegetation, using a range of techniques from simple percent-cover estimates to quantification of belowground biomass and species diversity. Other ecological metrics relevant to wetland TLP sites are invasive species; bird usage, such as number of nests; and benthic macroinvertebrates. An abundance of fiddler crab burrows following sediment placement at Avalon, New Jersey, was responsible for widespread bioturbation of the freshly placed sediments prior to vegetation recovery. Common ecological metrics for open water TLP typically consider benthic macroinvertebrate abundance and use. But if a site is near other ecological resources of concern, such as submerged aquatic vegetation or shellfish, additional monitoring may be required to determine whether the placement has caused any longterm benefits or impacts.

The timing and frequency of monitoring should reflect the expected timing of the change in the metric of interest. For instance, if vegetation recovery is expected to take between three and five years, annual vegetation measurements beginning in year 0 or year 1 are not recommended unless they are required to trigger planting in accordance with the adaptive management plan for the site. Conversely, consolidation occurs rapidly after placement, so monitoring to capture the initial rate of consolidation should occur in the initial weeks and months following placement if indicated by the adaptive management plan. Monitoring can also be initiated following storms or other energetic events that may move or redistribute TLP sediments. If a TLP site is expected to persist or to receive multiple placements, basic site monitoring may continue throughout the lifetime of the project (e.g. 50+ years). However, some projects may only require monitoring until the site meets some quality threshold, often identified as “success criteria.” Site recovery time must be reasonably predictable and, in cases where TLP sites are part of a DM management plan, should be compatible with DM capacity requirements.

Monitoring can also serve a larger purpose to ascertain how multiple TLP sites fare in the long term and to determine whether design and construction practices influence site function. Table 6 presents a summary of TLP monitoring considerations.

**CONCLUSIONS**

In recent years, the science and knowledge base for TLP has improved significantly, largely due to USACE’s focus on the Engineering with Nature® (EWN) program, to documentation of case studies and lessons learned on the ERDC website (USACE ERDC 2021), and to outreach efforts including this article. Several states and non-profit organizations have embarked on similar initiatives, and numerous TLP workgroups and workshops have been held around the country in the past five years. Further investigations and studies to answer the following questions would help advance the state of the science of TLP:

- How long does it take a marsh to degrade in the absence of TLP?
- Are there long-term negative impacts of TLP projects?
- Is there a need for new or improved methods to apply TLP, including an increase in pumping distances?
Are there enough long-term data on marsh function and utilization following TLP?

Can or should new methods for quantifying the economic benefits of TLP be developed?

ACKNOWLEDGMENTS

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Tidal marsh restoration at Blackwater National Wildlife Refuge, Maryland: A case study in thin-layer placement

By

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ABSTRACT

Tidal marsh loss at Blackwater National Wildlife Refuge (NWR) has been a major concern of refuge managers in recent decades. The approximately 2,035 hectares (5,028 acres) of tidal marsh that have converted to open water in Blackwater NWR since 1938 (Scott et al. 2009) represent one of the most significant areas of marsh conversion within the Chesapeake Bay. In 2013, a suite of climate adaptation strategies focused on sea level rise was developed for Blackwater NWR and surrounding areas of Dorchester County by the Blackwater Climate Adaptation Project (BCAP). The BCAP is a collaboration of The Conservation Fund, Audubon Maryland-DC, and the U.S. Fish and Wildlife Service, assisted by the Maryland Department of Natural Resources (MD DNR), U.S. Geological Survey, and others. In 2016, the BCAP implemented a thin-layer placement (TLP) project at Shorter’s Wharf in Blackwater NWR on 16 hectares (40 acres) of subsiding and fragmenting tidal marsh dominated by Schoenoplectus americanus, Spartina alterniflora, and Spartina patens. The purpose of the project was to increase the 16 hectares’ (40 acres’) resiliency to climate-driven sea level rise and storm impacts. The project built up the marsh elevation by applying thin layers of sediment dredged from the adjacent Blackwater River.

The sediment enhancement was designed to extend the longevity of the marsh and increase its resiliency by raising its surface elevation in relation to the tidal regime and to return the habitat to its prior high-marsh condition with S. patens dominating. The colonization of this site by saltmarsh sparrow would be an indicator of success in reaching this goal. Dredging operations in November and December 2016 placed approximately 19,900 cubic meters (26,000 cubic yards) of sediment on the project site. Post-restoration elevations obtained one year after material placement indicated that, although the target elevations were achieved in 78% of the surveyed placement area, the material was not distributed uniformly. Coarser material tended to stack up at the discharge location while the grain size declined and the slopes flattened toward the periphery of the discharge area. In 2017, natural vegetation had regenerated through the placed sediment with vigorous regrowth of S. americanus and S. alterniflora. This regrowth was supplemented with hand-planting of more than 200,000 plugs of S. patens. Vegetation monitoring is ongoing to determine the plant composition evolution within the placement site. Pre-dredge and post-dredge bathymetric surveys reveal 70% accretion nearly two years after dredging within the borrow area footprint.

KEYWORDS: Accretion, borrow area, climate adaptation strategies, elevation capital, inner meander bend, reference marsh, sediment transport.

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1938 (Scott et al. 2009) — one of the most significant areas of marsh conversion to open water within the Chesapeake Bay.

Rising sea levels can lead to marsh loss because salt marsh plants, although well adapted to life in the intertidal zone, can tolerate only a certain frequency, depth, and duration of flooding before their vigor declines and they drown. “Elevation capital” in a marsh system refers to the elevation of the marsh surface relative to the lowest elevation in the local tidal range at which native marsh plants can survive. The higher the marsh surface elevation relative to the growth range for these intertidal plants, the more elevation capital and the longer a marsh can exist with an elevation deficit. Much of the existing marsh along the Blackwater River appears to have a surface elevation below ideal growing conditions within the existing tidal range.

In 2013, a suite of climate adaptation strategies focused on sea level rise was developed for Blackwater NWR and surrounding areas by the Blackwater Climate Adaptation Project (BCAP). The goal of the BCAP was to develop strategies that, despite accelerating sea level rise, would ensure the long-term persistence of Dorchester County’s extensive tidal marsh ecosystem and its full assemblage of associated bird species and other wildlife. The BCAP mapped projections of wetland change according to the Sea Level Affecting Marshes Model (SLAMM), a computer-based model widely used to...
SLAMM forecast a near total loss of high tidal marsh at Blackwater NWR with 3.4 ft of sea level rise in the absence of adaptation measures (Lerner et al. 2013).

Planning for the migration of tidal wetlands into adjacent uplands is the most proactive response to relative sea level rise over much of the study area, but a key strategy of the BCAP is to enhance tidal marsh habitats’ resiliency to the impacts of sea level rise in priority areas. One of the highest priority areas for this type of work is the Blackwater-Fishing Bay Marsh Conservation Zone (MCZ). The MCZ (Figure 2) comprises approximately 10,000 hectares (25,000 acres) of tidal marsh surrounding Fishing Bay where management actions are likely to yield the greatest long-term conservation benefits for high tidal marsh and its suite of obligate salt marsh birds. The MCZ boundaries are based on an analysis of factors such as intact high-quality salt marsh and the presence of relatively large breeding populations of high-priority salt marsh species such as the black rail (Laterallus jamaicensis) and the saltmarsh sparrow (Ammospiza caudacuta). The BCAP recommended sediment enhancement to maintain the integrity of the MCZ in targeted areas.

**SITE DESCRIPTION**

Within the MCZ, the Shorter’s Wharf restoration site (Figure 3) was dominated by monotypic stands of common threesquare (Schoenoplectus americanus) with areas of smooth cordgrass (Spartina alterniflora). Areas dominated by S. alterniflora frequently had saltmeadow cordgrass (S. patens) as a minor constituent. Patches of S. patens and saltgrass (Distichlis spicata) were close to the river edge where the ground is higher. Big cordgrass (S. cynosuroides) formed a fringe of varying widths along portions of the bank of the Blackwater River and along interior creeks.

Tide range at the project site is estimated to be less than 25 cm (0.8 ft). Winds and precipitation, which often predominate during astronomical tides, greatly influence water levels in the project area. Wind-driven changes in water levels show pronounced seasonality; water levels typically are higher in the summer when prevailing winds tend to blow water into the river system and lower in the winter when prevailing winds tend to blow water out towards Fishing Bay.
PROJECT GOALS AND OBJECTIVES

The purpose of the thin-layer placement (TLP) project was to make approximately 40 acres of tidal marsh in the MCZ within Blackwater NWR more resilient to relative sea level rise and storm impacts by raising tidal marsh elevations, thereby increasing plant productivity to help the marsh keep pace with rising relative sea levels. Without these actions and the near-term tidal marsh elevation capital they provide, the marsh at the project site would likely convert to open water soon.

The project raised marsh elevation by applying thin layers of sediment dredged from the adjacent Blackwater River. This sediment enhancement would extend the longevity of the marsh by raising its surface elevation in relation to the tidal regime, resulting in increased root zone production, the main driver of vertical accretion rates in the Blackwater River system. Raising the marsh platform to an elevation that maximizes plant productivity will take full advantage of the marsh’s capacity to build future elevation. Monitoring the post construction vegetation response also provided important feedback on the predicted TLP target elevations.

PROJECT DESIGN SCOPE AND ANALYSIS

Designing and especially permitting this project benefitted greatly from two published studies. The first, Kirwan and Guntenspergen (2012), addressed wetland plant biomass production as it relates to the elevation of the marsh platform in Blackwater NWR. Tidal marsh restoration projects typically involve obtaining elevation targets for the restored marsh platform from nearby “reference marshes,” existing marshes that the restoration should emulate. This study determined that more than 80% of the marshland in the study was too low for optimum root growth, suggesting that these potential reference marshes may already have an elevation deficit. The study also suggested that an elevation of 30 cm (0.98 ft) relative to North American Vertical Datum of 1988 (NAVD88) was optimal for belowground biomass production of S. patens, the targeted plant species. Elevation targets for the restoration area were developed based on these findings. Given the imprecise nature of placing dredged materials and the hazards of exceeding target elevations, 20 to 30 cm (0.66 to 0.98 ft) NAVD88 was identified as the restoration target for the elevation of the marsh platform.

The second study, Ganju et al. (2013), provided critical information on sediment transport. This study describes the sediment source as derived from internal wetland collapse and shoreline retreat within Blackwater NWR. The
suspended sediment is due to wave erosion over open water. Flood tide velocities are relatively low, preventing appreciable sediment import upriver from Fishing Bay. Although the channel may slowly import sediment over several tide cycles, a single wind event (especially from the northwest) may force out enough water to export sediment from the channel back to Fishing Bay. This study determined the net average sediment export to be 1020 +/– 390 grams per second (2.24 +/– 0.86 pounds per second), with higher export rates expected in the winter and lower rates in the summer. This equates to an average of 85 metric tons (97 tons) of sediment — enough to load five tandem-wheeled dump trucks — permanently leaving Blackwater NWR every day. This finding provided the basis for not only identifying borrow sources in accreting areas of the Blackwater River but also in securing project authorization.

A bathymetric survey of the river channel was conducted early in the design process to identify potential borrow sources of material for thin-layer restoration. Because 1220 meters (4,000 feet) is the maximum distance for pumping sediment, 2,440 meters (8,000 feet) of sinuous river channel upstream and downstream of the project area were surveyed.

The bathymetric survey determined that most of the channel bottom lies at approximately -4.3 to -5.5 meters (14 to 18 feet) NAVD88, with deep scour holes down to -11.6 meters (-38 feet) in the outer meander bends. The inner meander bends were found to be sediment accretion zones.

The gathered information at this project stage was used to collaborate with the State of Maryland and Corps of Engineers regulatory reviewers. Typically, dredge materials for beneficial reuse arise from navigation channel dredging. The project is located well over 16 kilometers (10 miles) away from the nearest navigation channel, so this borrow source type was not available. Instead, borrowing the inner meander bend accreted sediments would result in a deposition-friendly post-dredging environment. Based on the Ganju et al. (2013) sediment export study and the results of a geotechnical study, the borrow source was expected to refill through accretion in three to five years after dredging ended. A suitable borrow area that could provide 44,100 cubic meters (57,700 cubic yards) of sediment was identified along a nearby downriver inner meander bend. The area was 1,060 meters (3,480 feet) long and 55 meters (182 feet) wide. It had a maximum depth of 3.7 meters (12 feet) and a 1:1 slope away from the marsh edge. Consultations with regulators also determined that the borrow area should not extend any deeper than the Blackwater River thalweg elevations.

A series of 20 subsurface vibrcore samples were collected to evaluate the composition of the borrow material. An analysis of representative samples from the borrow location predicted the dredged material would behave as presented in Figure 4.

To determine the total volume of material needed for the project area, the final consolidated marsh thickness plus any additional settlement of the underlying soils needed to be addressed. The geotechnical laboratory and field consolidation test results predicted that, after 7.3 to 34.1 cm (0.24 to 1.12 feet) of fill had been placed, the thick underlying peat layer would settle between 4.9 and 24.1 cm (0.16 and 0.79 foot).

The pre-dredge placement survey elevations and the ratio of 0.028 cubic meter (1.00 cubic foot) in situ to 0.026 cubic meter (0.92 cubic foot) final volume were used in determining the volume of borrow material required. For the
failed marsh zones, another 4.9 cm (0.16 foot) of depth was added for anticipated settlement. Because the existing vegetation would displace the dredge material and the Scirpus americanus holes would require more material, the volume calculations assumed an unvegetated surface without holes. This resulted in an estimate that 18,800 cubic meters (24,600 cubic yards) of borrow material would be required to achieve the final project elevations.

Four settlement plates (Figure 5) were installed immediately before layer thin-layer placement to aid in estimating the actual consolidation of materials and the settlement of materials into underlying substrates.

**PROJECT IMPLEMENTATION**

The dredging contractor used a 30 cm (12 inch) cutter head hydraulic dredger (Figure 6) that discharged through an on-ground six-inch swivel spray nozzle (Figure 7). A mini-pontoon excavator (Figure 8) repositioned the nozzle and discharge point as necessary. All work was completed under Wetland License No. 15-0932 from the State of Maryland and Nationwide Permit #27 (CENAB-OP-RMS 2015-61631) from the U.S. Army Corps of Engineers. Before placing the dredge material, a patch of phragmites in the project area was treated with glyphosate to reduce the likelihood that they would become a problem.

Sand wrapped in biodegradable coir mats was used to plug two tidal ditches on the west side of the project area. These two plugs, the natural levee along the Blackwater River channel, and the expanse of marsh vegetation surrounding the project area were sufficient to keep the placed material on site and to maintain water quality in the river channel during dredging.

A pre-dredge survey of the entire borrow area was conducted on 14 October 2016, with single-beam real-time kinematic (RTK) GPS sonar. Dredging began on 1 November and finished on 21 December 2016 (Figure 9). According to the daily production log, approximately 19,900 cubic meters (26,000 cubic yards) of borrow material were placed in the project area. A post-dredging survey was performed on 12 January 2017. An analysis of the daily logs and the pre- and post-dredging surveys found an additional 11,279 cubic meters (14,753 cubic yards) of material within the dredging template, which was attributed to the active accretion of sediment in the borrow area.

Witness boards (Figure 10) were used to help determine when sediment placement had reached the desired elevations. The witness boards consisted of two vertical 5-cm by 5-cm (2-inch by 2-inch) stakes driven into the marsh. Attached to the vertical stakes were two horizontal cross boards. The elevation of the horizontal boards was surveyed with a construction-grade laser level. The upper horizontal board indicated the maximum elevation during sediment placement. The lower board indicated the settlement predicted to occur within two weeks after placement.

Settlement plates (Figure 5) were deployed and surveyed on 11 November 2016, prior to dredge material placement, and surveyed again, on 20 December 2016, after material was placed. They revealed underlying soil settlement of 11 to 19 cm (0.36 to 0.63 ft). These values aligned more closely with the laboratory consolidation test results than with the in situ load test results.

During placement, the dredge material flowed about 46 meters (150 feet)
radially beyond the discharge point. Once the witness boards indicated the target elevations had been reached, the nozzle was repositioned about 92 meters (300 feet) away and pumping resumed. This sequence resulted in circular placement patterns with sandy centers gradually grading to finer grained sediments outward.

Common threesquare, a cool-season plant, had re-established itself over much of its pre-construction coverage area by May 2017. The plant was apparently able to push up through the overlying placed material and re-establish itself on the new marsh platform. Also beginning in 2017, smooth cordgrass quickly colonized large portions of the project area where the common threesquare did not reestablish (Figure 11). Areas that remained bare—primarily where material was placed over open water “holes” in the historical marsh—were planted June 2017 with a total of 213,000 two-inch plugs of saltmeadow cordgrass and saltgrass. A fixed-wing aircraft was used to obtain aerial orthophotographs on 13 June 2017, to aid the planting. Visual assessments made later in the 2017 growing season found some browning of the saltmeadow cordgrass while the saltgrass seemed to be healthy and actively spreading. An additional 35,000 2-inch saltgrass plugs were added in June 2018 to fill some of the areas where saltmeadow cordgrass did not survive. A combination of active planting and passive revegetation fully populated the project area with native plants by fall 2018, at which point the project was considered complete.

POST-RESTORATION EVALUATION

Post-placement elevations were obtained in December 2017 and January 2018, approximately one year after material placement was completed. Low temperatures persisted though January, freezing the upper layers of the marsh and greatly facilitating surveying the thin layering final elevations. Approximately 13.2 hectares (32.5 acres) of the project area were surveyed (Figure 12). Within this area, 10.3 hectares (25.5 acres) had an elevation >20 cm (0.66 ft) NAVD88 and 7.6 hectares (18.7 acres) had an elevation of 24 to 34 cm (0.79 to 1.12 ft) NAVD88.

The borrow area in the Blackwater River was predicted to accrete material and eventually return to its pre-dredging
depths. The borrow area was surveyed using RTK GPS sonar on 19 September 2018, and compared to the pre-dredging survey 10 October 2016 bathymetry (Figure 13). The surface model comparison revealed a total of 6,056 cubic meters (7,921 cubic yards) remain of the 19,900 cubic meters (26,000 cubic yards) to return the area to the pre-dredge bathymetry. Over the span of nearly two years, 70% of the inner meander bend borrow area has refilled, on track with the three- to five-year prediction.

There was some concern that, because the project used subaqueous soils to restore intertidal marsh, there was the potential for sulfidic materials to oxidize and develop into acid sulfate soils (soils with a pH less than 4.0). Acid sulfate soils would be detrimental to the establishment and growth of native plants and could encourage colonization by phragmites. Nine soil samples, three from each of three discharge locations, were collected on 4 November 2017, and submitted for analysis. The first sample was collected where material left the discharge pipe, the second at a point 15 meters (50 feet) from the discharge, and the last 30 meters (100 feet) from the discharge point. The pH of the nine samples averaged 6.5 (standard deviation of 0.5). The lowest pH detected was 5.4; the pH of the remaining samples ranged from 6.3 to 7.2.

It appears that heavier material settled out of the slurry soon after exiting the nozzle and finer material spread farther. Samples for particle size analysis were taken at the same points as the samples used to evaluate acidic sulfate soils. The soil gradation tests indicated a coarse-to-fine continuum along the sample intervals at each of the three discharge points evaluated.

Monitoring of vegetation cover and composition, breeding bird communities, below-ground biomass production, and marsh elevation changes began pre-restoration and will continue as long as resources allow. The results of these monitoring efforts will be made public as they become available.

**CONCLUSIONS**

Although the target elevations were achieved in 78% of the surveyed placement area, the material was not uniformly distributed. In general, the coarser material tended to stack up at the discharge location, while the placed material became...
finer grained and the slopes flatter toward the periphery of the placement area. This situation makes geotechnical elevation predictions challenging because the range of in situ soil textures is sorted during placement into a uniformly graded continuum. One possible solution is to move the discharge pipe more frequently, so a more-even soil texture and elevation are achieved. On the other hand, variation in microtopography may not be negative because it could promote an assortment of tidal wetland plant communities used by a variety of fish and wildlife.

Post-construction monitoring is valuable to gain a perspective on the nexus between predicted material behavior and observed results. Fortunately, this project accommodated this feedback mechanism.

Finally, using accretion friendly borrow sources in lieu of navigation dredging material allows more feasible thin layering marsh restoration sites. The results of this project are hoped to enhance regulatory acceptance of this practice type to move thin layering in a positive direction for tidal marsh restoration.

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Enhancing marsh elevation using sediment augmentation: A case study from southern California, USA

By

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ABSTRACT

Tidal marshes are an important component of estuaries that provide habitat for fish and wildlife, protection from flooding, recreation opportunities, and can improve water quality. Critical to maintaining these functions is vertical accretion, a key mechanism by which tidal marshes build elevation relative to local sea level. The beneficial use of dredged material to build marsh elevations in response to accelerating sea level rise has gained attention as a management action to prevent habitat loss over the coming decades. In January 2016, a sediment augmentation project using local dredged material was undertaken at Seal Beach National Wildlife Refuge in Anaheim Bay, California, USA, to benefit tidal marsh habitat and the listed species it supports. The application process added 12,900 cubic meters of sediment with an initial, average 22-cm gain in elevation over a 3.2-hectare site. Due to sediment characteristics and other climate change stressors will affect coastal habitats, especially in regions that have already experienced cumulative impacts from human modifications to the landscape (Thorne et al. 2018).

Coastal ecosystems exist at the interface between terrestrial and ocean processes, and human communities. These coastal habitats comprise some of the most productive ecosystems on Earth, but they have also been heavily degraded by human development and land use changes (e.g. Costanza et al. 1997). Threats from sea level rise (SLR) and other climate change stressors will affect coastal habitats, especially in regions that have already experienced cumulative impacts from human modifications to the landscape (Thorne et al. 2018).

Coastal wetlands across the world are threatened by SLR, and the Seal Beach National Wildlife Refuge (NWR) is one of the most threatened along the Pacific Coast of the United States (Thorne et al. 2016). Encompassing 390 hectares of tidal marsh habitat in the Anaheim Bay estuary of Orange County, California, USA (Figure 1), the Seal Beach NWR lies in a dense urban setting of over three million people (ocgov.com/about). Seal Beach NWR tidal marsh habitat provides food and cover for approximately 14 species of plants, 40 fish species, and more than 100 species of marine invertebrates (USFWS 2012). The Seal Beach NWR also supports a variety of protected marine and terrestrial species, including the federally and state endangered light-footed Ridgway’s rail (Rallus obsoletus levipes) and California least tern (Sterna antillarum browni). The light-footed Ridgway’s rail relies on tall and robust stands of California cordgrass (Spartina foliosa) for nesting and cover; however, the extent and quality of the cordgrass habitat in the Seal Beach NWR is threatened by SLR submergence due to sediment starvation and tectonic subsidence (Figure 2). When local subsidence was considered, one study estimated that the rate of relative SLR was about three times higher than other southern California marshes (Takekawa et al. 2013). Management interventions, such as sediment addition, strategic sediment placement, or elevation sediment augmentation efforts (e.g. beneficial use of dredged material, thin-layer application), have been widely used in some regions to offset elevation or habitat loss but are novel to California (Slocum et al. 2005; Schrift et al. 2008).

For Seal Beach NWR, sediment augmentation (thin-layer application using dredged materials) was selected as a viable option for bolstering tidal marsh elevations to offset relative SLR rates and prevent habitat loss. In 2013, Orange County (OC) Parks planned to conduct maintenance dredging in Anaheim Bay and Huntington Harbor adjacent to Seal Beach NWR. Use of the material for habitat enhancement at Seal Beach NWR was consistent with the National Dredge Team’s Dredged Material Management Action Agenda for the Next Decade (USEPA 2003). OC Parks and U.S. Fish and Wildlife Service conducted required chemical (contaminants) and physical analysis (grain size) of the sediments at the proposed dredge sites, which was compared to reference samples taken from the proposed augmentation site (Kinnetic Laboratories Inc. and Moffatt & Nichol 2014). Materials from the proposed dredge site were found to be clean and compatible. With these two elements met, OC Parks and U.S. Fish and Wildlife Service developed a plan to beneficially use this material for sediment augmentation.

To select a sediment augmentation location within Seal Beach NWR the following factors were considered: (1) a site within the area designated for tidal marsh enhancement in the Comprehensive Conservation Plan (USFWS 2012); (2) an area of low elevations that
Figure 1. The Seal Beach National Wildlife Refuge with the project area (i.e. the augmentation area), the control area, and the dredge location.

was not "keeping pace" with SLR; (3) an area with limited tidal creeks; and (4) an area accessible for a barge or boat for sediment application process. The project site selected met these criteria, and in addition, did not support light-footed Ridgway's rail nesting due to shorter stem heights and stem density of the *S. foliosa*. Also, a 15.2-meter-wide vegetation buffer was identified to be maintained around the project area to prevent runoff into nearby channels. Project design details included delineating the project boundaries, developing a biological and physical monitoring plan, identifying a control tidal marsh site, establishing measures to protect adjacent sensitive habitats, and coordinating with other landowners (e.g. U.S. Navy Naval Weapons Station Seal Beach) on access.

Identifying the right collaborative, science-management team early on was an important step in developing the project goals and monitoring plan, with an emphasis on informing future projects across California and elsewhere. The project team included both managers willing to participate in research questions as well as applied scientists who could be flexible in their approach and design to inform a larger goal. Management groups included the U.S. Fish & Wildlife Service and California State Coastal Conservancy, which ensured questions about the beneficial use of dredged materials could be addressed (Table 1). Researchers who had experience in the physical and biological process of southern California were identified, along with those that had experience in applied research and working with management agencies (Table 1). In addition, having willing scientists and managers on the project team ensured that, when questions or concerns arose throughout the project, adaptive management actions could be quickly identified and implemented. This team developed a multidisciplinary monitoring plan focused on informing future projects (Table 2).

Our overarching project goal was to build SLR resilience of the tidal marsh habitat at the Seal Beach NWR study site to benefit endangered species. Our specific objectives were to increase tidal marsh elevation with sediment augmentation, to track recovery of vegetation and fauna post-augmentation, and to identify lessons learned to benefit future similar efforts.

**SEDIMENT AUGMENTATION**

**Determining the application thickness**

The project design envisioned a final sediment thickness of about 7.6 cm two years following construction over a 4-hectare project site. It was estimated that a 20-25 cm thickness would be needed to reach the 7.6 cm target after consolidation, compaction, and dewatering of the soils over two years. These estimates were derived from communication with the science-management team.

This sediment application goal was thicker than what has been done in most published studies (e.g. La Peyre et al. 2009) and was envisioned to place the tidal marsh site above mean high water (MHW). The thicker application goal was based on: 1) local subsidence and relative SLR rates; 2) the desire to minimize the need for more frequent disturbances to listed and sensitive wildlife species; and 3) reduce conflicts with adjacent military activities.

**Table 1.**

A robust team of managers and researchers was formed to identify the problem, refine the project design, and develop and implement a monitoring plan for the Seal Beach NWR Sediment Augmentation Project.

<table>
<thead>
<tr>
<th>Science-Management Team</th>
<th>Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science</td>
<td>Management</td>
</tr>
<tr>
<td>U.S. Geological Survey</td>
<td>U.S. Fish and Wildlife Service (lead)</td>
</tr>
<tr>
<td>University of California, Los Angeles</td>
<td>California State Coastal Conservancy</td>
</tr>
<tr>
<td>California State University, Long Beach</td>
<td>Southwest Wetlands Interpretive Association</td>
</tr>
<tr>
<td>Chapman University</td>
<td>U.S. Army Corps of Engineers</td>
</tr>
<tr>
<td>Tidal Influence, LLC</td>
<td>U.S. Navy</td>
</tr>
</tbody>
</table>
Figure 2. Photos (A) During higher high tides, virtually all *Spartina foliosa* habitat in the Seal Beach National Wildlife Refuge is inundated; (B) U.S. Fish & Wildlife Service maintains floating nesting platforms for rails to prevent nest loss and provide cover from avian predators during high tides.

Table 2.
The physical and biological monitoring plan implemented for the Seal Beach NWR Sediment Augmentation Project.

<table>
<thead>
<tr>
<th>Parameter type</th>
<th>Method</th>
<th>Data type generated</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediment concentration and flux in nearshore</td>
<td>Optical turbidity instruments, acoustic doppler current profiler (ADCP), grab samples</td>
<td>Changes in turbidity in the nearshore during and after construction</td>
</tr>
<tr>
<td>Elevation and accretion</td>
<td>Sediment Elevation Table (SET)-Marker Horizon Plots, sediment stakes</td>
<td>Below and above ground elevation change and accretion following construction</td>
</tr>
<tr>
<td>Total elevation change</td>
<td>Photogrammetry surveys</td>
<td>Digital terrain models</td>
</tr>
<tr>
<td>Water quality and level</td>
<td>Continuous water loggers in nearby channel</td>
<td>Temperature, salinity in adjacent channels and flooding estimates for marsh elevations pre- and post-construction</td>
</tr>
<tr>
<td>Sediment characteristics</td>
<td>Shallow sediment cores</td>
<td>Soil characteristics (grain size, organic matter, bulk density)</td>
</tr>
<tr>
<td>Carbon storage</td>
<td>Deep sediment cores, loss on ignition, various dating methods</td>
<td>Carbon content, below-ground biomass, carbon accumulation rate</td>
</tr>
<tr>
<td>Historical sediment</td>
<td>Deep sediment cores, various dating methods</td>
<td>Historical grain size, sedimentation rate</td>
</tr>
<tr>
<td>Greenhouse gas emissions</td>
<td>Dark static flux chambers</td>
<td>Methane, NO fluxes, CO2 respiration from sediment and vegetation</td>
</tr>
<tr>
<td>Channel morphology</td>
<td>Aerial photographs, creek cross-section surveys</td>
<td>Map of primary/secondary/tertiary creek sinuosity and length, creek depth</td>
</tr>
<tr>
<td><strong>Biological</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marsh vegetation</td>
<td>Transect/quadrat based, sampling aerial imagery, time-lapse camera images, LiCor in situ CO2 chambers</td>
<td>Total percent cover, percent cover by species, allometric biomass of <em>S. foliosa</em> (species of interest), photosynthetic rates</td>
</tr>
<tr>
<td>Eelgrass</td>
<td>SCUBA surveys</td>
<td>Aerial extent, shoot density</td>
</tr>
<tr>
<td>Invertebrates</td>
<td>Shallow sediment cores, quadrat-based counts</td>
<td>Macroinvertebrates (&gt;300µm) from preserved sediment cores, surface inverts on surface</td>
</tr>
<tr>
<td>Birds</td>
<td>Time-lapse camera, observers</td>
<td>Bird use surveys, refuge-wide annual rail nest monitoring, spring call counts, and fall high tide counts</td>
</tr>
<tr>
<td>Green sea turtles/marine mammals</td>
<td>On-site monitoring by qualified biologists</td>
<td>During augmentation, monitor adjacent channels to ensure the safety of sea turtles and marine mammals</td>
</tr>
</tbody>
</table>
Construction approach

After initially using a 20.3-cm (8-inch) dredge to hydraulically pump material from Anaheim Bay and apply it to the augmentation site, the contractors switched to a 30.48-cm (12-inch) cutter-head suction dredge. The dredge slurry was passed through a 5-cm debris screen and pumped through a 30.48-cm (12-inch) pipeline, which was transitioned to a 20.3-cm (8-inch) pipeline at the augmentation site for ease of placement. The distance between the dredge area and the placement site required a booster pump to keep pipeline pressures up and sediment suspended in the pipeline to the discharge point.

Once the excavated sediment was pumped to the site, traditional methods of discharge (e.g., large pipe directly from the dredge) were not used to avoid scour and impacts to sensitive species habitat. After trying several nozzle sizes, nozzle shapes, and deflection plates, an elliptical high-pressure discharge nozzle was designed and used to achieve a minimally impactful “fan-like” spray with sufficient...
placement range (Figure 3). The elliptical nozzle was used until the contractor switched to the larger dredge. Due to timeline and budget constraints, the contractor switched to the larger dredge and employed an alternative sediment placement system referred to as a “spoon” was implemented. The spoon, consisted of an upward deflection crescent shaped pipe section that was installed directly at the end of the pipeline (Figure 4). This nozzle had less range, but a much larger placement radius. On the last day of operation, the nozzle was unintentionally left in place at one location for too long, creating a high elevation mound within the project site (Figure 5). Monitoring was conducted to ensure bird and marine species impacts were avoided during these construction activities.

**POST-CONSTRUCTION MONITORING**

* Sediments and elevation gain

Between January and April, 2016, a total of 12,900 cubic meters of dredged material was sprayed over a total of 3.2 hectares (Figure 5). Sediment augmentation raised the elevation across the tidal marsh site by 22 cm North American Datum of 1983 (NAVD88; Thorne et al. 2019). The total elevation gain across the tidal marsh varied due to topography differences and spraying approaches (Figures 6). Between 2016 and 2020, the marsh had a measured mean decrease in elevation, presumably due to soil consolidation, dewatering, and shallow peat subsidence, resulting in an overall mean increase of 11.1 cm (NAVD88) five years after application (Freeman and Thorne 2020), 3.5 cm higher than the original goal of 7.6 cm. A two-year study of sediment flux and turbidity during and following construction showed little suspended sediment leaving the tidal marsh and entering nearby channels (Thorne et al. 2019), a key management concern. Also, construction activities occurred over winter months with elevated water levels from El Niño storms; however, minimal increases in suspended sediment were observed when compared to levels measured during storms or when construction was not occurring (Thorne et al. 2019).

Dewatering of the soil, consolidation, and compaction of the deposited sediments were expected to occur, but the larger than expected amount of sand in the augmentation material may have also compacted the underlying peat layers (Figure 7).

The dredged material contained much less silt and clay than pre-conditions at the project site and a control tidal marsh (57% and 38% respectively; Figure 7). The soil in the project area after construction was significantly lower in silt and clay content (16%) and in organic matter (1.7%), and values at the control tidal marsh site were not statistically different from pre-application values (McAtee et al. 2020).

Tidal creek formation following construction was slower than anticipated, and many of the historical channel locations within the project area converted to shallow ponds or depressions. The tidal creeks that did naturally reform were few, small in size, and relatively shallow.
The vegetation buffer around the project area proved very important in minimizing sediment movement from the site into adjacent tidal channels and in assisting revegetation of the site, as various tidal marsh plant species established via rhizomes (Figure 9). *Spartina foliosa* plants are larger on the augmentation site than on the control site, suggesting that when plants do return to the site, they can grow well there.

Heterogeneous features across the project area have benefited marsh vegetation growth, likely by helping trap plant material or seeds. For example, pickleweed established throughout the high elevation sand mound, a heterogeneous feature. Also, small depressions throughout the project area, whether natural or created by construction and monitoring PVC poles, captured wrack, detritus, and seeds enhancing vegetation growth (Figure 10A-B).

**Marsh vegetation**

Before project implementation, tidal marsh vegetation covered 70% of the project area. In 2017, 6 to 12 months following augmentation, approximately 2% of the project area was covered. By November 2018, the vegetative cover, primarily *Salicornia bigelovii*, had increased to approximately 5% (Figure 8). The cover had grown to approximately 15% to 25% of the project area by July 2019, still mainly *S. bigelovii*. By July 2020 (prior to adaptive management planting), total cover remained at approximately 20% to 25% with additional species represented.

Vegetation continues to recover but at a slower rate than originally predicted. Currently, annual pickleweed (*S. bigelovii*), common pickleweed (*Salicornia pacifica*), and saltwort (*Batis maritima*) have the highest percent cover of all species present (Figures 8). California sea lavender (*Limonium californicum*), estuary seablite (*Suaeda esteroa*), and fleshy jaumea (*Jaumea carnosa*) are also present in small patches. Several patches of cordgrass (*S. foliosa*), first recorded on the site in fall 2017, have spread vegetatively from the *S. foliosa* in the buffer zone (Figure 9). The first patches that did not colonize by vegetative spread from the buffer zone were observed in spring and fall 2020 (four years after augmentation).

**Eelgrass**

The area selected for sediment augmentation is between two large tidal channels (Figure 6) that support *Zostera marina* (eelgrass). To determine how construction affected nearby eelgrass habitat, side-scan sonar surveys and diver transect surveys were conducted prior to construction and post-augmentation surveys were done in April 2016, July 2017, July 2018, and November 2019 (Marine Taxonomic Services [MTS]). The pre-augmentation surveys identified eelgrass habitat within approximately 42.2% or 8,909 square meters of the area surveyed adjacent to the augmentation area (eelgrass study area; *Marine Taxonomic Services, LTD*, 2016a, b). Following construction activities in spring 2016, monitoring showed decline in overall eelgrass cover to 3,950 square meters (MTS 2016a). Two years following construction, eelgrass expanded to an estimated 7,646 square meters within the study area, but did not fully recover to preconditions (MTS 2018). However, monitoring in 2019 showed eelgrass had returned to its pre-construction area (MTS 2015, 2019).

**Fauna**

Surface-dwelling and sediment-burrowing invertebrates recovered much slower in the project area than in other sediment addition projects (McAtee et al. 2020). At six months and 12 months after augmentation, the invertebrate communities in all habitats at the site were

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Figure 7. Map of sediment sample locations and the results from samples taken between January and July 2016 in the augmentation site and adjacent areas (R. Nye 2016, personal communication, 15 July). Samples marked R1, R2, and R3 were collected in January 2014 by Moffatt and Nichol.
very low in abundance, species richness, and diversity compared to their pre-augmentation levels and to the control sites (McAtee et al. 2020). Four years after sediment augmentation, abundance and species richness had increased, but remained below pre-augmentation levels and levels at the control site. In addition, the invertebrate community was dominated by mobile invertebrates such as insects, and detritivores, such as oligochaetes, remained low in abundance.

DISCUSSION

Beneficial use of sediment

One of the project goals was to achieve a uniform thickness and elevation gain across the site. This goal was not met due to the heterogeneous topography, novel spraying approach, and fluid nature of the sediment slurry. The original project design called for the application of 8,000 to 11,500 cubic meters of sediment to achieve a relatively uniform thickness of 20 to 25 cm over 4 hectares. Ultimately, insufficient sediment supply was available to meet the original 4-hectare goal because more sediment was needed to infill lower elevation areas (e.g. channel crevices) and construction activities raised some areas higher than originally planned. Therefore, adaptive management measures were taken, and the
project size was reduced to 3.2 hectares which met the goal of 24 cm thickness, with 12,900 cubic meters of sediment applied. This was 1,400 cubic meters over the original sediment estimate to complete the project. Between 2016 and 2020, the total mean elevation gain was 11.1 cm due to soil consolidation, compaction, and dewatering; this was greater than the original goal of 7.6 cm. The mean increase in elevation is similar to other thin-layer sediment placement projects across the United States (e.g. DeLaune et al. 1990).

Sea level rise resilience
An overarching goal of the project was to build SLR resilience of the tidal marsh habitat to protect obligate wildlife species. The current rate of SLR in southern California is 2.1 mm/yr (Steinbruner et al. 2012). At this rate of SLR, the elevation gain of 11.1 cm achieved in this project could provide about 53 years of extra resilience (assuming no additional accretion processes) before submergence. However, the Seal Beach NWR rate of relative SLR is 6.2 mm/yr (Takekawa et al. 2013) based on subsid-
Table 3.
Lessons-learned during project development, implementation, and monitoring. This information informed adaptive management actions for the project.

<table>
<thead>
<tr>
<th>Project component</th>
<th>Successes</th>
<th>Planning phase</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stakeholders</td>
<td>Early buy-in for the project by regulatory and funding agencies made the planning process more efficient.</td>
<td>Permitting and funding a new sea level rise strategy was considered a risk.</td>
<td>Several study design adaptations and experiments were needed throughout the study.</td>
</tr>
<tr>
<td>Research team</td>
<td>Multi-disciplinary team enabled data collection over a long timeframe (e.g. 5+ years) and across topics.</td>
<td>Sediment samples were not uniform across the dredging area or across horizons, making it difficult to identify areas of high sand content.</td>
<td></td>
</tr>
<tr>
<td>Dredged materials source</td>
<td>Partnering with a nearby dredging project that contained non-contaminated sediment.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contractors</td>
<td>Construction was done on time and within budget; Contractor was willing to conduct pilot tests of the methodology.</td>
<td>There were very few contractors with the experience to carry out the project.</td>
<td>Greater outreach to other regions for experienced contractors was needed.</td>
</tr>
<tr>
<td>Adaptive management</td>
<td>Allowed adjustments as the project proceed so that project objectives could be met.</td>
<td>Setting realistic measures for study site recovery was difficult. Incorporating adaptive management into budget and timelines is difficult.</td>
<td></td>
</tr>
<tr>
<td>Trash</td>
<td>N/A</td>
<td>Trash that was mixed with dredged materials at dredging locations near boat docks inadvertently ended up on the site.</td>
<td></td>
</tr>
<tr>
<td>Nozzle shape and size</td>
<td>Elliptical-shaped nozzle was tested, selected, and used.</td>
<td>Contractors had to test several nozzle shapes and sizes to determine the best spraying technique.</td>
<td></td>
</tr>
<tr>
<td>Sediment retention</td>
<td>Haybales, sandbags, and geotextile fabric kept sediment on site.</td>
<td>Removing haybales and fabric temporarily increased channel turbidity; Damming creeks with sandbags slowed channel reformation within the project area.</td>
<td></td>
</tr>
<tr>
<td>Coordination</td>
<td>Most of the site received the appropriate amount of sediment.</td>
<td>Site was sprayed in one location with too much sandy sediment on the last day of implementation; closer coordination needed.</td>
<td></td>
</tr>
<tr>
<td>Vegetation buffer</td>
<td>Vegetation buffer enabled contractors to access the site more easily; buffers also helped vegetation recover by rhizome.</td>
<td>Maintaining a vegetation buffer was important for our project, but is not applicable everywhere.</td>
<td></td>
</tr>
<tr>
<td>Aerial imagery</td>
<td>Effective way to evaluate elevations achieved and elevation changes throughout the study region.</td>
<td>Imagery can assist in assessing vegetation recovery, but was not used in this project.</td>
<td></td>
</tr>
<tr>
<td>Surface elevation tables – marker horizons</td>
<td>Installation and monitoring for elevation change that incorporated below- and above-ground processes were key in identifying the total elevation gain (e.g., below-ground processes were the reason for elevation loss following construction).</td>
<td>These are now permanent features in the habitat, but are beneficial because they allow long-term monitoring to measure elevation gains and losses against relative sea level rise rates.</td>
<td></td>
</tr>
<tr>
<td>Monitoring coordination</td>
<td>Early planning done with a multi-disciplinary research team, managers, and contractors promoted a robust study design and implementation plan.</td>
<td>Field sampling did not always align among the research monitoring teams; contractors inadvertently harmed some monitoring plots during construction.</td>
<td></td>
</tr>
</tbody>
</table>
the project areas were detrimental to seed emergence. The sediment collected from the project area also produced fewer plants compared to the control area sediment, suggesting a small seed bank or low seed dispersal could be contributing to the slow vegetation response. Sandy dredged material may have contained few seeds (a small seed bank), and the initial damming of tidal channels within the project area may have limited seed dispersal.

Prior to augmentation, the site was a heterogeneous tidal marsh surface with three distinct habitat types: (1) ponded areas that were consistently inundated; (2) vegetated marsh plain dominated by *B. maritima*; and (3) vegetated marsh plain dominated by *S. foliosa*. Following augmentation, the elevation was relatively similar across the site and plant cover was lacking; thus the heterogeneity of habitat type was lost. In 2020, we observed heterogeneity returning to the site as ponded areas reformed and lower elevation areas were colonized by additional plants. This heterogeneity facilitated natural plant recovery, with plants colonizing the ponds (former tidal channels) and other key features and with new plants returning to the site, natural and accidental (i.e. research stakes) depressions, and the high-elevation sand mound. Adaptive management measures discussed following, including channel notching (2018) and re-vegetation (2020), were undertaken to facilitate vegetation recolonization and recovery. Additional management measures, such as adding small depressions or additional stakes to catch wrack, could have been implemented earlier to increase the heterogeneity of the site following sediment application.

**Adaptive management**

**Revegetation.** Maintaining a vegetation buffer around the project area helped stimulate revegetation by rhizome around the edges of the project area but was not enough (Figure 9). After four years of post-construction monitoring, the management-science team decided active revegetation was needed.

Therefore, based on observed low vegetation cover, *S. foliosa* plugs were planted throughout 0.5 hectares of the project area, plugs were obtained from a donor site on the Seal Beach NWR (Figure 12). Since planting, mortality, stem height and photosynthetic rate have been monitored for approximately half of the 1,500 *S. foliosa* plugs that were planted in the sediment augmentation site (Figure 13). These plugs initially contained a mean of 5.6 live *S. foliosa* stems; most of the plants have survived the initial transplant.

**Channel notching.** Deployment of sediment barriers (hay bales etc.) successfully prevented sediment loss and negative impacts to nearby channel habitats including eelgrass beds (Thorne *et al.* 2019). However, these hay bale barriers prevented the reforming of channels and limited tidal waters needed for proper channel formation and marsh flooding. This required intervention and an adaptive management plan to remove hay bales and “notch” these dams slowly over time to stimulate channel formation.

Other wetland restoration projects in the region have had similar issues with channels not naturally forming post-restoration, such as at the San Dieguito Lagoon where channels were later re-contoured to improve drainage (Page *et al.* 2016).

Our project illustrates the importance of incorporating adaptive management into project planning to increase the likelihood that project goals can be met. For example, if we had planned to revegetate initially, we could likely have accelerated recovery by ameliorating harsh physical conditions (i.e. temperature and salinity), adding detritus to food webs, adding structure and rugosity to trap additional detritus and seeds, and positively affecting biochemistry. Including funding and time for adaptive management in our project planning, however, ensured the implementation of adaptation measures could be taken. This and other lessons learned are noted in Table 3.

**CONCLUSIONS**

Climate change and SLR will continue to threaten coastal habitats over the coming decades. Restoration and enhancement projects can offset loss and provide opportunities to expand our understanding of the best practices to implement projects essential to preventing biodiversity loss in the coastal zone. Having clear project objectives and an
engaged, diverse team of managers and scientists can result in an effective restoration project, as demonstrated here. This is especially important given the wide range of approaches that can be undertaken to build marsh elevations and the need to implement adaptive management when a project is not reaching its goals.

ACKNOWLEDGMENTS

The authors would like to thank Naval Weapons Station Seal Beach for their assistance in implementation of the project while balancing their operation and security needs; and Mayda Winter from the Southwest Wetlands Interpretive Association for managing contracts. The authors would also like to thank the funders: (1) California State Coastal Conservancy; (2) California Department of Fish and Wildlife, Wetland Restoration for Greenhouse Gas Reduction Program; (3) U.S. Army Corps of Engineers; (4) County of Orange; and (5) U.S. Fish and Wildlife Service. We would also like to thank all other research partners: (1) Rich Ambrose, Glen MacDonald, and the teams at UCLA; (2) Jason Keller and team at Chapman University; and (3) Eric Zahn and team at Tidal Influence, LLC. We would like to thank Kirk Gilligan and Richard Nye from the USFWS for their dedication to the development and implementation of this project, as well as the Friends of Seal Beach NWR who conducted most of the bird surveys and often assisted with boat operations needed for access to the project site. We would like to thank Curtin-Maritime for their willingness to learn about the sediment augmentation process along with us. KT would like to thank the USGS Western Ecological Research Center for support, and C. Freeman and many field technicians for their work on this project. CW would like to thank CSULB and many graduate and undergraduate students for their work on this project. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.
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Evaluating direct and strategic placement of dredged material for marsh restoration through model simulations

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ABSTRACT

Dredged material can be used for marsh restoration by depositing it on the marsh surface (thin-layer placement), by releasing it at the mouth of channels and allowing tidal currents to transport it onto the marsh platform (channel seeding), or by creating new marshes over shallow areas of open water. We investigate the efficacy of these different methods using a comprehensive 2D marsh evolution model that simulates tidal dynamics, vegetation processes, bank and wave erosion, and ponding. Total marsh area is assessed over 50 years in an idealized microtidal marsh under different relative sea level rise (RSLR) scenarios. For a given volume of total sediment added, the frequency of deposition is relatively unimportant in maximizing total marsh area, but the spatial allocation of the dredged material is crucial. For a given volume of sediment, thin-layer deposition is most effective at preserving total marsh area, especially at high rates of RSLR. Channel seeding is less efficient, but it could still provide benefits if larger amounts of sediment are deposited every 1-2 years. Marsh creation is also beneficial, because it not only increases the marsh area, but additionally slows the erosion of the existing marsh. The 2D model is highly computationally efficient and thus suited to explore many scenarios when evaluating a restoration project. Coupling the model with a cost assessment of the different restoration techniques would provide a tool to optimize marsh restoration.

In response to rapid coastal marsh loss worldwide (Gardner and Finlayson 2018), massive restoration projects have been implemented (Weinstein et al. 2001; Bakker et al. 2002; CPRA 2017). These projects often rely on the beneficial re-use of fine-grained dredged material (i.e., mud), which is produced on the order of tens of millions of cubic meters annually from federal navigation channels (Yozzo et al. 2004; Sharp et al. 2013). Dredged sediment has typically been used to create new marshes over shallow open water (Figure 1A) or sprayed directly onto existing marsh surface in a process known as thin-layer placement (Figure 1B). The latter technique has become a proven treatment for rapidly receding coastlines in the Gulf of Mexico over the past 20-30 years (Ford et al. 1999; Mendelssohn and Kuhn 2003; Parson et al. 2015).

“Strategic placement” of dredged sediment has received increased attention in recent years because it is a cheaper and potentially more sustainable alternative to direct placement strategies such as thin-layer placement or marsh creation (Gailani et al. 2019). Strategic placement involves seeding tidal channels and other nearshore areas with fine-grained sediment, which is then transported onto the marsh platform by natural hydrodynamic processes (Figure 1C). A pilot study from the Netherlands called the "Mud Motor" showed that repeated channel seeding over two years can deliver a significant amount of sediment from the disposal site at the mouth of a tidal channel to its ultimate destination on the marsh platform (Baptist et al. 2019).

Although case studies are available for all three placement strategies, a numerical model is necessary to compare the efficacy of each technique at a given location and, possibly, to optimize them. Such a model would need to reproduce marsh morphodynamics over multidecadal timescales and for a sufficiently large spatial domain. Many models used for restoration plans only consider vertical accretion and drowning while neglecting complex morphological processes such as tidal dynamics, wave-edge erosion, and ponding (Craft et al. 2009; Stralberg et al. 2011). High-fidelity (also referred to as “detailed”) models such as Delft3D can resolve these dynamics (Lesser et al. 2004), but at a great computational cost, thus limiting simulations to shorter timescales, usually months to years (Siemes et al. 2020). Even when longer simulations are achieved, few simulations can be considered, and it is difficult to modify the code to include additional, site-specific processes.

We present results from a coastal evolution model (MarshMorpho2D), which incorporates the relevant marsh processes over a decadal timescale. The model is used as an exploratory tool, aimed to provide theoretical insights about marsh restoration. To this end we simulate the impacts of thin-layer placement, channel seeding, and marsh creation over 50 years in an idealized microtidal marsh. For thin-layer placement and channel seeding, we investigate the effect of incrementally depositing the same total volume of sediment through time. We also consider different amounts of total dredged material, aiming to identify the volume needed to prevent net marsh loss. Each technique is assessed based on its ability to reduce the amount of marsh loss within the domain compared to the reference case in which no restoration occurs.

MODELING APPROACH

The model is described briefly here; all its equations can be found in previous publications (Mariotti and Murshid 2018; Mariotti 2020). The model calculates a tidal flow map by redistributing the tidal prism according to water depth and bed drag coefficient. Suspended sediment transport is simulated as a dispersion process, i.e. by considering the net effect of a tidal cycle. Bank slumping is simulated as a soil diffusion process (Mariotti et al. 2019). Marsh vegetation is formulated as a function of elevation, which is a proxy for the hydroperiod. Vegetation affects

KEYWORDS: Cohesive sediment, coastal geomorphology, sea level rise, beneficial use, thin-layer placement, sediment transport.

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the drag force, sediment erodibility, effective settling velocity, bank slumping, and the in-situ production of organic sediments. Pond dynamics include pond formation (either through the seeding of small new ponds or through the formation of large ponds by impoundment of the marsh interior), pond expansion (simulating biochemical erosion), and pond merging. Wind waves are calculated with a smoothed fetch model, and wind-induced edge erosion is implemented through a probabilistic algorithm (Mariotti and Canestrelli 2017).

Although some of the hydrodynamics and sediment transport are simplified, the model precisely conserves sediment throughout the domain. This enables it to fully capture the feedbacks associated with sediment recycling (e.g., an eroding marsh releases sediment, which could be beneficial for adjacent areas). At the same time, the model is highly computationally efficient; a typical 50-year simulation takes about four minutes with a single 3.2-GHz processor.

The model is used to generate a microtidal marsh in a state of moderate degradation, mirroring a previous modeling exercise (Mariotti 2020). We consider a 3- by 5-km domain with a spatial resolu-
tion of 10 m and the same parameters as in Mariotti (2020) (Table 1). The model is first run over 2,000 years under a slow RSLR rate (2.5 mm/yr) and high sediment supply at the seaward boundary (60 mg/l), which creates a healthy marsh with a tidal flat in front. Then, the RSLR rate is increased to 5 mm/yr and the sediment supply is decreased to 30 mg/l, and the model is run for another 200 years. The marsh configuration after 2,200 years shows some sign of degradation such as interior loss, channel widening, and eroded edges. This is considered the initial condition (Figure 2) for the simulations presented in this study.

Starting from this initial condition, the model is run for 50 years with a seaward boundary sediment concentration of 7.5 mg/l under two RSLR scenarios (5 and 10 mm/yr). The reference simulations are run without any other changes. The restoration simulations are performed by adding sediment at specific times and at specific locations throughout the 50-year period (Figure 2).

For thin-layer placement, sediment is distributed over the entire marsh area that is at least 1 km landward of the edge with the tidal flat. In this region, locations between -0.35 and 0 m (relative to mean sea level [MSL]) are aggraded to a maximum thickness of 0.1 m and locations between 0 and 0.3 m MSL (considered to be vegetated) receive up to 0.05 m of sediment. This spatial footprint is significantly larger than typical thin-layer placement projects (Ray 2007), so an undertaking of similar scale may be technically and/or economically infeasible in the field. Nevertheless, the restoration effects of thin-layer placement should scale linearly with the area over which it is dispersed because deposit thickness is modulated independently of area. In practice, most of the sediment ends up in the ponds (also called pannes), which are often targeted during this practice (VanZomeren et al. 2018). Previous studies have shown that Spartina alterniflora, a common marsh grass, can rebound from thin-layer-style treatments of 0.05 to 0.15 m, although vegetation can take months to recover when deposits are on the much greater than 0.1 m (Wilber 1992; Schaffner 2010). Here we assume that vegetation re-establishes immediately.

For the channel seeding technique, sediment is distributed to all locations below -0.35 m MSL in the seaward portion of the marsh platform defined in Figure 2. This is meant to approximate subtidal deposition at the mouths of tidal channels, as was done in the Mud Motor experiment. For simplicity’s sake, sediment is assumed to settle instantaneously onto the channel bed, rather than enter the system as suspended sediment. This sediment is preferentially placed in topographic lows, and deposited thicknesses are limited by the available sediment volume and the number of locations within the elevation criteria.

For the created marsh simulations, two rectangular open water areas along the shoreline are aggraded to a constant elevation of 0.3 m above MSL at the beginning of the 50-year simulations. The edges of the created marsh are assumed to be as erodible as the natural marsh, implying that any dikes present during the marsh construction are either removed after construction or naturally degrade within a few years.

Although the large-scale subsidence of the site is incorporated into RSLR, spatially variable subsidence due to compaction of the added sediment is not. In an actual setting, thin-layer deposits undergo some amount of initial self-weight consolidation after being sprayed onto

### Table 1.

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<th>Notable boundary conditions for the simulations described in this study.</th>
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<td><strong>Model parameters</strong></td>
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<td>Lower limit for marsh plant growth</td>
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the marsh as a slurry. Created marshes also undergo self-weight consolidation, and their added weight may compact underlying sediments (Ghose-Hajra et al. 2015). Because self-weight consolidation generally takes place within the first 1-2 years, we simplify the simulations by neglecting this step and assuming the added sediment consolidates instantaneously. Thus, the thickness of the added sediment represents the value after the self-weight compaction occurs. We also assume that the dry-bulk density of the added mud is the same as the dry-bulk density of the natural sediment.

**COMPARISON OF NEW MARSH CREATION, CHANNEL SEEDING, AND THIN-LAYER PLACEMENT**

We compare three restoration techniques with a dredged sediment allocation of 1 Mm$^3$ over 50 years. The techniques are assessed based on their ability to maximize total marsh area (i.e. the vegetated area) throughout the 50-year period of each simulation. The created marsh is constructed at the beginning of the simulation, and sediment is deposited incrementally every 10 years for the thin-layer and channel seeding techniques.

The created marsh approach initially maximizes total marsh area, but thin-layer placement becomes the most effective approach after approximately 20 years, restoring roughly 1 km$^2$ of marsh by year 50 compared to the no restoration reference case in both RSLR scenarios (Figure 3). This is enough to fully preserve total marsh area after 50 years in the low-RSLR case. Channel seeding is the least efficient per unit volume because only a fraction of the sediment is transported onto the marsh surface. However, it becomes relatively more efficient in the higher RSLR scenario.

Each technique exhibits a different spatial pattern of marsh loss and preservation (Figure 4). Marsh creation not only adds new marsh, but also prevents the loss of existing marsh. This includes reductions in marsh edge erosion behind the created marsh and in erosion from channel widening. Thin-layer placement mainly preserves marsh in landward areas by filling in ponds and shallow channel tips. Channel seeding mainly preserves marsh along its seaward boundary, although some benefits are felt throughout the marsh platform. The spatial distribution of retained marsh depends on RSLR. At higher RSLR, landward marsh drowning becomes an increasingly important process that can be mitigated most notably by thin-layer placement.

**DIFFERENT VOLUMES OF DREDGED SEDIMENT**

We modulate the total volume of dredged sediment addition from 1 to 5 Mm$^3$ during the 50-year simulations under both RSLR scenarios, considering deposition only once every 10 years (Figure 6). Increasing the volume for the channel seeding technique generally has a linear impact on marsh area restored. Thin-layer placement simulations show diminishing returns between 2 and 3 Mm$^3$ largely because marsh loss has been fully reversed. For both RSLR scenarios, channel seeding can restore the same area of marsh as 1 Mm$^3$ of thin-layer placement if 3-5 times more sediment is used. This approach can be used to estimate the total volume of dredged sediment necessary to fully maintain total marsh area for a given RSLR and placement strategy.
To achieve zero net marsh loss using thin-layer deposition, 1 Mm³ is needed for the low-RSLR scenario and 3 Mm³ for the high-RSLR scenario (Figure 6). When channel seeding is used, 5 Mm³ are needed for the low-RSLR scenario, while no reasonable amount of sediment prevents net marsh loss in the high-RSLR scenario (Figure 6).

We also found that depositing very large volumes (>5 Mm³) over a small number of sediment deliveries can cause negative impacts such as channel migration in the case of channel seeding. Thin-layer deposits will also approach the maximum limit of 5 cm on top of vegetated areas in these cases. Larger volumes could potentially be placed over 50 years if they were divided into 25 to 50 deliveries.

**DISCUSSION OF CHANNEL SEEDING TECHNIQUE**

Channel seeding is a relatively new marsh restoration technique, and this study provides some general insights about its impacts. When a large amount of sediment is used (i.e. 5 Mm³ over 50 years), marsh loss can be completely prevented, at least for the case with moderate RSLR (Figure 6). In this case, most of the marsh loss prevented is associated with marsh edge erosion at the boundary of the tidal flat and with channel widening throughout the domain (Figure 7). The restoration impacts of channel seeding would likely be larger and extend further landward in a system with a larger tidal range than the microtidal case presented here.

While quantifying the benefits of channel seeding is straightforward in an idealized modeling exercise, it may be difficult in real-world settings. Indeed, for all scenarios of channel seeding, there was net marsh retreat. Channel seeding did not cause marsh expansion — which was a prediction during the “Mud Motor” experiment (Baptist et al. 2019) — but rather reduced retreat compared to the reference case with no action. To quantify this reduction in erosion in a real-world setting, a robust prediction of marsh edge erosion for the reference case is needed. This could be achieved through a combination of modeling and historical measurements of retreat rates (i.e. over multiple decades) at the study site before restoration takes place. Alternatively, this could be quantified by comparing the restored site to a non-restored site with similar characteristics.

Channel seeding could also reduce marsh loss by pond expansion, especially in the seaward portion of the marsh. Although channel seeding might fill in existing ponds (as is the case with thin-layer deposition), a major feature of this restoration is to prevent the formation and expansion of new ponds. As for edge erosion, this effect can only be identified when compared to the reference case with no action.

These limitations might create obstacles to the adoption of channel seeding. First, most of the benefits are in preventing marsh loss, not in creating new marsh. Second, even if the reduction in marsh loss is accepted as valuable, quantifying it would not be straightforward and could be challenged by stakeholders and coastal managers. Therefore, it is important to improve our ability and our confidence in modeling marsh evolution.

**POTENTIAL APPLICATIONS**

All three restoration techniques assessed in this study can prevent significant marsh loss in the low-RSLR scenario if enough sediment is used. If we consider channel seeding or any technique in the high-RSLR scenario, more than 1 Mm³ is required to maintain total marsh area. These results are specific to the initial conditions of our reference marsh. However, the relative efficiency of thin-layer placement, marsh creation, and channel seeding should be generalizable. Theoretically, restoration techniques could be combined with emergent, non-linear impacts on total marsh area.

Site-specific volumes to meet project restoration goals could be estimated by matching model boundary conditions — RSLR rate, boundary sediment concentration, sediment parameters, tidal range, spatial domain, vegetation parameters, etc. — to those of a desired location. This would result in a reference marsh with a different “no restoration” trajectory. For example, a longer spatial domain with marshes very far from the tidal flat could have different results. In this case, significantly more drowning may occur in the landward region because tidally transported sediment cannot easily reach these areas (Ganju et al. 2013). This could make thin-layer placement an increasingly attractive option because it deposits sediment directly onto the marsh surface.

This study does not account for environmental or economic impacts. Vegetation recovery after thin-layer placement is assumed to be immediate in the model.
but actually takes some time depending on site-specific conditions and on the thickness of sediment deposited (Wilber 1992; Ford et al. 1999; Schaffner 2010). High concentrations of suspended sediment from sediment nourishment could also harm benthic organisms. The model can track the distribution of suspended sediment through space and time, so this concern can be assessed for each simulation. Field studies have suggested that artificial marshes do not fully convey all the ecosystem services that natural marshes do (Streever 2000). Therefore, natural marsh area retained vs. new marsh area retained could be weighted differently when considering the positive environmental impacts between different restoration strategies. Our modeling approach allows us to distinguish these two areas, as shown in Figure 4.

Because of its high numerical efficiency, the model could be coupled easily with a cost assessment of each restoration strategy to optimize the economics of marsh restoration by simulating hundreds, if not thousands, of scenarios. A study by Wiegman et al. (2018) took a similar approach by pairing a 1D ecogeomorphic model to assess necessary sediment volumes with a cost projection of hydraulic dredging over the next century. However, their model did not resolve spatial patterns of marsh loss and is unable to compare different restoration strategies. MarshMorpho2D is suitable for assessing the sediment volumes necessary to achieve the same result for each restoration technique. Channel seeding is the least effective technique per unit volume, but likely the cheapest because it relies on natural processes to distribute sediment onto the marsh surface. A cost tool would help assess its viability. This cost tool would need to account for the volumes of sediment available from nearby maintenance or new project dredging. If those volumes are greater than the volumes deposited over the spatial domain of the model, there would be an additional cost to dredge the remainder.

Finally, the model has many hydrodynamic and sedimentary parameters that can be calibrated to specific sites based on field measurements. For example, discrete storm surges can be added to the equivalent tidal range which already includes astronomical and meteorological tides (Mariotti 2021). One of the strongest validations, however, is to run the model to hindcast the evolution of the marsh over the previous 50-100 years. Future improvements of the model should relax the assumption of instantaneous compaction of the deposited dredged material. Rather than developing a compaction module in the model, time series of sediment consolidation could be given as inputs to the model; they are often already calculated using sophisticated geotechnical models during existing marsh assessments (Graham and Mendelssohn 2013). Without such a compaction model, the benefits of restoration techniques involving rapid deposition of thick sediment layers (particularly for new marsh creation) may be somewhat overstated.

**CONCLUSIONS**

MarshMorpho2D is a coastal evolution model that resolves morphodynamics and marsh accretion over years to centuries while conserving sediment mass within its domain. This makes it an ideal tool for planners to project the impacts of thin-layer placement, channel seeding, and marsh creation over the life of restoration projects. The impacts of beneficially used dredged material can scale non-linearly for different RSLR rates, placement techniques, and volumes of sediment added. The application of the model to an idealized microtidal marsh reveals the following:

- For a given total amount of dredged sediment, thin-layer placement is the technique most effective at maximizing total marsh area after 50 years. Marsh creation is most effective for the first 20 years. Channel seeding is the least effective.
Figure 7. Spatial distribution of marsh loss and gain for channel seeding with different volumes of sediment added. Blue graph above each panel is the area of marsh restored (equivalent to yellow area in each panel) as a function of distance in the x direction.

- The frequency of sediment deposition is relatively unimportant for maximizing total marsh area, but placing large volumes earlier is marginally better simply because the benefits the deposited sediment provides are available for a longer time.

- Channel seeding can restore as much marsh area as thin-layer placement if three to five times more sediment is used.

This study provides a proof-of-concept of the model’s capability, and it paves the way for more realistic predictions of marsh restoration. Model predictions can be combined with environmental and economic considerations to optimize the success of marsh restoration projects.

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Ghose-Hajra, M., Mebust, C., and G. Matt-
Incorporation of coarse-grained dredged material into marsh and shoreline restoration projects in coastal New Jersey

By

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ABSTRACT

Millions of cubic yards of sediment are dredged every year in coastal New Jersey for the operation and maintenance of an extensive marine transportation system stretching from the New Jersey Harbor south along the Atlantic Coast from Sandy Hook to Cape May and north up the Delaware River. Dredged material from these public and private projects has been managed using a variety of placement approaches and technologies, from open-water disposal to landfiling to construction materials. For the past several decades, the State of New Jersey has advocated for and implemented a policy of beneficial use of dredged material rather than its disposal. The New Jersey Department of Transportation’s Office of Maritime Resources (NJDOT/OMR) is the lead state agency for research and implementation of beneficial use statewide. NJDOT/OMR is also responsible for the recovery of the 200-mile network of shallow-draft navigation channels along the Atlantic coast of New Jersey that was damaged by a series of severe coastal storms, most notably Superstorm Sandy in 2012. For the past decade, considerable effort has been made to develop methods that use clean dredged material from the Atlantic region to rebuild and improve coastal features such as marshes, dunes, and beaches, thereby retaining the sediment in the ecosystem. Although there have been a number of successful beneficial use projects, concerns remain about the long-term sustainability of the program due to high cost, timelines, scalability, habitat sensitivity, resiliency, aesthetics, and other factors. This paper explores some of these issues and proposes solutions. It focuses on the use of available coarse-grained material as a way to provide resiliency to these restored features while increasing scale and efficiency, protecting aesthetics, and providing increased habitat value.

The State of New Jersey’s marine transportation system is the largest in the country, with more than 600 miles of engineered waterways across the state from 5 to 50 feet deep. The system is separated into three distinct regions that differ in usage, channel depth, sediment type, and project volumes. The first region is the New York-New Jersey Harbor region, which extends from the Hudson River to Sandy Hook and serves primarily to provide navigable waterways for deep-draft commercial and international cargo. The second is the Delaware River region, which extends from Trenton south to the western entrance of the Cape May Canal and also primarily serves deep-draft commercial and international cargo vessels. The third is the Atlantic Coast region between Sandy Hook and Cape May. This region primarily serves shallow-draft recreational vessels, but also serves commercial fisheries and emergency services. Responsibility for operations and maintenance are divided by region as well; the New York District of the U.S. Army Corps of Engineers (USACE) and the Port Authority of New York and New Jersey are primarily responsible for the Harbor region, the Philadelphia District of the USACE is primarily responsible for the Delaware River region, and the State of New Jersey Department of Transportation (NJDOT) shares responsibility for the Atlantic Coast region with the Philadelphia and New York Districts of the USACE.

The ravages of Superstorm Sandy and subsequent storms have spurred the State of New Jersey to look carefully at the resiliency of its coastal communities (NJDEP 2021). It is now widely accepted that healthy coastal marshes, dunes, beaches, and other “green infrastructure” are essential for sustainable coastal living. What has become increasingly apparent is that sediment — rather than being at best a nuisance, and at worst a pollutant — is vital for maintaining and improving the resiliency of natural and built environments. Beaches and dunes protect ocean-front homes from storm surge and damaging waves, whereas coastal marshes, of which New Jersey has close to 300,000 acres, dampen storm surge and reduce flooding of bayside homes and businesses (USACE 2014).

Increasingly frequent and violent coastal storms damage beaches and marsh shorelines. Rising sea level elevations cause the frequent inundation of, and slow drainage of saltwater from, coastal marshes. The result is the destabilization and eventual loss of marsh platforms. Some 59,000 acres of saltmarsh have converted to open water since 1977 (Ferencz et al. 2017), and another 75,000 acres are in danger of being lost in the next several decades if programmatic actions are not undertaken to reverse these trends (Lathrop and Love 2007). Because climate change and sea level rise are global issues that will take many years (if not decades) to address, there is an immediate need to utilize sediment to enhance or restore dunes, beaches, and marshes and to develop effective practices to keep it there to provide protection to coastal communities. (Valuable habitat for wildlife and fish will also benefit greatly.) Undoubtedly, the marine transportation industry and the agencies that operate and maintain the channel networks are in a position to help. Although dredged sand has long been used to maintain beaches and dunes in New Jersey, little if any attention has been paid to protecting...
marshes and shorelines from the ravages of climate change.

The New Jersey Department of Transportation’s Office of Maritime Resources (NJDOT/OMR) is responsible for the operation and maintenance of 200 nautical miles of state navigation channels in the Atlantic coastal region. These shallow-draft (5-15 feet deep) navigation channels connect local channels and berths to the federally maintained New Jersey Intracoastal Waterway and Atlantic coastal inlets. Primary maritime usage in this region is recreational, but a large and productive commercial fishery and shellfish fleet are also served by this network of waterways. NJDOT/OMR is also responsible for the state’s decade-long effort to recover from Superstorm Sandy’s damage to the channel network, set to be completed by 2024.

Dredging in coastal New Jersey has historically been done with small- to medium-sized hydraulic cutterhead pipeline dredges, and the sediment has either been used for beach replenishment or stored in confined disposal facilities (CDFs) located primarily on coastal marshes. Although there are hundreds of CDFs throughout the region, many have been filled, have reverted to natural areas from disuse, or have been leveled and developed for housing (Farrell et al. 2008; Farrell et al. 2009a, 2009b, 2009c; Barone et al. 2012a, 2012b). The remaining few dozen CDFs leave gaps in a system with few, if any, options for managing dredged material. Consequently, much attention has been paid in recent years to developing dredged material management alternatives for the region, and that is the focus of this paper.

Since taking over routine operation and maintenance of the system in 2013, NJDOT/OMR has pursued innovative solutions to manage dredged material in areas where traditional management options are not available. Marsh enhancement, shoreline stabilization, confined and unconfined benthic restoration, and upland beneficial use are a few techniques that have been developed or advanced by NJDOT/OMR. These projects would have been infinitely more difficult, if not impossible, without the cooperation of resource agencies such as the New Jersey Division of Fish and Wildlife (NJDFW), the New Jersey Department of Environmental Protection (NJDEP), the U.S. Fish and Wildlife Service (USFWS), and the National Marine Fisheries Service (NMFS), as well as nongovernmental entities including The Nature Conservancy, the Partnership for the Delaware Estuary, and the Barnegat Bay Partnership. This forward-looking approach has made it possible to dredge more than 1 million cubic yards of sediment from the Atlantic coast region in the past decade, with much of it used beneficially.

Our understanding of how to efficiently and safely place sediment in sensitive ecosystems has vastly improved over the years. But the scale of these beneficial use projects has been small, the costs relatively high, and the project timelines too long for sustainable dredged material management. The dredging industry (including dredging companies and channel/berth owners) requires projects that can be constructed in a predictable manner to manage risk, maintain schedules, and keep costs down. Resource managers, including wildlife, fisheries, and land managers, have struggled with the long timelines of recovery projects and are concerned about the damage caused by heavy machinery operating in sensitive habitats. Aesthetics are also a problem; engineers prefer hardened shorelines to protect against wave and wind damage and to retain fines, while resource managers prefer softer features more in keeping with the natural features of the region. Striving to balance the needs of both engineers and resource managers, regulators often end up permitting projects that have insufficient work windows and burdensome and often ineffective protective measures and that require expensive short- and long-term monitoring. These disparate issues need to be reconciled if beneficial use projects are to be sustainable. This paper discusses some of the issues that have arisen during beneficial use projects for coastal resiliency and habitat restoration and offers insights into how they might be resolved.

**TYPES OF BENEFICIAL USE PROJECTS**

The policy of the State of New Jersey is to beneficially use dredged material wherever and whenever possible. Many techniques have been successfully employed in New Jersey, both for clean and contaminated sediment. The following is a summary of techniques suitable for clean or relatively clean sediment as well as some of the issues surrounding their sustainable use.

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**Marsh enhancement**

Marsh enhancement, often also called thin layer placement, is the use of dredged sediment to stabilize and raise the elevation of the marsh platform in the absence of adequate natural accretion. The challenge is to provide enough sediment to enhance marsh structure and function in a way that results in increased marsh vegetation rather than a conversion to uplands. A good understanding of the hydrology of the system is essential to design the project and ensure that the post-construction hydrology will allow for an adequate daily cycle of flooding and draining. For most projects, the size of the placement site(s) will dictate the rate of dredging and the retention of solids on the marsh. Techniques for placement range widely and include open pipelines with and without diffusers, spray nozzles, and complex distribution arrays. The U.S. Army Corps of Engineers (USACE) expects to publish an engineering manual on thin layer placement techniques in the coming months (Piercy et al. in press).

There have been problems associated with damage caused by equipment and by wide fluctuations in sediment chemistry due to mismatched sediment types and inadequate tidal flushing. Depending on the initial site conditions and the consolidation rate of the sediments, multiple applications of sediment may be needed to achieve the goals for a marsh. Lengthy recovery timelines — often much longer than anticipated or desired — appear to be unavoidable. Fines have been contained in a variety of ways that involve bringing in non-native materials, including coconut logs, hay bales, and plastic sleeves filled with compost. Regardless of the materials used, initial placement and eventual removal are expensive and time-consuming, can introduce non-native materials to the marsh, and in some cases can lead to extensive rutting and loss of vegetation caused by the machinery used in the operation (Doerr et al. 2021).

That these marshes are subject to continued inundation and erosion from wave action is particularly concerning. Newly placed sediments can easily be relocated from the intended placement boundaries and may clog natural drainage runnels, resulting in continued degradation rather than improvement. Leaving containment on site is not an option because sediment stabilization and vegetative regrowth require tidal flushing, which containment
prevents. Rock sills and riprap revetment have been used in several New Jersey projects, but these solutions are expensive and not typical of the saltmarsh ecosystem.

**Shoreline stabilization**

Marsh and beach shorelines are threatened by coastal storms and sea level rise. Rising water and increased wave and current energy erodes sand and soil away from natural features. This erosion not only creates problems for navigation and resource managers, but also reduces the protection natural features provide to coastal communities. Stabilization involves bringing in materials that can withstand increased wave energy. These materials have ranged from the organic (e.g. coir logs) to stone to metal. Used alone or in combination, they vary wildly in cost and effectiveness (Traylor 2017). The emphasis on using natural materials to provide habitat has led to these projects being referred to as “living shorelines” (Miller et al. 2016).

Although many of these materials may become suitable habitat, using non-native materials will often result in the introduction of a non-native, or regionally atypical, ecosystem that is also functionally and aesthetically different than the native shorelines. Hardening shorelines can deflect wind and wave energy to nearby unprotected areas and may result in continued loss of habitat and resiliency.

**Marsh and island creation**

Where marsh has converted to open water, a combination of techniques will be needed to replace the lost habitat. These projects have the potential to provide large volumes of capacity for dredging projects, but they have been notoriously difficult to permit due to the permanent loss of benthic habitat. Loss of islands has been particularly damaging to coastal resiliency in Barnegat Bay, where 13 islands have “drowned” since 1931, exposing traditionally well-protected bayside homes and businesses to increased damage from storm surges and wind-induced waves (Kimberly McKenna, Stockton Coastal Research Center, personal communication).

Replacing sediment in natural features is not straightforward because the imported materials are often even less resistant to erosion than the existing material. Dredged material, particularly hydraulically dredged sediment, is not only un-consolidated, but is typically pumped at a rate of only 5% to 10% solids. The primary challenge, therefore, is to create a facility that will hold the dredged material long enough for it to consolidate and to sculpt a naturally appearing shoreline that will be resilient to waves and currents. Among the containment techniques have been used in New Jersey are rock revetments, geotubes, and natural berms such as coir logs (Pecchioli et al. 2021; Douglas et al. 2019; Traylor 2017). Wave attenuation and sediment retention devices such as concrete pilings and oyster castles have yet to be used in dredging projects in New Jersey. The primary objections to them have been cost, appearance, and longevity.

**Unconfined benthic restoration**

Intertidal and subtidal habitats are critical for healthy shore ecosystems. Sea level rise results in decreased light penetration and shrinks the area of suitable conditions. If marshes are allowed to retreat, the shallow area can retreat with it. However, in highly developed shorelines such as the ones in New Jersey, retreat is limited by built infrastructure. If not maintained, these habitats will ultimately be lost. Side-casting dredged material into nearby shallows can augment the shallow water habitat if the layering is not too frequent or too thick. The challenge is to place the sediment in a way that retains fine-grained material and to limit placement to areas that are already too deep to support a healthy benthic community. A corollary is to reintroduce shoaled sediment into the swift water that carried it there, but on the opposite tide. This was done for the sand shoals at the Hereford Inlet in southern New Jersey. This deep and swift inlet has a large and important network of ebb tide shoals, but is also notorious for rapid flood tide shoaling in its channels and marinas. Simply pumping dredged material into the ebb tide and allowing it to augment ebb shoals has proved successful. Both techniques are relatively straightforward and affordable, but they do require extensive up-front evaluations and monitoring.

**Confined benthic restoration**

The use of sediment for commercial purposes has resulted in the creation of underwater borrow pits, or “dredged holes,” throughout coastal New Jersey. These sites are often many acres in size and 10 to 20 feet (or more) deeper than the surrounding water. The silty, organic-rich sediments they retain can create hypoxic or even anoxic conditions in their lowest spots, and they may even inhibit water circulation in the surrounding area, reducing water quality (Howard et al. 2015). Dredged holes close to dredging projects are good candidates for restoration using dredged material. The resulting elevated bottom can be designed to replicate desired habitat conditions for fish and shellfish. These sites can be filled mechanically or hydraulically, with minimal impact to the surrounding healthy habitat, at an affordable cost. Unfortunately, due to finite capacity, dredged holes only provide a temporary relief for dredged material management needs.

Several dredged holes have been restored with dredged material in coastal New Jersey (USACE and NJDEP 2003; USACE 2010; USACE 2014), and several more are targeted for restoration in the coming years. The hole itself is a primary container of solids, but the placement technique and grain size of the dredged material could result in undesirable levels of turbidity and the loss of fines. Consequently, expensive containment and monitoring have been incorporated into project permits (Douglas et al. 2021a). Because the goal of these projects is to restore subtidal benthic habitat, the grain size and organic content of the top several feet should match that of the surrounding bottom. The use of sand as a cap, when
appropriate, can assist with stabilization and consolidation of the fill, isolate potentially contaminated sediments, and provide protection from erosion during severe conditions.

**CASE STUDIES**

**Route 52 causeway**

Dredged material was not used in this shoreline stabilization project, which was required to mitigate impacts in Great Egg Harbor Bay caused by reconstructing the Route 52 causeway between Ocean City and Somers Point. It consisted of rock revetment, sheetpile, coir logs and vegetated mats (Figure 1). The installation process had a number of setbacks that required adaptive management strategies, including erosion of regraded marsh soils, instability of coir logs and loss of filling, herbivory, as well as being forced by permit to work in less than ideal timeframes. However, the project has prevented loss of shoreline that would have been likely in the face of several major storms including Superstorm Sandy (Traylor 2017).

**Brigantine Islands**

The Brigantine restoration project was designed to increase intertidal and subtidal habitat around two marsh islands on the western side of Brigantine Beach in Absecon Bay. Erosion of the marsh edge had severely damaged the shores of Boot and Sunflower islands, and portions of

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**Figure 1.** Completed shoreline stabilization for the Route 52 causeway.

**Figure 2.** Aerial view of the Brigantine Shoal project site.
Figure 3. Completed shoreline stabilization at Sunflower Island.

Figure 4. Constructing the protective dune at Fortescue marsh.
Sunflower Island had broken off, resulting in a matrix of hummocks and open water. Sixteen acres of deep water due to scour lay between the marsh edge and an extensive sand shoal that extended off Boot Island (Figure 2). Both islands and the sand shoal are used by a large number of shorebirds, and Boot Island is home to a large heron rookery.

The eroded material had substantially blocked the navigation channel between the two islands, cutting off several marinas and numerous private berths from the rest of the Brigantine community. Condition surveys indicated that approximately 27,000 yd$^3$ of coarse-grained material (78% sand) was available in the adjacent channel. Previous dredging projects in the area had placed material from this shoal on a narrow natural beach adjacent to the channel, but after discussions with the New Jersey Division of Fish and Wildlife (NJDFW), it was decided that the material could be used to increase shallow water habitat adjacent to Boot Island by filling in the scour area and to stabilize the shoreline of Sunflower Island.

NJDOT hired Wickberg Marine Contracting, of Belford, NJ, to hydraulically dredge the material and place it directly in the targeted restoration areas. A final elevation of 2-3 ft below mean low water (MLW) was targeted for the Boot Island scour area, and a final elevation of 5 ft North American Vertical Datum of 1988 (NAVD88) was targeted for Sunflower Island. Approximately 21,800 yd$^3$ of material was placed between the two areas (Figure 3). Submerged aquatic vegetation (SAV) and the benthic community, including shellfish, were monitored prior to the project, and turbidity and placement elevation were monitored during placement. No impacts to water quality were observed (McKenna et al. 2021). SAV and the benthic community will be monitored for two years post-construction.

Fortescue Marsh

The Fortescue Wildlife Management area is an extensive area of saltmarsh in Downe Township, Cumberland County, managed by the NJDFW. Land managers had identified several areas in the marsh that were being damaged by poor drainage due to rising sea level and increased storm surge. Enhancement of the marsh platform with dredged material was determined to be a suitable approach to restoring the area. Extensive evaluations revealed that a 22-acre portion of the marsh would benefit from the addition of up to 16,000 yd$^3$ of dredged material (Douglas et al. 2021b).

NJDOT/OMR was approached by NJDEP to provide dredged material from the nearby Fortescue Channel, a 3,800-ft-long shallow-draft navigation channel that provides access to several marinas, a public boat ramp, and U.S. Coast Guard search and rescue operations from Fortescue Creek to Delaware Bay. Surveys of the condition of the Fortescue channel indicated 11,350 yd$^3$ of fine-grained material and 24,500 yd$^3$ of coarse-grained material.
material were available at a target depth of -7 ft MLW. The disparity between the material available and the type and quantity needed concerned NJDOT dredging managers. Most of the coarse-grained material available was not suitable for the nearby bathing beach or the marsh. To satisfy the marsh requirements and still complete a navigation project, additional placement sites would have to be identified.

On the seaward edge the targeted marsh site were 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 to 1 m/yr 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 at least some of the coarse-grained material from the channel could be used to restore the dune. Restoration would also provide an opportunity to replace an extensive stand of common reed (Phragmites australis) with native plants.

A 1,100-ft-long by 100-ft-wide dune was constructed using 21,045 yd$^3$ of coarse-grained sediment (Figure 4). Material was hydraulically dredged into a scour hole for initial settling, and the sand was removed with an excavator for sculpting the dune. The slurry water was allowed to flow onto the marsh behind the dune, where fines were retained, and the water eventually returned to the bay. The completed dune was planted with 16,000 plants from nine native species (Figure 5). Another 7,000 yd$^3$ of coarse-grained material was used to replenish a nearby natural beach used extensively by shorebirds. Recent inspections of the project indicate that the rate of shoreline loss in front of the dune has been significantly reduced.

**Mordecai Island**

Mordecai Island is an undeveloped 45-acre marsh island in Barnegat Bay, on the western shore of Beach Haven. It shelters the highly developed bay shore of Beach Haven from the brunt of wind and waves coming across Barnegat Bay, but over the years Mordecai Island had been reduced and fragmented by the same wind and waves. The Mordecai Land Trust, a local environmental advocacy group, had long bemoaned the degradation of the island and sought help to restore the breach.

In 2015, the USACE, dredging sand shoals in the Intracoastal Waterway, hydraulically placed 25,000 yd$^3$ of sand in the area of shallow water between two of the larger marsh fragments, effectively joining them. To protect extensive SAV beds adjacent to the island, a system of hay bales and silt curtain was deployed to retain the solids (USACE 2019). Besides effectively joining the two fragments, the project created valuable shorebird breeding habitat and restored the protection provided to Beach Haven. Additional applications of material have been made since first constructed to replace consolidation losses and to raise the area high enough to avoid nest losses during storms.

**Good Luck Point marsh**

The Good Luck Point marsh was previously identified by the Edwin B. Forsythe National Wildlife Refuge as a candidate for marsh enhancement as part of a larger USFWS effort to identify marshes at risk from erosion and sea level rise. Biologists determined that an elevation of 1.11 ft above MLW would stabilize the platform and the hydrology of the high marsh. As much as 17,000 yd$^3$ offine-grained material would be needed to achieve this target elevation (AMEC/Foster Wheeler and EA Engineering 2016). NJDOT was approached by the USFWS to provide dredged material from a nearby navigation project. Approximately 14,000 yd$^3$ of material in nearby channels could be used; however, about half of this material was coarse-grained and, due to shoaling patterns, would need to be dredged before the fine-grained material could be accessed and removed. After consulting with USFWS, it was decided that the coarse-grained material could be used to augment natural beaches along the eastern edge of the marsh that had been steadily eroding and were no longer protecting the marsh edge from wave damage.

Because the target beach was narrow and used by wildlife, heavy equipment could not be used to grade out the sand, as is typically done. Instead, sand was pumped directly into the nearshore and allowed to integrate naturally onto the beach (Figure 6). A total of 6,000 yd$^3$ of coarse-grained material was placed along 1,700 ft of shoreline. Although post-construction storms moved the sand about considerably, most of it settled within the project template, protecting 750 ft of marsh shoreline (Figure 7). Ongoing wave and current monitoring has enabled project scientists to better predict where
sand could be placed in the future to target the areas that still require protection (Barone 2021).

**Dredged Hole 18**

Dredged Hole 18 is a subaqueous borrow pit in northern Barnegat Bay next to the barrier island in Brick Township, Ocean County. The site had been mined for sand used for beach replenishment following severe storms in 1962. The hole was more than 20 feet deep below MLW (Figure 8) and had nearly vertical sides. (Average depth in this portion of the bay is less than 4 ft below MLW.) The unnatural bottom configuration impeded normal tidal circulation resulting a stratified water column in the hole. Evaluations of water quality and benthic life performed by Stockton Coastal Resource Center in 2014 and 2015 showed dissolved oxygen dropped precipitously inside Dredged Hole 18 and no benthic organisms were present in grab samples collected from the bottom surface of the dredged hole (Howard et al. 2015). Adjacent to the feature are high-quality sand flats that contain beds of annually occurring SAV including widgeon grass (*Ruppia maritima*). That the site would benefit by filling to match surround depths had been recognized for many years (Murawski 1969, USACE 2009).

The NJDOT/OMR had identified more than 240,000 yd$^3$ of dredged material that needed to be removed from state navigation channels in the area, but no management options were available. The material varied in quality and characteristics from clean sand to silty clay that was contaminated with metals, pesticides, and petroleum at levels slightly above residential soil remediation standards. The restoration of the hole provided an opportunity to manage the available material. Sediment was dredged mechanically and transported by scow to be placed mechanically into the hole. The contaminated silty material was placed at the bottom, followed by coarser and clean material. Approximately 83,500 yd$^3$ of sand (averaging more than 75% sand) were reserved for the required 2-ft cap. Placing this material at the top of the fill resulted in rapid consolidation and stabilization of the site. An additional 35,000 yd$^3$ of clean sand was added one year later following an evaluation of the thickness and grain size of the cap (Douglas et al. 2021a). SAV recruitment and benthic recolonization will be monitored for several years.

**Popular Point saltmarsh**

The 120-acre Popular Point saltmarsh is southwest of the unincorporated community of Beach Haven West in Stafford Township on the western shore of Barnegat Bay (Figure 9). The site was targeted for additional residential development in the 1960s, but that development was halted by protective land use regulations implemented in the 1970s. The saltmarsh is now among the extensive marshlands managed by the USFWS’s Edwin B. Forsythe National Wildlife Refuge. Before development was stopped, some canals were cut into the marsh platform and a berm was constructed partially around the site. And although the site is also cut with shallow, narrow mosquito ditches, the marsh platform appears to be largely healthy. The berm, however, has steadily eroded over the years and was severely damaged by Superstorm Sandy in 2012. The unprotected marsh edge now receives the full brunt of wave and storm energy and is deteriorating rapidly.

Shoaling is moderate to severe in the collector channels serving Beach Haven West and nearby communities in Ocean County, and many lagoons serving residences are silted in. More than 500,000 yd$^3$ of material needs to be excavated to return all the waterways to a state of good repair. But options for dredged material management are limited; historical CDFs located nearby are now protected habitat and unavailable for use.

Therefore, NJDOT/OMR plans to restore the eroded marsh edge and replace the protective berm using dredged material. Several options for retaining fine-grained dredged material were explored, including rock revetment, sheet pile, and sand. Because the area is residential and the existing shoreline is not rocky, the USFWS prefers a solution that uses sand. Approximately 72,000 yd$^3$ of sand from the community lagoon system will be hydraulically dredged and placed in open water in front of the existing marsh edge to create a berm 2,600 ft long and 100 ft wide at its base (Figure 10). The berm will allow as much as 110,000 yd$^3$ of fine-grained dredged material to be pumped between the berm and the marsh edge. The slurry will be held to retain solids, and the excess water will discharge, through a series of weirs, out over the marsh where additional solids will be removed before the water flows back to the bay, as was done at Fortescue marsh. An important aspect of this strategy is ensuring that the berm does not disrupt...
the hydrology of the marsh. To ensure
proper tidal exchange, the berm may
require modifications once the dredged
material has been placed. A hydrologic
study of the area was underway at the
time this paper was published.

**DISCUSSION**

Marshes, shorelines, and benthic
habitats in New Jersey have been restored
and enhanced by the NJDOT and USACE
using dredged material in traditional and
innovative ways, as outlined in the preced-
ing case studies and summarized in Table
1. These projects have shown that dredged
material can be placed so that sediment
is not lost from the system, and that this
practice not only can create or restore lost
habitat but also may help improve the
resiliency of coastal ecosystems and com-
unities. However, these demonstration
projects tend to be small and relatively
expensive (Douglas et al. 2019).

Contractors acknowledge that the
risks associated with tight work windows,
working during the winter months, and
the potential for delays due to adaptive
management actions force them to bid
higher prices. Having multiple, permit-
ted placement options available for both
coarse and fine-grained materials may
reduce costs by increasing flexibility.
The traditional retention systems used to
stabilize and consolidate fine-grained ma-
terials not only can be expensive but may
also require the use of heavy equipment
that can damage sensitive ecosystems.
Hardened structures such as riprap,
rock revetment, or sheetpile may attenu-
ate waves and retain fine-grained materi-
als when installed correctly, but they are
expensive and can be ecologically and
aesthetically undesirable. Coarse-grained
materials that would have been used
typically for beach replenishment may
prove to be an acceptable substitute for
hard structures. Although not as resil-
ient, these softer alternatives will be less
expensive and may provide acceptable
service lives.

Restoration projects should incorpo-
rate features that efficiently use as much
of the available dredged material as pos-
sible. From the dredging perspective, the
availability of multiple placement options

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Table 1.
Summary of beneficial use projects using dredged material in coastal New Jersey.

<table>
<thead>
<tr>
<th>Project</th>
<th>Total</th>
<th>Coarse (&gt;75% sand)</th>
<th>Fine (&lt;25% sand)</th>
<th>Coarse material</th>
<th>Beneficial use</th>
<th>Fine material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dredged Hole 18</td>
<td>244,000</td>
<td>118,500</td>
<td>125,500</td>
<td>Benthic habitat</td>
<td>Restorative fill</td>
<td></td>
</tr>
<tr>
<td>Mordecai Island</td>
<td>25,000</td>
<td>25,000</td>
<td>0</td>
<td>Island/marsh restoration</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Fortescue Marsh</td>
<td>37,140</td>
<td>28,620</td>
<td>8,520</td>
<td>Protective dune and beach</td>
<td>Marsh enhancement</td>
<td></td>
</tr>
<tr>
<td>Good Luck Point Marsh</td>
<td>10,200</td>
<td>6,000</td>
<td>4,200</td>
<td>Beach replenishment</td>
<td>Marsh enhancement</td>
<td></td>
</tr>
<tr>
<td>Brigantine Shoal</td>
<td>21,830</td>
<td>21,830</td>
<td>0</td>
<td>Intertidal/subtidal shallows</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Popular Point Marsh*</td>
<td>182,000</td>
<td>72,000</td>
<td>110,000</td>
<td>Retention berm</td>
<td>Marsh enhancement</td>
<td></td>
</tr>
</tbody>
</table>

*This project has not yet been constructed. Numbers are estimated.
can not only increase the scale of a given project, but also has the potential to reduce risk by decreasing the potential for standby delays. This material is readily available in coastal New Jersey and will certainly be less expensive and provide habitat more typical of the region. Even when placed in the center of marshes, coarse-grained material has provided habitat that is readily used by breeding shorebirds.

CONCLUSIONS
The following conclusions should be taken from this work:

1) Both fine- and coarse-grained dredged material can be used for habitat enhancement, shoreline stabilization, and marsh restoration. Doing this has the potential to decrease cost by increasing scale and flexibility.

2) Coarse-grained dredged material may protect beneficial use projects that use fine-grained material.

3) Coarse-grained dredged material may be a suitable alternative to harder and non-native materials for shoreline stabilization.

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ABSTRACT
Lightning Point, located in Alabama at the confluence of the Bayou La Batre navigation channel and Mississippi Sound, is a culturally and ecologically valuable site with an extensive history of shoreline erosion. Between 1916 and 2019, the shoreline experienced approximately 750 to 1,000 ft of shoreline retreat as a result of severe weather events and anthropogenic causes such as shoreline modification and response efforts related to the Deepwater Horizon oil spill. Moffatt & Nichol worked with The Nature Conservancy to restore the lost habitat and resources through ecology-based engineering and design. The Lightning Point Shoreline Restoration Project is a 1-mile-long living shoreline that includes approximately 4,700 ft of segmented, overlapping breakwaters, 40 acres of marsh and upland habitat creation, and 10,000 linear feet of tidal creeks. The project was designed to include a diversity of habitat types (subtidal, intertidal, higher scrub-shrub) and to serve as a resilient restoration solution capable of adapting in the face of sea level rise and increasing storm activity.

PROJECT DESIGN LIFE
Projects with marsh creation components are sometimes tied to funding sources that specify a required project design life, such as the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) which mandates a 20-year project life. However, the NFWF GEBF does not require a specific design life. An appropriate project design life was determined by considering the function of the main project features (marsh creation and rock breakwaters), the magnitude of the environmental forcings, and the recurrence interval of the controlling environmental forcings. Controlling project forcings indicated a longer project design life was possible. For example, the relatively low-lying nature of the project features resulted in controlling wave forces associated with relatively lower water levels, as the project features are inundated under extreme conditions. Additionally, the marsh creation area settlement curves indicate the marsh habitat will remain intertidal well past the 25-year design life due to minimal effects of subsidence and foundation soil consolidation. However, several factors limited the project design life. While sea level rise is accounted for, it remains a significant risk to the marsh habitat as climate futures are uncertain. Also, while the project team considered the expected number of storm events for various return periods and design life scenarios, specific suites of storms over the design life for varying storminess scenarios were not considered for this project, which may help inform the effect of storm impacts for future project designs. Ultimately, taking into account the CWPPRA 20-year project life as precedent for marsh creation projects, and the above discussed factors, the project team set a 25-year project life.

WATER LEVEL AND WAVE CONDITIONS
Relative sea level rise (RSLR) was an important design consideration to en-
Figure 1. The Lightning Point project area.

Table 1. Interpolated Lightning Point operational water levels associated with various probabilities of exceedance for future conditions (with RSLR).

<table>
<thead>
<tr>
<th>Probability of exceedance (%)</th>
<th>Water level (ft, NAVD88)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>-0.6</td>
</tr>
<tr>
<td>95</td>
<td>-0.1</td>
</tr>
<tr>
<td>90</td>
<td>+0.2</td>
</tr>
<tr>
<td>75</td>
<td>+0.7</td>
</tr>
<tr>
<td>50</td>
<td>+1.1</td>
</tr>
<tr>
<td>25</td>
<td>+1.6</td>
</tr>
<tr>
<td>10</td>
<td>+2.0</td>
</tr>
<tr>
<td>5</td>
<td>+2.3</td>
</tr>
<tr>
<td>1</td>
<td>+2.8</td>
</tr>
</tbody>
</table>

Table 2. Interpolated Lightning Point extreme water levels associated with various return periods for future conditions (with RSLR).

<table>
<thead>
<tr>
<th>Return period (yr)</th>
<th>Water level (ft, NAVD88)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>+3.2</td>
</tr>
<tr>
<td>1</td>
<td>+4.0</td>
</tr>
<tr>
<td>2</td>
<td>+4.8</td>
</tr>
<tr>
<td>5</td>
<td>+6.1</td>
</tr>
<tr>
<td>10</td>
<td>+7.5</td>
</tr>
<tr>
<td>25</td>
<td>+9.9</td>
</tr>
</tbody>
</table>

The derived water levels were used to develop operational (typical, day-to-day conditions) and extreme (1-year and greater return period) water levels. Water levels for various frequencies of exceedance were calculated using a cumulative frequency analysis, and an extreme value analysis (Goda 2010) was conducted to characterize more infrequent water levels associated with return periods up to 100 years. The anticipated RSLR of 0.83 ft was incorporated into the interpolated water levels, and the operational and extreme analyses were performed once more (Table 1 and Table 2). These data informed a cost- and risk-based breakwater and marsh design. Various breakwater crest elevations were evaluated to determine the degree of protection provided to the restored marsh platform under the operational and extreme conditions. Additionally, operational water level conditions with consideration for RSLR informed the design elevation of the marsh creation areas, and a range of operational and extreme water level and wave conditions were analyzed to size the armor stone.

A Mike 21 Flexible Mesh Spectral Wave (Mike 21 FM SW) model was also

breakwater crest elevations were evaluated to determine the degree of protection provided to the restored marsh platform under the operational and extreme conditions. Additionally, operational water level conditions with consideration for RSLR informed the design elevation of the marsh creation areas, and a range of operational and extreme water level and wave conditions were analyzed to size the armor stone.

A Mike 21 Flexible Mesh Spectral Wave (Mike 21 FM SW) model was also
developed to calculate wind-wave generation in Mississippi Sound and wave transformation processes as the waves propagate toward the Lightning Point shoreline. Waves were simulated for a period from 2001 to 2014 for which model wind and water level boundary conditions were available. This 2001-2014 period hindcast is long enough to enable robust frequency analysis to determine operational-level events and includes Hurricanes Ivan (2004), Katrina (2005), and Isaac (2012) which informed extreme value analysis results. To characterize the current wave climate, the interpolated Lightning Point water level record was used without alteration. For wave conditions at the end of the project design life used to inform design, waves were modeled using the water level record with the additional 0.83 ft of RSLR.

BREAKWATER DESIGN

Rock has been studied and used extensively for coastal engineering, and the ability to quantitatively predict wave transmission based on previous robust physical testing was an important factor in its selection for design. Although many alternatives to rock exist in the market, the project team found that physical testing for these products was typically limited in scope or provided only qualitative results so quantitative estimates of wave transmission could not be calculated. The decision to use rock was also based on the risk of failure, because the failure mode of rock riprap is typically limited to individual unit displacement. This “flexible” nature of rock allows for environmental forcing design criteria to be exceeded with lower risk of critical structural failure. Rock structures are also easily adapted to future sea level rise by placement of additional rock.

To protect the shoreline, rock breakwaters were incorporated into the project design to attenuate the wave energy during moderate (i.e. operational, not extreme) events impacting Lightning Point. The defense provided by this shoreline protection would allow for marsh restoration, habitat creation, and associated ecological benefits with reduced shoreline erosion rates, increasing the sustainability and resilience of the restoration. Previous work performed in the project vicinity has examined the wave climates associated with the presence or absence of stable marsh shorelines. Roland and Douglass (2005) computed the thresholds for the presence or absence of *Spartina alterniflora* marshes along the shorelines in coastal Alabama based on a wave height frequency analysis. M&N completed a spectral wave modeling study for the project site for a range of operational wind conditions and aggregated the modeled spectral significant wave heights in a frequency analysis overlaid on the results of the Roland and Douglass study (see Figure 3). The 80th to 100th percentile wave heights exceed the erosional threshold estimated by Roland and Douglass, confirming that the typical wave climate at Lightning Point is net erosional and that continued shoreline recession is driven by these more frequently occurring (though not extreme storm driven) waves. Similarly, Mariotti and Fagherazzi (2010) produced a model that correlates the rate of marsh edge retreat with wave power over a certain threshold value for...
stability, ranging from 0.9 to 4.6 watts/foot. Research by Trosclair (2013) in Lake Borgne, Louisiana, used the methods of Mariotti and Fagherazzi to model edge erosion during cold fronts. In this work, the critical wave power of 4.6 watts/foot is computed to correspond to a significant wave height of approximately 0.5 ft. Higher wave heights produce more wave power, so wave heights above this threshold are assumed to erode the marsh edge at a rate proportional to the difference over the threshold value. These findings indicate that shoreline protection features were needed to limit transmitted wave heights to less than approximately 0.5 ft and prevent significant shoreline erosion for selected risk scenarios. While other research has found that global marsh erosion rates are linearly correlated to wave power at all magnitudes without a critical threshold (Leonardi et al. 2016), our threshold-based design method derived from measured erosion in the project vicinity still primarily limits the heights of waves generated during moderate but frequent events (i.e., higher operational levels) which are the highest contribution to cumulative erosion (Leonardi et al. 2016). The elevated water levels associated with higher wave events could submerge the marsh edge and reduce erosion impacts (Tonelli et al. 2010); however, our conservative design approach neglected the potential reductions in erosion during high water level events, assuming that waves transmitted at any water levels fully impact the marsh edge.

The breakwater crest elevation was chosen to reduce the height of transmitted waves impacting the leeward marsh while minimizing material costs. The transmission coefficient and associated transmitted wave height were computed using robust empirical equations for low-crested structures (CIRIA, CUR, and CETMEF 2007) for different breakwater crest dimensions under various design scenarios. Operational-level wave heights were determined through frequency analysis of the spectral-wave model hindcast output, while extreme wave height values were computed using the extreme analysis methods of Goda (2010). The wave transmission results are shown in Table 3. This table was an essential tool for TNC in decision making as it provided risk- and cost-based scenarios using site-specific conditions. A breakwater crest elevation of +3.0 ft NAVD88 was selected by TNC based on this analysis (Figure 4). This crest elevation provides the necessary protection against the moderate and frequent (operational) wave conditions that contribute most to marsh edge erosion (Leonardi et al. 2016) while also providing wave-energy-attenuation benefits during lower return period extreme storm events. Seaward and landward side slopes of 3:1 (H:V), a crest width of 10 ft, and a seaward berm with a 5 ft width and 3:1 (H:V) side slope were designed and constructed. The breakwater sections are constructed entirely of Alabama Department of Transportation Class 5 armor stone, which was sized to remain stable when exposed to 25-year return period extreme wave conditions. Gaps were incorporated in the breakwater alignment to enable tidal exchange and to allow for

### Table 3.
Wave transmission results for various operational and extreme environmental scenarios and breakwater crest elevation alternatives.

<table>
<thead>
<tr>
<th>Type</th>
<th>Probability of exceedance (%)</th>
<th>Return period (yr)</th>
<th>Water level (ft, NAVD88)</th>
<th>Significant wave height (ft, NAVD88)</th>
<th>Peak wave period (s)</th>
<th>1.0</th>
<th>1.5</th>
<th>3.0</th>
<th>5.0</th>
<th>8.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational</td>
<td>50</td>
<td>1.1</td>
<td>0.4</td>
<td>3.9</td>
<td>0.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Operational</td>
<td>25</td>
<td>1.6</td>
<td>0.7</td>
<td>3.9</td>
<td>0.4</td>
<td>0.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Operational</td>
<td>10</td>
<td>2.0</td>
<td>1.0</td>
<td>3.9</td>
<td>0.7</td>
<td>0.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Operational</td>
<td>5</td>
<td>2.3</td>
<td>1.2</td>
<td>3.9</td>
<td>0.8</td>
<td>0.6</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Operational</td>
<td>1</td>
<td>2.8</td>
<td>1.8</td>
<td>4.0</td>
<td>1.2</td>
<td>1.0</td>
<td>0.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Extreme</td>
<td>1</td>
<td>4.0</td>
<td>2.8</td>
<td>4.1</td>
<td>1.9</td>
<td>1.7</td>
<td>1.1</td>
<td>0.3</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Extreme</td>
<td>2</td>
<td>4.8</td>
<td>3.1</td>
<td>4.1</td>
<td>2.3</td>
<td>2.1</td>
<td>1.5</td>
<td>0.7</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Extreme</td>
<td>5</td>
<td>6.1</td>
<td>3.7</td>
<td>4.1</td>
<td>3.0</td>
<td>2.8</td>
<td>2.2</td>
<td>1.4</td>
<td>0.2</td>
<td>–</td>
</tr>
<tr>
<td>Extreme</td>
<td>10</td>
<td>7.5</td>
<td>4.3</td>
<td>4.2</td>
<td>3.7</td>
<td>3.5</td>
<td>2.9</td>
<td>2.1</td>
<td>0.9</td>
<td>–</td>
</tr>
<tr>
<td>Extreme</td>
<td>25</td>
<td>9.9</td>
<td>5.4</td>
<td>4.3</td>
<td>5.0</td>
<td>4.8</td>
<td>4.2</td>
<td>3.4</td>
<td>2.2</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 3. Plot of computed wave cumulative frequency (thick black line) compared to the wetlands thresholds established in Roland and Douglass (2005).
nekton access to the newly created tidal creeks and marsh edge habitat. The length of each breakwater was limited to 500 ft to minimize the distance between the 50-ft fish passages, and the overlapping breakwater orientation was optimized for the dominant wave directions to minimize wave penetration through the fish passages. Geotechnical analyses included the calculation of long-term breakwater settlement, which was estimated to vary between 1.2” to 9.4” across the project site.

MARSH DESIGN

The material used to create the marsh platform consisted of approximately 50% coarse and 50% fine-grain soils. It was sourced from a borrow site to the east of the navigation channel and a nearby dredged material placement site. The design elevation of the marsh platform was driven by an analysis of dredged material settlement, including primary consolidation and secondary compression processes. Figure 5 displays the time rate of settlement for a range of constructed fill elevations and the calculated mean high water and mean low water levels (including RSLR) throughout the project design life. M&N specified a fill elevation of +1.5 ft NAVD88 to maximize the time throughout the project design life when the marsh platform elevation is between mean high water and mean low water (i.e. is intertidal). A similar analysis was completed to determine the elevation of the scrub-shrub habitat along the breakwaters and tidal creeks. An elevation of +3.5 ft NAVD88 resulted in an inundation frequency of less than 1% throughout the design life, which is optimal for scrub-shrub habitat productivity.

TIDAL CREEK DESIGN

Tidal creeks were incorporated into the Lightning Point design to serve as a connection between Portersville Bay, the newly restored marsh, and the historical marsh to the north of the site. By re-connecting to a relic tidal creek in the adjacent marsh habitat to the north, the project also restored hydrologic exchange to approximately 30 acres of impounded marsh habitat. Restoration through re-establishment of natural hydrologic connections supports the ecological productivity of the marsh habitat as a whole.

Work performed in California by Coats et al. (1995) used natural analogs to calculate various tidal creek metrics and mimic naturally formed tidal creeks. M&N extended this work to the project site by analyzing existing natural tidal creeks in the adjacent Little Bay marsh system to the west of the project site, ensuring the natural analogs that inform the design are exposed to similar coastal and hydrologic conditions. Field measurements of tidal creek depth and width were collected in the Little Bay system on 12 July 2018. The channel order, channel length, bifurcation ratio, sinuosity, and drainage area of the reference tidal creeks were estimated using geographic information system software, aerial imaging, and Light Detection and Ranging (LiDAR) elevations and were used to inform the morphometry of the designed tidal creek networks. Five separate tidal creek
networks and their respective orders and drainage areas were delineated (Figure 6). These data were used in conjunction with guidance on the patterns and processes involved in natural tidal creek development, ecological and engineering goals and criteria involved in channel design, hydraulic geometry relationships and regime equations, and channel characteristics to support design (Coats et al. 1995). Tidal creeks must be sized to support proper tidal exchange, circulation, and water quality because stagnant water can present environmental hazards. Flushing is strongly influenced by the tidal amplitude and maximum depth and cross-sectional area of the channel. The Lightning Point tidal creeks were constructed with trapezoidal cross-sections with 2H:1V side slopes with the understanding that natural scour and deposition would ultimately result in an equilibrium cross-section.

A Mike 21 FM hydrodynamic (HD) model calibrated to measured water level data was used to assess tidal creek hydraulics at the Lightning Point project site. To design the tidal creeks, the restored marsh area was first divided into separate drainage areas that were proportional to the simulated tidal prism contribution of each breakwater gap. The location of each numbered gap is provided in Figure 7. Due to gap orientation and proximity, Gaps 1 and 2 were assumed to drain the full west marsh creation area, Gaps 4 and 5 were grouped to connect the same drainage area, and Gaps 6 and 7 were similarly grouped (Figure 7). The tidal prism distribution through each fish gap is indicated in Table 4. The Lightning Point drainage areas were found to be most similar to the Little Bay drainage areas that contained third-order channels. As a result, comparable drainage densities were specified for the Lightning Point drainage networks (Table 5). A preliminary tidal creek network was designed using the literature guidance, field data, and information calculated from the HD model (Table 6 and Figure 7). In addition to the tidal creeks, a tidal pond was incorporated into the design. The pond is located along the existing sandy beach and preserves beach habitat, accommodates existing community recreational uses, and provides

Figure 6. Little Bay tidal creek network delineation.

Table 4.
Prism distribution through the breakwater gaps.

<table>
<thead>
<tr>
<th>Fish gap</th>
<th>Average prism (ft³)</th>
<th>Gap percent</th>
<th>Network percent</th>
<th>Channel network</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90,760</td>
<td>31</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>202,072</td>
<td>69</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>612,751</td>
<td>33</td>
<td>33</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>609,502</td>
<td>33</td>
<td>43</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>187,170</td>
<td>10</td>
<td>–</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>277,611</td>
<td>15</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>162,131</td>
<td>9</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 5.
The drainage area and drainage density of the Lightning Point tidal creek networks.

<table>
<thead>
<tr>
<th>Network</th>
<th>Sum of total length (ft)</th>
<th>Drainage area (ft²)</th>
<th>Drainage density (ft²/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,543</td>
<td>493,159</td>
<td>0.0052</td>
</tr>
<tr>
<td>2</td>
<td>3,822</td>
<td>787,993</td>
<td>0.0049</td>
</tr>
<tr>
<td>3</td>
<td>2,369</td>
<td>375,875</td>
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</tr>
<tr>
<td>4</td>
<td>5,269</td>
<td>1,004,078</td>
<td>0.0052</td>
</tr>
<tr>
<td>Average</td>
<td>3,501</td>
<td>665,276</td>
<td>0.0054</td>
</tr>
</tbody>
</table>
Table 6. Lightning Point network characteristics.

<table>
<thead>
<tr>
<th>Network</th>
<th>Average channel length (ft)</th>
<th>Average sinuosity</th>
<th>Average bifurcation ratio</th>
<th>Average channel length (ft)</th>
<th>Average sinuosity</th>
<th>Average bifurcation ratio</th>
<th>Average channel length (ft)</th>
<th>Average sinuosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>98</td>
<td>1.09</td>
<td>3.3</td>
<td>325</td>
<td>1.27</td>
<td>3</td>
<td>568</td>
<td>1.28</td>
</tr>
<tr>
<td>2</td>
<td>138</td>
<td>1.11</td>
<td>2</td>
<td>397</td>
<td>1.18</td>
<td>4</td>
<td>1142</td>
<td>1.32</td>
</tr>
<tr>
<td>3</td>
<td>108</td>
<td>1.11</td>
<td>2.3</td>
<td>253</td>
<td>1.20</td>
<td>3</td>
<td>843</td>
<td>1.28</td>
</tr>
<tr>
<td>4</td>
<td>128</td>
<td>1.14</td>
<td>2.6</td>
<td>364</td>
<td>1.28</td>
<td>2.5</td>
<td>889</td>
<td>1.48</td>
</tr>
<tr>
<td>Average</td>
<td>118</td>
<td>1.11</td>
<td>2.6</td>
<td>335</td>
<td>1.23</td>
<td>3.1</td>
<td>860</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Figure 7. The drainage areas and preliminary tidal creek layout at Lightning Point.

additional functional marsh edge habitat to boost ecological productivity.

As a final confirmation of proper tidal creek sizing, the circulation and flushing behavior of the proposed creek network were analyzed using the Mike 21 FM HD model. Simulations were performed using astronomical tides to simulate water level forcing with tides only and meteorological tides to simulate the rapid drawdown that occurs during cold fronts. The astronomical tide simulations resulted in maximum water velocities of 0.33 ft/s in the proposed tidal creek network. Several cold front events with large variations between the predicted water level and the measured water levels were also simulated. The higher wind speeds during these events accelerate the water level changes and generate maximum current velocities of 0.15 m/s. Although not modeled, wind forcing also contributes to water circulation in the tidal creeks and will aid in preventing stagnation in the proposed tidal creek network and tidal pond.

To analyze the flushing abilities of the proposed tidal creek network, the Mike 21 FM HD model was coupled to the advection-dispersion (AD) module to simulate the transport and dispersion of a conservative constituent such as dissolved oxygen. Simulations were initialized with a constituent concentration of 1 in the creek network and 0 over the rest of the domain; reductions in constituent concentration in the creek network over time are an indication of successful flushing. In the astronomical-tide-only case, concentrations were reduced to insignificant values in most of the network after two weeks of simulation. In the cold front case, the additional flushing due to the higher water velocities resulted in concentrations reduced by over 99% throughout the tidal creek network after several days of simulation. In reality, the behavior of the tidal creek network will likely fall between the tide-only condition (lower extreme) and the cold front condition (higher extreme). The AD simulations indicated adequate flushing throughout the tidal creek network.

EAST MARSH CREATION AREA CONSTRUCTION

Construction plans and specifications for the detailed marsh and tidal creek design balanced the need for tight tolerances with constructability and reduced construction costs. Construction was sequenced to allow the rock breakwaters to be used for dredge fill containment on the southern boundaries of the marsh.
creation areas (Figure 8). The marsh creation areas were designed to be fully contained based on the higher percentage of fine-grain material in the borrow material. M&N worked with the contractor to construct the east marsh creation area in three separate marsh creation cells to allow for dredging to occur prior to finishing the breakwaters on the eastern side of the project (Figure 9). Marsh creation cells were delineated along the approximate borders of the three tidal creek systems with temporary earthen containment dikes. These internal containment dikes allowed for phased dredged material placement to better control turbidity and retain material during dewatering.

Dredging was completed with an 18-in cutterhead suction dredge, with sediment transport to the marsh creation areas through a hydraulic dredge pipeline. The dredge pipeline was split at a manifold into two smaller diameter pipelines to allow placement at multiple locations and to slow the discharge velocity. Discharge was further controlled using a baffle plate. Dewatering occurred through spillways into adjacent marsh creation cells, which reduced turbidity of the effluent prior to discharge from the overall marsh creation area into surrounding water bodies.

The tidal creek layout was modified between the preliminary design (Figure 7) and the final 100% design based on the constructability of the layout and various cost factors. Once project construction had begun, the creek layout was further modified based on the as-built marsh platform. Second- and third-order tidal creeks were excavated from the marsh platform using amphibious excavators almost immediately after dredge fill placement in each marsh creation cell. The excavated material was used to create adjacent elevated berms designed to support scrub-shrub habitat. Instead of excavating the first-order tidal creeks, they were allowed to incise naturally over time as water drained from the marsh platform into the larger creeks. This approach resulted in cost savings by reducing the necessary excavations.

A planting plan to establish vegetative growth in the different habitat types was implemented by the contractor. Five species were planted to aid the stabilization of the sediments and to support habitat development along the tidal creeks and elevated berms designed for scrub-shrub habitat. Approximately 84,000 plugs of *Spartina alterniflora*, *Juncus roemerianus*, *Spartina patens*, *Iva frutescens*, and *Baccharis halimfolia* were planted across the site. The marsh plants are expected to establish naturally and advance across the remainder of the project site through several growing seasons. Seed dispersal from the adjacent marsh habitat should also support maturation of the site.

**WEST MARSH CREATION AREA CONSTRUCTION**

Construction of the west marsh creation area relied on material from an old U.S. Army Corps of Engineers dredged material placement area (DMPA) located adjacent to and north of the west marsh creation area. Construction of the rock breakwaters occurred prior to hydraulic dredging so the breakwaters could function as containment of the dredged material. After breakwater construction, a 12-in swinging ladder cutterhead suction dredge was used to excavate tidal creeks in the DMPA, and the excavated material was pumped through a dredge pipeline to the west marsh creation area. Tidal creeks in the DMPA were sized based on the draft and maneuverability limits of the dredge and on the necessary cut volume to construct the west marsh creation area. As a result, these creeks were required to have a greater cross-sectional area than the tidal creeks designed for the marsh creation areas. The larger cross-sectional area will result in lower water velocities which is expected to result in sedimentation over time, and the creeks should experience infill. Using the material generated from dredging the tidal creeks within the former U.S. Army Corps of Engineers placement site to create the west marsh area provided a unique opportunity for project benefits. These included the construction of a restored marsh platform and the added ecological benefits of the new tidal creeks in a historic DMPA. A planting plan similar to the one described above was implemented in the restored areas of the west marsh creation area.

**ECOLOGICAL SERVICES AND MONITORING**

An ecosystem services analysis was performed to demonstrate that the project would remedy harm to the resources injured by the DWH oil spill. This analysis used the ecological systems model (AQUATOX) that was developed for the
Alabama Department of Conservation and Natural Resources to estimate for the Natural Resource Damage Assessment (NRDA) settlement the ecosystem resources injured by the DWH oil spill. The AQUATOX outputs (as validated from local Alabama data) were used to estimate baseline biomass ecological production of various aquatic habitats along the Alabama coast. To estimate the net ecosystem service benefits of the habitats being created, enhanced, or replaced by this project, habitat equivalency analysis was used for individual marsh and upland habitat acreage, and a resource equivalency analysis was used for the various ecosystem services produced by aquatic habitats. Based on the NRDA Early Restoration negotiated monetary values of these habitats and resources, the responsible party would have compensated approximately $67.6 million to the DWH NRDA Trustees for the net natural resource credits attributable the various habitats and comparable resources that will be enhanced and restored at Lightning Point. This means that, once established, the project would essentially triple the value of existing ecosystem services for the various resource categories at Lightning Point based on methodologies used to determine injuries in Alabama due to the DWH oil spill.

A monitoring and adaptive management plan, to be implemented annually over the next five years, was developed to document the physical and ecosystem-level changes that will result based on the restoration activities. Metrics include breakwater elevation and area, habitat elevation, shoreline profile and position, and the spatial extent of the habitat. The monitoring plan implemented a Before-After, Control-Impact (BACI) monitoring design. A BACI design provides information to determine how the restoration activities change the site through time (Before-After), while also incorporating changes that may occur from natural variability and disturbances (e.g. tropical storms, oil spills) and trends in the larger area (Control-Impact). In addition, a long-term site sustainability plan was developed to serve as a framework for future adaptive management activities as guided by the monitoring plan. The sustainability plan is primarily focused on as-needed modifications to the marsh platform and breakwaters. For example, thin-layer placement of dredged material to increase the elevation of the marsh platform is explored as an approach for habitat maintenance or repair. These documents together support monitoring, adaptive management, and sustainability of the Lightning Point project site.

Figure 9. Construction of the east marsh creation area in a phased approach using three cells created from temporary earthen containment dikes (the tidal pond is located on the right side of the image).

LESSONS LEARNED
Knowledge gained from nearby natural analogues was used to design the tidal creek features. The objective design process provided greater confi-
The detailed tidal creek design, with continuously changing cross-sections, required compromises during construction. Construction specifications were provided for standardized cross-sections along various segments of the tidal creeks. This allowed for efficient excavation of the tidal creeks, which are expected to equilibrate over time.

The tidal creek systems were designed to use the gaps between breakwaters as tidal creek inlets with the understanding that one inlet for each tidal creek system would naturally become the primary inlet. The decreased water velocities in several of the secondary inlets for each tidal creek system resulted in shoaling.

Only the second- and third-order tidal creeks were excavated during construction. This provided cost savings and allowed for natural drainage patterns to develop from the marsh platform to the higher order creeks. This approach has been a success to date, and the first-order tidal creeks are continuing to develop and provide drainage to the marsh platform. The long-term efficacy of the Lightning Point tidal creek design will be determined over time through yearly project monitoring.

CONCLUSIONS

A coastal engineering study was performed to characterize current and future (with RSLR) operational and extreme water levels at Lightning Point. In addition, empirical prediction formulae were used to assess wave transmission across the breakwaters. The results of these analyses supported optimization of breakwater and marsh platform design with consideration for RSLR and geotechnical conditions. The breakwaters were designed to protect the shoreline from wave impacts while encouraging accretion and retention of sediment, and the segmented nature of the eight individual breakwaters allows for tidal exchange between Mississippi Sound and the constructed tidal creeks. Dredged material from a nearby borrow site and from a former U.S. Army Corps of Engineers placement site was used to create approximately 40 acres of marsh habitat on the leeward side of the breakwaters. The estimated rate of settlement was compared to the anticipated rate of RSLR to specify the elevations of the marsh platform and the scrub-shrub habitat. The elevation of the marsh platform was selected to maximize the intertidal habitat throughout the design life of the project, and the elevation of the scrub-shrub habitat was selected to reduce inundation. The tidal creeks were designed to mimic the natural conditions of the adjacent Little Bay tidal creek system using field data and ecological design guidance. Characteristics such as order, sinuosity, drainage density, bifurcation ratios, etc. were accounted for and numerical modeling was performed to analyze the flushing performance of the creek network and ensure there would be adequate tidal exchange. Construction consisted of placing 51,000 tons of rock for breakwaters, 240,000 cubic yards of dredged material for the marsh platform, 10,000 linear feet of tidal creek excavation and scrub-shrub berm construction, and 84,000 vegetative plantings (Figure 10). During and after construction, which was completed in summer 2020, the northern Gulf Coast experienced eight tropical cyclones, four of which resulted in extreme water levels at the project site. The project experienced no negative effects and successfully minimized storm impacts to the shoreline and the adjacent community. Ultimately, the project contributed to revitalization of a locally important waterfront by restoring and protecting the shoreline, enhancing coastal habitat, and providing improved community access.

REFERENCES


Restoration of estuarine wetlands using thin cover placement: A pilot application in Brunswick, Georgia

By

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ABSTRACT

This paper presents the design concepts and basis for using a thin layer cover (TLC) of sand to restore historically impacted wetlands in Georgia's Brunswick estuary. The project site is a mix of tidal creeks, marshes, brackish estuary, and an adjacent upland area that has been affected by historical industrial operations. A pilot project to test cover placement methodology and performance in advance of future full-scale TLC implementation was completed in 2018. It involved placing 6-9 inches of material in a 2/3-acre marsh area. Two material types — sand and higher organic content fines — were tested. The contractor, Sevenson Environmental Services, identified the appropriate equipment, means, and methods to hydraulically convey and place the TLC material within the pilot area in accordance with stated performance objectives. A mat-based access road was installed to enable equipment to move the pipeline and spray nozzle for fine placement control within the pilot marsh area. The thin cover placed in the field ranged from 6-12 inches thick (versus the design thickness of 6-9 inches) to meet the minimum required thickness and account for over placement. A 30- to 45-degree spray yielded the best distribution of materials for the equipment used. Placement of sandy material was faster and more uniform than fines due to the material's enhanced settling characteristics and ease of distribution. A modified topsoil-fines mix with a baffle plate eventually permitted optimal placement of fines within the study area while maintaining the target organic content. Turbidity in the water discharged from the pilot area was minimized by environmental controls (e.g. perimeter hay bales) installed by the contractor. The mat-based access road initially experienced some settlement due to loading on the soft sediments and marsh root mat; the road required restoration following project completion. Physical and vegetative monitoring conducted in six-month increments over a two-year period indicated strong natural recolonization of vegetation and the re-establishment of benthic species including fiddler crab. This paper presents lessons learned, design implications, and best management practices for future thin cover placement projects in estuarine settings.

KEYWORDS: Cover, thin layer, natural recovery, marsh, wetlands, vegetation, dredging, placement, natural solution, construction, monitoring.

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The LCP Chemicals Superfund Site (site) is in Glynn County, Georgia, immediately northwest of the city of Brunswick. The site is a mix of tidal creeks, marshes, brackish estuary, and an adjacent upland area. The upland property was initially developed for industrial use in the early 1900s; historically it supported an oil refinery, power plant, paint factory, and chemical plant. These historical operations resulted in legacy contamination of sediments and surface water at the site, and thin layer cover is being implemented as part of overall site restoration. The marsh portion of the site is the area discussed in this paper (Figure 1). The environmental remedy for the marsh consists of multiple technologies, including dredging of tidal creeks and placement of backfill, and placement of a site-specific thin cover over the marsh to enhance natural recovery. Engineering design of these components is ongoing, and construction is slated for 2022.

The marsh comprises about 760 acres of the site and consists of approximately 662 acres of vegetated tidal marsh and 98 acres of tidal creeks (Figure 2). The principal feature of the marsh is Purvis Creek, which divides the marsh roughly in half from north to south. Purvis Creek enters the marsh on the site from the Turtle River at the southwest corner and ends at the northeast upland-marsh border. At high tide, Purvis Creek has a maximum depth of approximately 11 feet and a maximum width of 500 feet. Purvis Creek and its associated smaller channels are tidally influenced and considered saltwater. Tidal range is 7-10 feet with a semidiurnal cycle. The low marsh is flooded by tides for several hours each day, and the high marsh is inundated by tides for an hour or less each day.

ENVIRONMENTAL RESTORATION OVERVIEW

The EPA-approved environmental remedy for this site includes a restoration approach that will improve existing conditions with minimal impact to the marsh's ecosystem. It consists of dredging creek channels and disposing of the dredged material off site, backfilling the creek channels with clean sand material, and placing thin layer cover (TLC) over marsh areas with lower levels of contamination. The concept
of TLC placement is innovative from a site restoration perspective and offers a noninvasive way to introduce a clean substrate into the surface of a marsh system. The added material mimics natural deposition and leads to marsh building, which can improve the overall resilience of the marsh to processes such as sea level rise and storms. Because TLC has not been part of a contaminated site restoration plan before, EPA and the State of Georgia requested a pilot-scale demonstration project, with two years of monitoring, prior to full-scale design and implementation.

The TLC concept consists of placing a thin 6- to 9-inch layer of sand, soil, or clean, previously dredged material onto the surface of the 12-acre marsh remedy footprint to enhance the process of natural recovery. TLC was chosen because the concentration of contaminants is relatively low in these 12 acres of marsh and more aggressive remedies, such as dredging/excavation, would do irreparable harm to the marsh. TLC is also one of the more sustainable remediation options available for conducting sediment remediation in marshes and wetland systems.

THIN LAYER COVER AS A RESTORATION TECHNIQUE

For TLC, material is placed hydraulically or pneumatically in thin layers to raise marsh surface elevations or to provide a beneficial nutrient, or growth, medium to encourage the expansion and resilience of an existing marsh system. Projects to restore or enhance uncontaminated marshes using TLC have been implemented across the country. A publication for the World Dredging Congress (Mohan et al. 2016) provided a status update on TLC as a means to restore or enhance coastal wetlands and summarized monitoring results from TLC projects in the southeastern United States. Key observations from the case studies included:

- Marshes where TLC thicknesses were 12 inches or less showed revegetation, generally within 1-3 years.
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Figure 3. Vegetative recovery processes following thin layer placement (adapted from Wilber 1993).

- Marshes where TLC thickness was over 24 inches took longer to partially revegetate (usually on the order of 5+ years) and did not fully re-establish.

Vegetative recovery processes following TLC placement were documented by Wilber et al. (2007). As illustrated in Figure 3, regardless of the TLC thickness, vegetation will be smothered once placement occurs and the recovery rate varies depending on the TLC thickness. Studies by the U.S. Army Engineer Research and Development Center (ERDC) show that as long as the TLC thickness is below 12 inches (30 cm), as in the left panel of the figure, within two to four growing seasons following placement new shoots will emerge from old rhizomes and new vegetation (often more robust than the preexisting vegetation) will establish. If the TLC thickness exceeds 12 inches, hypoxia and increases in sulfide concentrations occur, which will likely kill the rhizomes. After four to six growing seasons, new plants will establish from seeds entering the site, often by tidal action, rather than regrowth from rhizomes. As such vegetative recovery does occur, but typically at a lower density than the pre-existing conditions. In these circumstances, additional seeding or planting should be included in the designs.

Potential loss of benthic infauna is another concern for TLC placement; however, a study of benthic community response to TLC placement of dredged material at sites within the Mississippi Sound found that infaunal abundance was similar to pre-disposal conditions within three to 10 months of TLC placement (Wilber et al. 2007). Thus, TLC of 12 inches or less can emulate the natural deposition that occurs in marsh systems, leading to marsh building and thereby providing enhanced coastal resiliency from sea level rise.

**THIN LAYER COVER PILOT STUDY**

The TLC pilot study was intended to evaluate the considerations, impacts, and system recovery associated with TLC placement over a representative area of the 12-acre marsh. The pilot study was intended to gather information related to specific items, which are outlined below:

- Potential short-term impacts and marsh vegetative recovery process after TLC placement.
- Reduction of contaminant exposure potential based on surface sediment sampling results.
- Development of specifications (target thickness, over placement allowances, grain size, and organic carbon content) for TLC placement.
- Monitoring data to inform full scale engineering design, construction, and long-term monitoring.

Essentially, the pilot study had three stages (Figure 4): baseline data collection (sediments, vegetation and benthic), placement of the TLC (and associated documentation), and documentation of marsh restoration and recovery (via monitoring conducted every six months, for a period of two years). Data from these three stages are being used to inform the engineering design for the TLC in other areas of the marsh. The 2/3-acre pilot study area was subdivided into two areas of approximately 1/3 acre each (Figure 5). Figure 6 shows the location of the two reference sites that were used to establish background conditions for the baseline assessment.

Material was placed hydraulically within the designated pilot study areas in March 2018. The amount of material was controlled through various means as the material was placed through a “rain-in” or “water surface drop” process, with an operator controlling the placement and the material slurry density. Close management of the process allowed for layers of material to be placed within specified tolerances and minimize stress on the marsh system, although some vegetation smothering did occur. The degree of smothering and level of impacts were
largely a function of the actual thickness of the material placed on the vegetation and equipment.

In southeastern marsh systems like the Brunswick estuary, smooth cordgrass root systems stabilize the sediments and provide critical protection against erosion. Therefore, it is important not to cover the vegetation with sediment to the point that it cannot grow new shoots from the rhizomes. Consequently, the TLC pilot included two minimum thicknesses for the thin cover: 6 inches and 9 inches, both with an allowable over placement of up to 3 inches. These thicknesses also represent less than 10% of the tidal range of the site, and the new material would represent minor changes to surface elevations that would not be expected to cause a difference in habitat function or impact local or regional flushing.

Cover materials were selected based on several characteristics, including availability of clean source material, grain size distribution, and total organic carbon (TOC) depending on the area being covered (see Table 1). Specific means and methods of application, layer placement, measurement, and verification were coordinated with the selected contractor, Sevenson Environmental Services, Inc. (SES). The pilot study was implemented
in April 2018 by SES (Figure 7), under contract to Honeywell, with Anchor QEA performing construction management, providing quality assurance, and directing the work.

The pilot study locations were surveyed, and tidal channels and pools were marked for protection prior to TLC material placement. Prior to installation of TLC material, tracer materials (an inch of green-colored sand) were placed manually at one representative 5-foot by 5-foot plot within each quadrant of the pilot study area to evaluate the potential for material movement, though the deep root mass of the marsh vegetation was expected to limit vertical mixing with the underlying sediments. An offset of approximately 5-10 feet from the edge of steeper banks along Eastern Creek was maintained to limit the potential for bank stability issues during placement and allow room for equipment. Future engineering design for the full-scale effort will incorporate slope stability, dredging side slopes, and other considerations to address the perimeter areas of the channels. Following application, verification of placement thickness, post-placement sampling, and monitoring of vegetation response were conducted over a two-year period to assess the data quality objectives (DQOs) in Table 2.

Baseline data collection
Baseline data were collected in the pilot study area prior to TLC placement to supplement the existing dataset and provide a baseline of site conditions in the area. The baseline data collected within the marsh included:

• High-resolution (10-foot by 10-foot grid) topographic survey data in the pilot study area,

• Aerial drone imagery from multiple altitudes,

• Tide elevation monitoring via an automated tide gauge placed in Purvis Creek,

• Assessment of habitat conditions, including vegetation density and species composition,

• Fiddler crab (Uca spp.) abundance, and burrow density and morphology,

• Chemical analysis of surface sediments, and

• Chemical analysis of thin cover material.

Two 1-meter by 1-meter quadrats were established in each of the pilot study area’s subareas, for a total of eight vegetation assessment survey points (see Figure 8, which shows a representative quadrat). Plant species observed included smooth cordgrass (Spartina alterniflora) and black needlerush (Juncus roemerianus), with percent cover ranging from 35% to 80%. A similar vegetation assessment was conducted in the two reference areas shown in Figure 6. Three 1-meter by 1-meter quadrats were established in each reference area, for a total of six reference plots. As with the pilot study area, plant species observed included smooth cordgrass and black needlerush, with percent cover ranging from 35% to 80%. A summary of the habitat assessment program is shown in Table 3.

Fiddler crab burrow morphology and density, and fiddler crab abundance were assessed concurrent with the vegetation assessment described above. The fiddler crab burrow morphology assessment was completed at the same locations as the vegetation assessment in the pilot study area (at the four locations, one per quad-

Table 1.
Pilot study area materials and placement thicknesses.

<table>
<thead>
<tr>
<th></th>
<th>Area A*</th>
<th>Area B*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>1/3 acre</td>
<td>1/3 acre</td>
</tr>
<tr>
<td>Material type</td>
<td>Fine sand</td>
<td>Silty material</td>
</tr>
<tr>
<td>TOC %</td>
<td>0% to 1%</td>
<td>2% to 5%</td>
</tr>
<tr>
<td>Placement thickness</td>
<td>Subarea 1</td>
<td>Subarea 2</td>
</tr>
<tr>
<td>Minimum</td>
<td>6 inches</td>
<td>9 inches</td>
</tr>
<tr>
<td>Tolerance</td>
<td>+0-3 inches</td>
<td>+0-3 inches</td>
</tr>
<tr>
<td>Expected range</td>
<td>6-9 inches</td>
<td>9-12 inches</td>
</tr>
</tbody>
</table>

Note: Refer to Figure 6 for locations of study areas.
Figure 7. Photographs of thin layer cover placement (A), close-up of specialized nozzle (B), and mushroom-style placement (C)
rant), as well as at two random locations within the reference marsh areas. At the selected fiddler crab burrow assessment locations, casts were poured using an aqueous solution of plaster of paris, following the method in Qureshi and Sahar (2012). Multiple attempts were made in each area to ensure retrieval of multiple full-borrow casts in each targeted area. Hand tools were used to excavate the casts from the soft sediments and minimize the potential for damage.

The plaster approach was generally effective in creating casts of the full burrows assessed. In the pilot study area, burrow depths generally ranged from 1.1 inches to 6.4 inches; burrow width (measured as the horizontal distribution of the individual burrow network) ranged from 0.9 inch to 5.5 inches, and average diameter ranged from 0.2 inch to 1.0 inch. In the reference areas, burrow depth ranged from 1.5 inches to 9.0 inches; burrow width ranged from 0.8 inch to 6.5 inches, and average diameter ranged from 0.4 inch to 1.1 inches.

**Construction means and methods**

The TLC was installed in the pilot study area by hydraulically pumping materials from a slurry plant located on the earthen causeway 500 feet north of the pilot study area (Figure 5). The use of hydraulic slurry transport systems (i.e. centrifugal dredge slurry pump) reduced short-term impacts to the marsh compared to mechanical placement using conventional landbased construction equipment. To control the TLC placement, an excavator or other similar equipment moved the slurry discharge nozzle as needed. Accessing the pilot study area with the appropriate equipment was accomplished by trial and error. First a Hyundai 220LC long-reach excavator equipped with aluminum pontoon floats was used, but it caused marsh surface rutting and consolidation. This was followed by construction of HDPE mat access roads using 8 feet by 14 feet mat panels, but those required post-placement removal and restoration.

Construction of a land-based slurry plant was required to feed the transport pipeline for cover placement. SES widened the causeway at the location of the slurry plant by approximately 10 feet using crane mats placed along the bank of the causeway. Geotextile was placed under the crane mats, and gravel was placed on top of the crane mats to create a level surface. Major components of the slurry plant included the following:

- A stockpile area for the thin cover materials, constructed using concrete bin blocks and HDPE mats,
- A conveyor fed by an excavator to load thin cover material from the stockpile to a V-bottom slurry tank,
- A generator to power the conveyor,
- A V-bottom slurry tank with a horizontal auger at its base, where the material fed from the conveyor system was agitated and mixed with intake water, and
- A hydraulic booster pump that conveyed the thin cover slurry from the Vbottom tank through a 10-inch-diameter HDPE pipeline to the pilot study area.

Makeup water for the thin cover slurry was obtained from two 6-inch-diameter pumps located at the western terminus of the causeway; the pump intakes were placed in Purvis Creek at the end of the causeway. The intakes for the pumps were attached to floats to keep each intake approximately 1 foot below the water surface. This configuration allowed slurry to be placed during most tidal conditions, but brief shutdown periods occurred around low tide when there was insufficient water depth in Purvis Creek. Once the slurry was pumped to the pilot study area, the TLC was placed using an excavator to direct the slurry flow through either a slurry sled or a mushroomstyle attachment (Figure 7). Depending on the...
Figure 10. Photographs showing the increase in percent cover for Grid A2 at each six-month monitoring event as anticipated.

Table 2. Data quality objectives, monitoring programs, and associated metrics.

<table>
<thead>
<tr>
<th>Data quality objective</th>
<th>Data collection and monitoring program</th>
<th>Evaluation metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>DQO 1: Identify potential impacts of thin cover material placement on vegetative recovery of the marsh</td>
<td>Field observations during thin cover application and aerial surveys</td>
<td>Comparison of percent cover to reference areas</td>
</tr>
<tr>
<td>DQO 2: Evaluate marsh recovery processes following thin cover placement</td>
<td>Habitat assessment for percent cover with aerial photography and fiddler crab burrow density</td>
<td>Comparison to marsh conditions in reference areas</td>
</tr>
<tr>
<td>DQO 3: Identify effectiveness of thin cover placement for meeting surface weighted average concentration (SWAC) goals</td>
<td>Vertical profiling of sediments before and after thin layer placement</td>
<td>Evaluation of contaminant flux with vertical sediment profiles</td>
</tr>
<tr>
<td>DQO 4: Evaluate differences in marsh grass response to sand materials in comparison to existing fine sediments</td>
<td>Habitat assessment for percent cover and vertical profiling of sediments before and after thin layer placement</td>
<td>Evaluation of sediment core monitoring for stability, comparison of regrowth of existing marsh grasses, contaminant fluxes calculated from sediment concentrations</td>
</tr>
<tr>
<td>DQO 5: Evaluate stability of placed cover material, and assess surficial contaminant concentration following cover placement</td>
<td>Vertical profiling of thin cover material and sediments; monitoring of tracers placed prior to thin layer placement</td>
<td>Evaluation of sediment cores and presence of tracers for thickness and stability (where applicable), and vertical profiling of sediment chemistry</td>
</tr>
</tbody>
</table>
Table 3. Habitat assessment program.

<table>
<thead>
<tr>
<th>Pilot study location</th>
<th>Analyses</th>
<th>Habitat metrics</th>
<th>Location</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area A*</td>
<td>Vegetative percent cover</td>
<td>Comparison to reference areas</td>
<td>Two fixed plots of 1 square meter within both subareas (total of four plots)</td>
<td>Prior to thin layer placement; 12, 18, and 24 months after placement</td>
</tr>
<tr>
<td></td>
<td>Vegetative species diversity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fiddler crab burrow density</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fiddler crab burrow depth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area B*</td>
<td>Vegetative percent cover</td>
<td>Comparison to reference areas</td>
<td>Two fixed plots of 1 square meter within both subareas (total of four plots)</td>
<td>Prior to thin layer placement; 12, 18, and 24 months after placement</td>
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<tr>
<td></td>
<td>Vegetative species diversity</td>
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<td>Fiddler crab burrow density</td>
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</tbody>
</table>

Note: Refer to Figure 6 for locations of study areas.

type of the material placed, SES used two types of slurry discharge points to act as a diffuser during thin cover placement: a slurry sled with discharge nozzles and an open-ended pipe fitted with a mushroom-style attachment.

**Sand placement**

Thin cover slurry placement for the sand portion of the pilot cover was primarily completed using a slurry sled. The primary advantage of the slurry sled is the ability to increase the broadcast length of the slurry; the thin cover slurry could be placed ("rainbowed") up to 100 feet from the discharge point of the sled. The sled consisted of a steel fitting to reduce the diameter of the pipeline from 10 inches to 4 inches. The sled directed the slurry through a steel pipe to another reducer, which discharged the slurry through two 3-inch-diameter nozzles with a 40-degree angle to direct the slurry upward as it exited the pipeline. The nozzles could be angled in any direction and the sled platform directed by the excavator to modify the distance of the slurry and the thickness of the thin cover placement as needed.

Initially, the two nozzles were angled straight upward on the slurry sled so that the slurry was placed in two immediately adjacent streams. After operating with this orientation for one day, SES angled the nozzles toward each other at 45 degrees so the slurries from the two nozzles met and formed a single stream. The contact of the two streams caused turbulence in the slurry stream that reduced placement energy and dispersed the slurry spray, resulting in gentler and more even placement of the cover material. The slurry sled was effective in placing the sand portion of the TLC in the pilot study area, but it was less effective in placing the fine-grained material because debris (primarily root matter) in the fine-grained material frequently blocked the slurry sled pipe. Each plugging of the slurry sled required a shutdown of several hours to locate and remove the blockage. Therefore, the slurry sled was only used on a limited basis during fine-grained material placement.

**Fine-grained material placement**

As noted, the slurry sled was used on a limited basis because root matter in the fine-grained material frequently blocked the sled pipe. In lieu of the slurry sled, an open-ended pipe was used, with the open end held vertically and the slurry discharging from the end of the pipe approximately 4-6 feet above the surface of the marsh.

During the first day of TLC placement, it was observed that the energy of the placement was sufficient to displace previously placed cover materials adjacent to the slurry pipeline. SES outfitted the end of the open-ended pipe with a steel plate to create a mushroom-style attachment. To minimize the energy of the discharge, the open end of the pipe was held vertically, and the steel plate was affixed approximately 6 inches above the end of the pipe. Slurry discharged from the pipe contacted the steel plate, which reduced the slurry's momentum and energy and distributed the slurry evenly in a 360-degree pattern around the discharge point.

Because the open-ended pipe had the same 10-inch diameter as the slurry pipeline, blockages did not occur at the discharge point. For this reason, mushroom-style placement proved to be the more effective method for fine-grained material. The slurry sled was still necessary for placing fine-grained material at the westernmost and easternmost ends of the pilot study area because the distance of the slurry placement via the mushroom attachment was limited by the length of the excavator reach from the HDPE mat roadway. Using either placement technique (sled or mushroom) during the fine-grained material placement, significant turbidity was observed in the surface water exiting the pilot study area. The turbidity consisted primarily of the TOC portion of the fine-grained cover material, which settled poorly and often not fast enough to remain in the pilot study area before draining to Eastern Creek.

**Water quality controls**

To minimize the amount of TLC material moving from the pilot study area to adjacent creeks via surface drainage, a berm of hay bales was constructed around the pilot study area (except adjacent to the HDPE mat road) to act as a natural filter. Two 4-foot stakes were driven through each bale to hold it in place. A silt fence was installed between Areas A and B to separate the two types of cover material and limit overlap in placement. If the surface water level in the pilot study area was near the top of the hay bale berm at or near high tide, placement was postponed until the surface water level dropped to approximately 1 foot below the top of the berm.

During installation of the sand portion of the pilot cover, the hay bale berm was observed to be generally effective at retaining the cover materials during placement. During installation of the fine-grained materials, however, significant turbidity was observed entering Eastern Creek from the pilot study area primarily through two natural drainage points at the east end of the area and underneath the HDPE mat road where hay bales could not be placed. This turbidity appeared to consist primarily of the
slurry’s topsoil material, which tended to float after hydraulic placement. Organic turbidity often benefits marsh systems by adding short-term natural nutrient loads that are oxygenated by the slurry transport and energy dissipaters used in the TLC placement process (USACE 2007).

**Confirmation of placement**

Quality control measures were performed to monitor the precision of the TLC placement and evaluate whether design and construction criteria were viable and were met. Prior to and during the TLC placement, environmental controls were established to protect existing drainage systems within the marsh and limit impacts to the surrounding areas. TLC material placement was verified through the collection of core samples.

During TLC placement, SES used grade stakes, like those used in upland grading and fill earthwork, placed at regular intervals in the pilot study area to guide cover placement to the appropriate target thickness. Once SES believed that the target thickness had been met, Anchor QEA used 2-foot-long, 3-inch-diameter clear polycarbonate tubes to collect core samples and measure the cover thickness. Each core tube was handpushed through the cover material into the native marsh underneath. The core tube was then filled with water and capped to create vacuum pressure. The core sample was retrieved, and the thickness of the cover material was measured. If the cover material in the core sample did not meet minimum thickness requirements (6 or 9 inches of cover material, as appropriate), additional cover material was placed, and another core sample was advanced in the same location. A minimum of six core sample locations were measured from each of the four quadrants of the pilot study area.

**Supplemental data collection**

Additional data were collected for the slurry operation to inform the future engineering design. Approximately 615 cy of sand and 627 cy of fine-grained material were placed in the pilot study area. Production rates were 63 cy per hour for sand and 40 cy per hour for fine-grained material. The lower production rate for the fine-grained material was due primarily to the increased downtime from pipeline blockages during the fine-grained material placement. For a full-scale operation, screens will be added to remove materials that might clog the sled spray nozzles. Active slurry placement occurred during approximately 32% of total work time, with downtime primarily caused by slurry pipeline blockages, postponement of cover placement due to high tide and low tide, and downtime to allow for confirmation core sampling in the pilot study area.

**Site restoration**

Site restoration activities were completed in the marsh areas outside the pilot study area that were disturbed during construction. These activities included removing the hay bales surrounding the pilot study area, removing the temporary HDPE mat road and the temporary bridge connecting the causeway to the pilot study area, and replanting areas of the marsh affected by the HDPE mat road and pontoon excavator tracks.

Smooth cordgrass is the dominant plant species throughout the tidal marsh and was the dominant plant species in the areas affected by the pilot TLC installation. The smooth cordgrass plants used for restoration were procured from a commercial native plant supplier, Aquatic Plants of Florida, and were approximately 2-inch-wide and 5-inch-deep container stock. Approximately 9,750 plants were installed using dibble bars or hand tools on 2-foot spacing. The replanted areas covered approximately 2/3 acre. After the smooth cordgrass was planted, herbivory protection measures were installed to protect the new plants from predation. Herbivory protection consisted of a chicken wire fence around the perimeter of the replanted areas and jute twine installed between stakes over the replanted areas, with reflective mylar tape affixed to the jute twine at regular intervals to

![Figure 11. Photograph of TLC pilot areas after two seasons (approximate extents outlined for reference).](image-url)
discourage birds from entering the re-planted areas.

Post-placement monitoring results

Data to assess marsh recovery were collected at six months, 12 months, 18 months, and 24 months after TLC placement using a combination of surveys, aerial photographs, and in situ sampling (sediments, fiddler crab burrows and vegetation type and density). Figure 10 shows the vegetative recovery progress over time, and Figure 11 shows an aerial photograph of the pilot study area two seasons after TLC placement.

A review of the monitoring data reveals that all the goals of the pilot study were achieved:

- Chemistry results in all four quadrants were below EPA risk-based restoration goals.
- Vegetation regrew in TLC placement areas and continues to expand, as anticipated.
- The marker layer at the base of the TLC remains intact, indicating overall cover stability and no vertical mixing of underlying sediments.
- Fiddler crabs recolonized the TLC areas and burrow depths are similar to pre-placement burrow depths.

These results are being incorporated into the final engineering design for the site. Given the process needed for the overall engineering design and the requirements of the project schedule, full-scale implementation is expected to begin in late 2022.

LESSONS LEARNED

Although the pilot was a successful program, it was not without lessons learned and identification of key areas that need to be incorporated into the full-scale designs and construction. Material thickness controls were successfully maintained in the field and were generally within the 3-inch allocated placement tolerance, indicating good placement control. A 30- to 45-degree spray yielded the best distribution of materials for the equipment used. Sandy material was placed faster and more uniformly than fines due to its enhanced settling characteristics and ease of distribution. Using a baffle plate to place a modified mix of topsoil and fines eventually permitted placement of fines within the study area while maintaining the target organic content, but increased runoff of material. The mat-based access road initially experienced some settlement due to loading and required restoration following project completion. For full-scale construction, additional mats creating a wider, lower ground pressure working platform could be built. Physical, chemical, and vegetative monitoring conducted at six-month intervals over two years indicated strong natural recolonization of vegetation and the re-establishment of fiddler crabs. Some of the key takeaways from the TLC placement include:

- Portions of the marsh could not support the use of a low-ground-pressure pontoon excavator. Detailed geotechnical studies with high sample density should be performed as part of the design to evaluate the load-bearing capacity of key marsh locations and variability within the system. Alternate access approaches should be considered during design to minimize equipment requiring marsh access or to distribute machine loads, such as the HDPE mat roadway used during the pilot study.
- Low-density materials for TOC were difficult to place effectively due to their tendency to float and be carried away from the target area by surface water from the slurry system. Alternate sources of TOC should be considered, if including organic material in the TLC is needed.
- Debris in the cover material (primarily root matter in the TOC-containing material) caused significant negative impacts to production due to frequent plugging of the slurry pipelines, which took time to identify and clear. Ideal source material for the thin cover would be loose, friable, and free of root matter, debris, and other deleterious materials. A shaker screen may be required prior to the slurry tank to remove of large pieces of debris.

- TLC material placement was enhanced by increasing the dispersion of the slurry as it exited the slurry pipeline. For the slurry sled, angling the two slurry nozzles at a 45-degree angle so the slurry streams crossed increased dispersion of the spray and resulted in gentler and more even placement. For the mushroom-style placement, the addition of a steel plate reduced the energy of the slurry, preventing the slurry from displacing previously placed cover materials.

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REFERENCES


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REFERENCES


Can sea level rise help us restore coastal wetlands? The hydrologic restoration of the Slop Bowl, Brazoria National Wildlife Refuge, Texas

By

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ABSTRACT
The Slop Bowl marsh in the Brazoria National Wildlife Refuge provides extraordinarily high quality, heavily used bird habitat. Much of this habitat has experienced hypersaline conditions due to both hydrologic alteration by humans and a rapidly and changing physical environment over the past several decades. Oil and natural gas extraction activities have resulted in excavation and channelization along pipelines and hydrologic obstruction by an access road. In addition, subsidence along growth faults has altered hydrologic pathways and lowered surface elevations in the center of the marsh. Our objective was to understand the underlying processes that contribute to hypersaline conditions and to evaluate possible restoration alternatives to reduce the severity of those conditions. Accordingly, we conducted extensive field and hydrologic modeling efforts, and identified the past, present, and future of this marsh habitat under a baseline scenario. We then compared various restoration action scenarios against this baseline. We found that, beginning in about 15 years, relative sea level rise will improve the hydrologic conditions by enhancing tidal flushing. However, if fill material is continually added to elevate the obstructing road as the sea rises, this hydrologic relief may never be realized. Moreover, we found that if a drought occurs during this critical period, a difference of only a few centimeters in the relative water level and road elevation, or changes in marsh surface elevations driven by fault motion and subsidence, may have catastrophic consequences. The modeling also suggests that several potential interventions can bridge this gap over the next 15 years and beyond. Actions that improve tidal circulation, reduce salinity, and enhance marsh accretion are being developed by the project team to enhance and restore habitat in the near term. The most optimal approaches evaluated thus far include the installation of culverts at critical locations, the excavation of a small channel, the modification of flow pathways, and the beneficial use of sediments and vegetative plantings. We conclude that, under specific circumstances or at unique locations such as the Slop Bowl marsh, sea level rise can be leveraged to improve coastal wetland health.

Relative sea level (RSL) rise is generally thought to negatively affect the sustainability of coastal wetlands. When the sea level rises faster than the wetland surface vertically accretes, due to sedimentation and vegetative growth, the relative elevation of the wetland drops in the tidal frame and erosion and vegetation transition can occur (Morris et al. 2002; Kirwan and Megenigal 2013). However, RSL rise can also increase wetland area (Feagin et al. 2010; Schuerch et al. 2018) or cause shifts in the patterns of vegetation while maintaining the overall area (Kulawardhana et al. 2015). Here we show that, when wetland restoration and management activities are properly planned, RSL rise can enhance hydrologic flows and reduce the occurrence and severity of hypersaline conditions. Our study takes place in the 1,350-acre Slop Bowl marsh at the southern end of the Brazoria National Wildlife Refuge in Brazoria County, Texas (Figure 1). This area has been known historically for the heavy utilization of its extraordinarily high-quality habitat by waterfowl, shorebirds, wading birds, wood storks, and reddish egrets, a species listed in Texas as endangered.

The Slop Bowl landscape has been subsiding since the 1940s (Feagin and Huff 2018). Hydrocarbon extraction (White and Tremblay 1995; Dokka 2006; Chan and Zoback 2007), fluid injection (Ellsworth 2013), and exploration activities in general can lead to growth fault-driven subsidence (Feagin et al. 2013). Growth faults are a specific type of normal fault, commonly found in depositional basins like the western Gulf of Mexico. At depth below the surface, their fault plane often intersects and is associated with large hydrocarbon deposits. As hydrocarbon deposits are removed, pore pressures can drop and hydrocarbon reservoirs can collapse, triggering motion at the fault plane. Hydrocarbon extraction activities have been hypothesized by White and Morton (1997) as a cause of wetland loss at this location. At least five apparent faults have been visually identified here. Notably, several active hydrocarbon production and injection wells are co-located with them (Feagin et al. 2021).

An access road known as Oil Rig Road surrounds the Slop Bowl and restricts tidal flow into and out of the marsh (Figure 2). Excavation and channelization along pipelines have also interrupted hydrologic flow patterns. Fault-driven differences in elevation across the landscape have also negatively impacted flows.

Today, the conversion of marsh into open water is accelerating, and refuge managers are concerned about the long-term future. Water in Essex Bayou and the Slop Bowl is often hyper-saline (>45 ppt, or >66 mS/cm at 25°C). Salinities have

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become so high vegetation and aquatic life are stressed, particularly during prolonged periods of high temperatures, low tides, and low rainfall. The site includes several hundred acres where highly saline water has been trapped multiple times for extended periods, killing vegetation, preventing the re-establishment of plants, and accelerating the conversion of marsh into open water.

Our objectives were to understand the underlying processes that contribute to the development, occurrence, and severity of these hypersaline conditions and to evaluate possible restoration alternatives to reduce them and their impacts. To achieve these objectives, we conducted extensive field work and created a hydrologic model to identify the past, present, and future of this marsh habitat. We carefully included the effect of rising relative sea level and the relative elevations of the marsh surface. We then used the modeled outputs to create an action plan for restoring the wetland’s hydrology.

**METHODS**

**Data collection: Sensor setup**

We deployed sensors throughout the Slop Bowl study area to measure salinity, water level, flow velocity, and precipitation (Figure 1A). We first placed 10 conductivity (note: conductivity is the physical surrogate for measuring salinity), temperature and depth (CTD) sensors, recording measurements every hour from 27 April to 19 September 2017, to obtain a general understanding of how water level and salinity interacted across the study area. This time period contained both wet and dry periods, with precipitation close to the monthly averages until 24-30 August 2017 when Hurricane Harvey deposited a large amount of precipitation. Measurable storm surge also occurred during this event.

We deployed a second sensor array from 3 October to 23 November 2018, to better understand water flow in the main channel of Essex Bayou leading into and out of the Slop Bowl (Figure 1B). This time period was relatively wet. This array consisted of two CTDs, one rain gauge (HOBO Pendant tipping bucket), and one Acoustic Doppler Current Profiler (ADCP, Nortek Aquadopp HR profiler). One CTD was in the center of the channel at a depth of approximately -0.133 m relative to North American Vertical Datum of 1988 (NAVD88), and the other was attached to a buoy floating above it. The CTD and the rain gauge recorded measurements every hour.

The ADCP was located immediately adjacent to these CTDs, on the bottom of the channel. Water flow direction and velocity were recorded by the ADCP for 2 minutes at the beginning of each hour, at a sample rate of 1 Hz, within 88 vertically arrayed bins each 1 cm in height. The bins were averaged to provide the average velocity per hour for the entire water column. The flow direction for each hour was determined based on the direction measured for most bins; flow was characterized as either toward the Gulf Intracoastal Waterway (GIWW) or into the Slop Bowl. Flow direction and velocity were also calculated separately for the top and bottom halves of the water column and compared with the salinity data recorded by the top and bottom CTDs.

It should be noted that throughout the text, we do not describe relative water level or tidal prisms at a given location in terms of Mean Sea Level (MSL), Mean High High Water (MHHW), or other similar descriptions. These descriptions are typically used at a gauge that is located in a body of water that is well connected to the ocean, and they are statistical assessments of the water level at that gauge only. In hydrologically disconnected or recessed water bodies, the water level often does not follow a regular tidal beat and the prism is skewed and dependent on time of record, and so these descriptions are not particularly useful.
Moreover, these descriptions cannot be transferred from one location to another in a complex hydrologic environment. For these reasons, we do not use these descriptions, but rather present water level in NAVD88 units and leave the interpretation of the tidal prism to the reader based on the recorded and graphically-presented data.

**Data collection: Basin geography**

We surveyed the Essex Bayou channel bathymetry at the location of the second array, all sensor locations from both arrays, and the topography along the adjacent Oil Rig Road. The channel data were used to produce a two-dimensional cross-section. At the road, we focused particularly on its lowest portions because they are where a rising tide would first exceed its base elevation and spill into the central Slop Bowl. All surveys employed a survey-grade global navigation satellite system (GNSS) and theodolite leveling. The GNSS survey was conducted on 21-23 May 2019, using the real-time kinetic (RTK) with infill style with two Trimble R10s and a Trimble TLD 450 radio. Data were post-processed through a Trimble Center Point RTX to calculate all baselines. Final point locations were set into Universal Transverse Mercator (UTM) NAD83 Zone 15N in meters, with the vertical datum set as GEOID12A, NAVD88 in meters. The survey achieved an average vertical error of <3 cm. Theodolite leveling introduced an additional 5 cm of vertical error to the height of ADCP1/CTD 6. All other points did not involve theodolite leveling and came directly from the GNSS survey alone.

We next acquired light detection and ranging (LiDAR) elevation raster imagery from 2017 (dataset from the Federal Emergency Management Agency via Texas Parks and Wildlife Department) and referenced it with the field data sets by measuring the vertical offset between the LiDAR-derived elevations and survey point-derived elevations. These points were located along the side of Oil Rig Road, and their average offset was used to adjust the LiDAR vertically. The elevations of these points were assumed to have not changed since the image was captured, although in the intervening time subsidence had likely occurred and some gravel had been deposited on the road.

We also delineated the watershed basin that drained into the Slop Bowl and calculated its area (Figure 1C). This work was conducted in a GIS by digitizing the watershed boundaries by hand, using expert knowledge of the area and the LiDAR dataset. The total watershed area, which did not include Essex Bayou, was 6,784,523 m². In the north and northwest, elevated ridges along Ridge Slough delineated the boundaries of the watershed. In the west, southwest, and south, higher elevations in upland areas delineated these boundaries. In the southeast, east, and northeast (i.e. in the lower tidal areas), Oil Rig Road blocked water flow into the central Slop Bowl Basin unless water levels were relatively high. This edge of the bounded watershed could be exceeded only by extremely high tides. For this reason, we investigated this barrier further with hydrologic modeling.

**Data exploration and water budget calculations**

We analyzed the acquired datasets to investigate several initial questions about the hydrology. We first hypothesized that there were three primary sources of water available to the central basin of the Slop Bowl: inflowing tidal water arriving via Essex Bayou, inflowing freshwater arriving from local precipitation or runoff within the watershed, and inflowing tidal water arriving during high water via breaches in the road.

To determine the volume of water that flowed through the Essex Bayou channel in any hour, the flooded cross sectional area (found when the water level measured by CTD 6 was referenced relative to the surveyed cross section) was multiplied by the average velocity measured at ADCP1 for that hour. This volumetric flow was assigned a direction for the hour,
either south toward the GIWW or north into the Slop Bowl.

We also found the imbalance, or the net flow quantity of Essex Bayou going in the downstream direction, by subtracting the Essex Bayou inflow from its outflow (Figure 3). This value was calculated for the 3 October to 23 November 2018 record. Next, the area of the portion of the watershed that fed into the Slop Bowl was multiplied by the recorded precipitation per hour to estimate the volume of freshwater inflow due to local precipitation and runoff for the same period. This calculation assumed there was no storage time for the precipitation and it ran off immediately into the central portion of the Slop Bowl. It also assumed there was no net loss of precipitation via infiltration, nor evaporation, and any additions into the soil were considered to migrate through the subsurface and into the central portion of the Slop Bowl. Although this would not be the case in the real world, it was considered adequate over the aggregated time scale at which we built the water budget. Still, the model potentially underestimates salinity in the central Slop Bowl because, in reality, this fresh water may be captured upstream or in upslope soils within the watershed.

We did not have a measure of the water volume that arrived via breaches in Oil Rig Road, so we subtracted the volume of freshwater inflow from the imbalance to find the quantity that was not readily explained by the two datasets. The difference was assumed to be the tidal volume that flowed over the top of the road during high tides for the period of record. This calculation assumed that when water levels exceeded the lowest road elevation, the excess water volume moved freely in and out of the Slop Bowl over breaches in the road. The calculation also assumed that, after this flooding concluded and the water dropped below the lowest part of the road, the flood water was forced to exit downstream through Essex Bayou as the water level continued to fall.

Using the various datasets and calculations as starting points, we then asked the following questions:

1) Is water flow in the Slop Bowl restricted, and is restriction affecting salinity?

2) Is there a vertical salinity gradient in Essex Bayou?

3) Can the water flow in Essex Bayou be calculated as a function of hypothesized inputs to the Slop Bowl?
4) What was the relative magnitude of inflowing water that breached the road?

**Slop Bowl model**

We next developed a model focused on predicting the salinity at the interface of Essex Bayou and the Slop Bowl, where ADCP1/CTD 6 were located. The model predicts conditions in other locations of the study area as well, but this location was used for calibration, validation, and as the primary location for simulations. The model was written in the Python programming language.

Water in the model persisted in and was traded among these three compartments based roughly on elevation and geography (Figure 1c, Figure 4):

1) **Essex Bayou.** This compartment contained the relatively deep channel and had a surface area of 53,881 m². Essex Bayou is quite long (approximately 2,800 m) and thus acted as a time-delay mechanism for water moving between the GIWW and the lower portions of the Slop Bowl. The length of this time delay affected the rate at which salinity could change in the next higher compartment.

2) **Subtidal channels inside the Slop Bowl.** This compartment had a surface area of 104,297 m² that was always underwater. (The total area of the Slop Bowl was 292,399 m².) It represented the salinity of the water in the main portions of the Slop Bowl.

3) **Flats inside the Slop Bowl and higher elevation areas.** This compartment included all areas that had intermittent water coverage, whether they were intertidal vegetated, unvegetated salt flats, or vegetated high marsh areas. The surface area varied depending on the water level, from 0 m² at its lowest to a maximum of 6,680,226 m² at its highest (across the entire watershed area, excluding compartments 1 and 2).

The model moved water of different salinities across the three compartments. When the tide was rising at ADCP1/CTD 6, the model moved water out of Essex Bayou (compartment 1) and into the subtidal channels of the Slop Bowl (compartment 2), where it mixed with water already there. To meet the water level deficit then created in compartment 1, the model pulled in from the adjacent GIWW water whose salinity was approximately 54 mS; this value was based on the average GIWW water salinity recorded at CTD 1 from 27 April to 19 September 2017. Once the water level in compartment 2 exceeded the maximum elevation of this compartment, any additional water spilled onto the flats inside the Slop Bowl and higher elevational areas (compartment 3) and additional salinity mixing occurred. When the tide dropped, the process reversed.

Evaporation and precipitation in each of the three compartments was based on their respective surface areas, and the water volume and salinity accordingly changed in each. All precipitation that fell outside the three compartments, but inside the watershed, was added to compartment 3 alone. There was no time delay in this runoff process. This assumption was considered reasonable at the aggregated time scales over which the model was intended to be used. The salinity of all precipitation and runoff was set at 0 mS. For quantifying the salinity and its relationship to evaporative processes, we used salt mass per water volume. This representation allowed the freshwater portion to be incrementally removed or added, while leaving the salts, thereby altering the salinity of the remaining water.

The model had three possible inflow sources: Essex Bayou tidal water, precipitation and freshwater runoff, and road-breaching tidal water. All outflow was forced down Essex Bayou, except when the water level exceeded the elevation of Oil Rig Road and the water could also exit over the road.

The volume of Essex Bayou tidal water entering the Slop Bowl was driven by NOAA’s longterm, observed water level records at the Freeport tidal gauge station.
The volume of precipitation and runoff entering the system was driven by NOAA’s National Climatic Data Center (NCDC) long-term precipitation records at the San Bernard National Wildlife Refuge weather station (station ID: USC00417957; records available from 1984 to present). Although this location is approximately 22 km away to the west, precipitation does not vary greatly in this part of Texas due to the lack of orographic effects. The hourly precipitation was multiplied by the surface area of each compartment, and this 0 mS salinity water was added to that compartment. As described earlier, compartment 3 also included the runoff from the entire watershed above it, regardless of its current water surface area.

The volume of tidal water that entered the system by breaching Oil Rig Road was driven by the same modeled water level for Essex Bayou discussed above. When the predicted water level exceeded the minimum road elevation, we increased the water volume coming up from Essex Bayou by 1.5 times and then input this incoming water into compartment 2. Water filled compartment 2 until it exceeded the maximum elevation of these tidal channels, and then began filling compartment 3. The decision to use a factor of 1.5 was based on the determination that Oil Rig Road-breaching volumes were of this magnitude compared to those of Essex Bayou (the water budget calculation found that approximately 2.6 million m$^3$ of water came in from this direction as compared with approximately 1.9 million m$^3$, as we describe in greater detail below).

Water evaporation rates were driven by NOAA’s NCDC long-term records from Angleton, Texas (station ID: US1TXBRZ021; records available from 1954 to present), approximately 22 km away to the north (evaporation was not available from the San Bernard station mentioned above, and the Angleton station had data gaps in precipitation records, thus explaining the use of these two separate stations). Evaporation and temperature do not vary strongly in this portion of Texas. We first took the average evaporation rate per month and statistically regressed it against the average temperature per month from 1954 to 2018. The slope and intercept of the linear fit ($y = 158.75x^2 + 23356x - 0$, $R^2 = 0.998$) was then used to predict evaporation with a given temperature as input.

### Slop Bowl model validation and simulations
All model runs began in the year 2006 and ended in 2061. Model inputs included NOAA water level, NCDC precipitation, and NCDC temperature. NOAA water-level historical data through 2006 were available via download, and this is...
the reason for our chosen start date. We chose to use observation-verified data from 2006 to 2020 and iterated them to obtain future predictions because they included the true water-level deviations that occurred due to wind-driven tides along the Texas coast. Although future predicted astronomical water levels are also available from NOAA, they generally cover only approximately 50% of the overall tidal signal in coastal Texas (Huff et al. 2020).

To appropriately model sea level rise, we increased the water level for future dates an average of 5.7 cm per decade based on Freeport tidal gauge trends (obtained by statistically regressing water level against time and then determining the linear slope of the trend line). Thus, mean sea level slowly increased hourly over the period of the model. This value subsumes eustatic, isostatic, and subsidene components of RSL rise, because it originates from the nearby Freeport gauge. For precipitation, we used the historical data from 2006 to 2020 that we downloaded and then iterated into the future (taking these data and concatenating them approximately every 14 years until 2061). We did the same for the temperature records, but we increased the temperature an average of 0.32°F per decade based on NOAA predictions (NOAA 2019). This value is similar to the median predicted by the Intergovernmental Panel on Climate Change (IPCC 2018) for the time period of our model runs. Thus, evaporation also slowly increased hourly over the period of the model.

Water levels in compartments 1 and 2 were initialized at the average water level from our records (based on the data from 27 April to 19 September 2017), and the salinity was set at approximately 54 mS. Compartment 3 did not contain water.

To validate the model (Figure 5), we compared its predicted water level and salinity to our empirical records from CTD 6 for 27 April to 19 September 2017. We found that the overall and apparent trend suitably captured the aggregated trends at weekly time scales, but in general the salinity was overestimated at lower water levels and underestimated at higher levels. The relative amount of overestimation or underestimation was primarily due to bias in the model caused by the water volume; when there was little water, the salt concentrated and salinity went up, but our calibration over-estimated the rate at which this happened. Another interesting feature was that the model broke from this trend in June; this occurred due to complex interactions among the various driving variables, as well as exchanges among the compartments as they passed water of varying salinities through time.

Figure 7. Future sea level rise is expected to decrease the number of hours exceeding 60 mS in Essex Bayou, the Slop Bowl channels, and the flats.

Figure 8. Restoration actions and their effect on mean salinity over the 2011 drought and 2022 timeframe. A severe drought with low precipitation and water level occurred during 2011. The 2022 event is modeled as a similar event. EX = Essex, BC = subtidal Slop Bowl channels, and flats = flats inside the Slop Bowl.
To further validate the model, we compared the model-predicted water level with historical imagery to assess whether the marsh had indeed flooded to that level. We first identified the acquisition date of each image. Then, we found the average model-predicted water level on that date and “flooded” the LiDAR image to the corresponding elevation. The historical image was then visually compared to the flooded LiDAR image. Where the two images appeared to deviate, we selected reference points along the uppermost edge of the flooded LiDAR image, then compared each point’s elevation to the model-predicted water level and calculated the difference. We found the average difference to be 4 cm across all images. We considered this difference relatively small, given that the model-predicted water level had been averaged over 24 hours to match the date of the historical imagery. Overall, we considered the model to be a valid representation of real-world conditions, particularly at aggregated time scales of months to years.

Using the validated model, the following questions were explored:

1) How will future relative sea level rise affect water level and salinity?

2) Can potential management actions reduce salinity between now and 2061? Could these actions have reduced salinity during the extreme drought of 2011? Will management actions reduce salinity if a similar drought happens in 2022 or later? Could these actions have reduced salinity during the extreme drought of 2011? Will management actions reduce salinity if a similar drought happens in 2022 or later?

RESULTS

■ Is there a vertical salinity gradient in Essex Bayou?

We found evidence that the channel in Essex Bayou has a vertical salinity gradient and that a saltwater wedge migrates up and down its length. During rainy periods, outflowing freshwater moved mainly along the surface of Essex Bayou while the bottom remained saline. During dry, hot periods, like one from 29 June to 13 August 2017, a pool of saline water up to 120 mS lay at the bottom of Essex Bayou (Figure 6).

■ Can the water flow in Essex Bayou be calculated as a function of hypothesized inputs to the Slop Bowl? What was the relative magnitude of inflowing water that breached the road?

We found the imbalance between water inflow and outflow in Essex Bayou to be approximately 3.9 million m$^3$ in the downstream direction (Figure 3) during the high-precipitation period of 3 October to 23 November 2018. Freshwater inputs from precipitation and runoff contributed approximately 1.3 million m$^3$ of this imbalance. We estimated the remainder — the net inflow contribution from tidal water that breached Oil Rig Road — at approximately 2.6 million m$^3$.

The tidal inflow from over Oil Rig Road was a relatively large and important source of water, roughly the same volume as the tidal inflow arriving via Essex Bayou (i.e. 2.6 million versus 1.9 million m$^3$). Ultimately, however, we did not capture the quantity of freshwater inflow that could be lost over the road during these extreme tide events (because we did not have a method that could identify it separately from the overall mixed water body, and yet we know that salinity tends to be stratified by depth and that the freshwater lies primarily on the surface, in general). In other words, does the water that exits over the road originate solely from tidal water that earlier had entered over the road, or could it also come from freshwater inflow/precipitation? Our calculations assume it is all tidal water that entered into the system either from over the road or from Essex Bayou. This lost quantity could increase the relative amount attributed to over-the-road tidal inflow. Alternatively, for high-water events that exceeded the calculated dimensions of the Essex Bayou cross section, more water could have been exiting and entering via this route than was otherwise tied up in the imbalance. Given the available data, however, we considered the water budget a reasonable estimate of the relative magnitude of each of the three components over the aggregate timescale of the record.

■ How will future sea level rise affect water level and salinity?

The model showed that future sea level rise will increase the water level, which will reduce salinity over time at ADCP1/CTD 6, the intersection of Essex Bayou and the Slop Bowl (Figure 7). In a hydrologically restricted location, where salinities are high due to infrequent tidal flushing and the evaporation of trapped saltwater, a rising water level can enhance tidal connectivity. In this manner, rising sea levels can reduce salinity by providing a hydrologic mechanism that mediates the concentration of salt in these areas. The high spike in water level approximately every 14 years (Figure 7) was due to the iteration of the past dataset into the future and included the effects of Hurricane Ike-like events in the future. The several instances of low water level were due to similar iteration and related to extreme low-water events during drought years, particularly during summers. The model represented the 2010-2012 drought well, estimating that the salinity spiked over 100 mS for nearly two months in 2011.

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As the average water level increased in the model, several hydrological features were altered in Essex Bayou, the subtidal channels inside the Slop Bowl, and the flats. First, the tidal volume of 54 mS water that entered all three compartments from the GIWW increased. Second, high-water events drove water to flow over the Oil Rig Road into the subtidal channels of the Slop Bowl and flats more often and for longer periods of time. Third, and as a result, more water exited downstream via Essex Bayou. The net result for all three compartments was to increase the water exchange volume and to decrease the salinity.

- **Can potential management actions reduce salinity?**

With the single 7.5 m wide box culvert added into the model, where water was allowed to freely exchange under the road down to 0.2 m NAVD88, salinity was greatly reduced in the Slop Bowl channels for the hindcasted drought of 2011 (Figure 8). It should be pointed out that the model assumed that this single culvert provided full connectivity and was not restricted by flow rate (a reasonable assumption given that tidal flows are relatively slow, minus the potential for erosional scouring in real-world application). For the 2022 forecast period, the culvert reduced the salinity by only approximately 2 mS as compared to taking no action. The 2022 period had the same poor drought conditions as the 2011 period, but with warmer temperatures and a higher mean sea level. The contrast between 2011 and 2022 indicated that RSL rise is likely already reducing the potential negative impacts of extreme drought conditions.

**DISCUSSION**

**Relative sea level rise and hydrologic restoration**

Rising RSL will remediate the hypersaline conditions in Essex Bayou and the Slop Bowl. Under current projections, the average number of hours exceeding 60 mS in the flats is expected to drop by 25% between now and 2035, and by 50% between now and 2050. Thus, the challenge for restoration is to bridge the gap between the poor hydrologic conditions today and the better conditions we expect in the future. We see the next 15 years as critical.

Any deviation from the predicted RSL rise rate, even if only a few centimeters, within that timeframe will likely have large impacts. For example, the model showed wildly different salinity when the same action is taken in 2011 or in 2022; the only difference is a change in relative elevation of approximately 5 cm. It is important to consider that the difference in salinity may be due largely to modeled assumptions about water level. Near-surface faults and fault blocks are changing relative surface elevations at different rates that can easily counteract or amplify this 5 cm difference (Feagin and Huff 2018); therefore, we contend that taking no action is incredibly risky.

Our projections assume that Oil Rig Road will stay at its current elevation. In fact, oil and gas companies are likely to continue to supplement the road’s caliche and rock base over time, thus continuing to raise its elevation and prolonging the problem well beyond the next 15 years.

Using the science that we generated, we next designed a restoration plan to bridge this gap in time (Figure 9). Our plan uses the installation of multiple two-way culverts and the excavation of new water flow pathways to increase flushing of the Slop Bowl. It also takes advantage of the fault locations and differential subsidence, leveraging this altered topography. In additional work that we had conducted but do not present in further detail here, we optimized the depth and locations of these pathways based on predicted hydrologic flow rates and National Wildlife Refuge conservation concerns. We also optimized the location and size of the culverts based on various concerns about the hydrology, predicted fault evo-
ution, road right-of-way, construction costs, and conservation needs.

While RSL rise can be expected to relieve the hypersaline conditions of the Slop Bowl, it will also complicate wetland plant survival. The RSL rise rate at the nearby Freeport tidal gauge, 5.7 cm per decade, is considerably higher than the global average due to regional subsidence. In the Slop Bowl, the potential future rate is further complicated by complex faulting, local and differential subsidence. To alleviate the effects of rapid RSL on the vegetation, the plan could also beneficially use sediments excavated from the new water flow pathways to build mounds and sustain suitable marsh and seagrass elevations in the deeper portions of the Slop Bowl. However even without this additional action, we expect the plan to result in a net benefit to over 1,000 acres of currently degraded wetlands.

Eventually, the Slop Bowl wetlands will convert into open water due to RSL rise. One could identify a projected date for their demise with SLAAM or similar rise. One could identify a projected date and the date of their demise, we still must decide whether we want to:

(A) Allow the hydrologic restriction and hypersalinity to continue, which accelerates the conversion to open water by killing plants and reducing marsh vertical accretion, in addition to reducing the immediate benefit of this critical habitat for several species of birds and fish, or

(B) Hydrologically reconnect this wetland and potentially leverage RSL rise in the near term to help provide a greater habitat benefit, although we know that RSL will inevitably degrade these same benefits over the long term.

RSL rise and marsh loss are inevitable at the Slop Bowl. The only question is whether we want a functional habitat between now and the date of ultimate demise.

CONCLUSIONS

The marsh at Essex Bayou and the Slop Bowl is at a tipping point due to hydrologic restriction and fault-driven subsidence. The Slop Bowl is flat and quite sensitive to RSL rise. Restoration actions can take advantage of RSL by raising the water level in this basin which will result in daily tidal inundation (as opposed to episodes of infrequent flooding and evaporation) and thus moderate its salinity.

Although RSL rise will improve the hydrologic conditions and reduce salinity within the Slop Bowl over the next few decades, restoration action is likely needed to better leverage its potential benefits. At this time, only a few centimeters of error in the modeled water levels, vertical fault motions, or fault block subsidence portend catastrophic consequences for the vegetation and habitats in the Slop Bowl during a “bad” year. Moreover, oil and gas companies are likely to continue to elevate the Oil Rig Road surface, thus making hydrologic restoration necessary in order to leverage the potential benefits offered by RSL rise.

RSL rise will ultimately result in the loss of wetlands at the Slop Bowl in the long-term. However, coastal managers can decide whether they would like a functional habitat in the near-term. Restoration actions can promote tidal flushing, reduce hypersalinity, slow the loss of vegetation, and enhance vertical accretion. Our science-driven design plan includes the installation of culverts at critical locations, flow modification along several flow pathways, the beneficial use of sediments to build suitable elevations in the central portions of the Slop Bowl, and the planting of vegetation in those areas. We expect that implementing the plan will give these currently hypersaline wetlands their best shot at survival.

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