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Systematic Beneficial Use of Dredged Sediments: Matching Sediment Needs with Dredging Requirements

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PURPOSE: This technical note (TN) will outline a framework to identify beneficial and cost-effective coastal beneficial use of dredged sediment (BUDS) projects. Creation of a BUDS framework that can be applied at scale will promote sustainable BUDS practices, facilitating the delivery of flood risk management, social, and environmental benefits while still fulfilling the US Army Corps of Engineers (USACE) navigation mission. This proactive forecasting approach uses multi-criteria decision analysis (MCDA) and optimization tools to balance tradeoffs between navigation dredging and BUDS goals over project-scale timespans. The proposed framework utilizes available tools to quantify ecological system evolution and current and future dredging needs to develop a systems-level approach to BUDS. Required data include current and future information on (1) existing and planned natural and created aquatic ecological systems, which may include natural and nature-based features (NNBFs), (2) dredging requirements and costs, and (3) aquatic system physical and environmental data.

INTRODUCTION: Coastal ecological systems such as beach-dune systems, coastal wetlands, tidal flats, and islands provide several valuable goods and services such as habitat, flood risk management, and recreation. Recent research has worked to quantify the value of these coastal ecosystems (Arkema et al. 2017; Ouyang et al. 2020). Due to these efforts, interest in coastal restoration and resiliency projects has increased in recent years because of the increasing threat of degradation of coastal habitats from sea level rise combined with a history of intensive coastal development. Restoration and creation projects utilizing sediments can be expensive, especially if sediments must be sourced from scarce borrow areas. Beneficially utilizing dredged sediment (DS) from maintenance and new work navigation dredging can potentially provide a much-desired sediment resource for proposed restoration, creation, NNBF, and coastal resiliency projects as well as maintenance of existing projects. However, BUDS is often viewed as cost-prohibitive or unnecessarily complicated, limiting its application in some areas. Indeed, analyzing potential BUDS options on a project-by-project basis is generally difficult and time-consuming so a more systematic approach is required to fully operationalize sustainable BUDS practices.

While not all navigation DS is well-suited for beneficial use, combining modern geospatial tools and process-based ecological models with MCDA and optimization algorithms can facilitate broader use of BUDS in support of coastal restoration and resiliency efforts. Additionally, a cost-effective general framework can provide a systems-level view of how navigation DS can be used to support restoration and resiliency goals currently and into the future. While many tools already exist to predict future dredging requirements, coastal ecosystem change, or to optimize dredging practices using MCDA and optimization algorithms, these tools have not been combined to provide a systematic process for linking sediment needs for restoration and resiliency projects to current and future dredging requirements.

FRAMEWORK FOR ALIGNING COASTAL RESTORATION SEDIMENT NEEDS WITH DREDGING REQUIREMENTS: Figure 1 demonstrates the logic governing the systems framework of developing coastal restoration BUDS. This framework is an extension of the Regional Sediment Management Strategy for BUDS on Construction of NNBF included in Bridges et al. (2015), broadening the scope to include an operationalized method to estimate BUDS sediment requirements for current and future conditions. The framework is designed for use by USACE District operations and planning in conjunction with their non-Federal sponsors to advance BUDS within coastal systems whenever feasible. Note that the framework as presented herein is generalized to accommodate commonly available geospatial data sets and tools. Generally, the framework can be described in four parts informed by the overall system characteristics: (1) the sediment need of the ecological systems of interest, (2) the sediment available through dredging, (3) MCDA to determine the critical criteria and constraints governing dredging and placement, and (4) the optimization of the sediment needed with the sediment available based on associated costs and benefits.

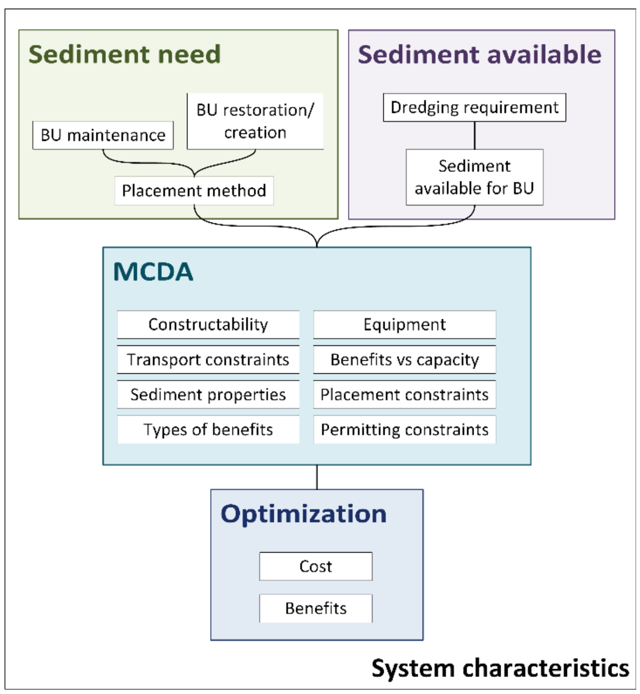

Figure 1. Flowchart showing four parts of the framework and the controlling system characteristics.

The ecological system sediment need must be quantified and included as part of the assessment of possible current and future BUDS projects. Some regions have compiled planned restoration and resiliency projects into a single database while others have not applied a master planning approach. In cases with no master planning approach, future planned projects will have to be assembled from various sources or assumed based on projected changes in the ecological systems of interest under future conditions. Not all projects will require sediment so the site condition must be assessed to determine the current and future sediment need based on planned project phasing and adaptive management. Generally, coastal BUDS projects will require sediment if the elevation and/or area of the habitat is insufficient to provide the ecological system function (i.e., a proposed wetland restoration in a subsided impoundment requires sediment addition to achieve adequate elevation for wetland vegetation whereas a project focused solely on invasive species control may not). Sediment needs may increase due to sea level rise (SLR), projected future sediment deficits, or other projected habitat changes that may impact sediment requirements. Similarly, projected changes to existing ecological systems must also be considered. A current functional ecological system may require restoration utilizing sediment in the future, especially if environmental conditions that support the ecological function are changing.

Sediment availability (which will be limited to the projected dredging requirements in this context) must also be quantified. In some systems, confined or upland disposal facilities are being considered as a potential sediment source and can be incorporated into this framework. If a navigation channel is included as a sediment source in the framework, the sediment coming from the channel will be assumed to be sufficient quality and compatible type for placement and all maintenance dredging will be assumed to produce BU quality material (e.g., free from debris and rock, safe levels of contaminants). In the absence of any future new dredging or deepening projects, historical dredging requirements can be used to project future dredging requirements. While sediment supply and sea level change may alter future dredging requirements, the long-term impact of these factors on dredging requirements is still unknown. Inter-annual variability in dredging requirements caused by episodic storm and flood events is still likely to drive dredging requirements in the future and is accounted for in recent dredging histories.

MCDA is used to capture the funding, design, logistical, and permitting constraints as well as restoration site requirements, restoration goals, stakeholder preferences, and DM transport and placement requirements (Figure 1). These criteria are used to determine which dredging and BUDS locations have compatible constraints and requirements. The next section outlines common types of project requirements and constraints associated with dredging and placement. The MCDA process also should clearly identify types of benefits associated with BUDS and how those benefits will be determined, since applying an optimization approach requires an accounting of costs and benefits. Benefits may be related to any number of project BUDS goals; for example, ecological benefits may be associated with creating and/or maintaining habitat area, flood risk management (FRM) benefits may be achieved through wave or surge attenuation, navigation benefits may be achieved through reduced channel shoaling rates, social benefits may be associated with recreation or aesthetic quality, and/or economic benefits may be achieved through cost savings due to reduced transport distances of DM.

Optimization allows projects that utilize BUDS to advance beyond projects-of-opportunity and become operationalized at a system scale. Optimization tools combine the data on sediment needs and availability with MCDA outputs to determine the most efficient and beneficial linkages between dredging locations and BUDS placement sites. Optimization results depend on the types of benefits considered as well as the method by which they are quantified. The framework is flexible so benefits of BUDS can be defined narrowly, considering only benefits to navigation, for instance, or more broadly, considering a full array of benefits. Additional tools may be required to calculate certain types of benefits, although cataloging all relevant tools for this purpose is beyond the scope of this TN. Optimization also requires an assessment of costs associated with BUDS to determine if a project is feasible. Many BUDS projects will require special equipment or impose different restrictions on the dredging and placement, which can reduce production rates or incur additional costs for personnel or specialty equipment. While most costs associated with BUDS are intrinsic to meeting the project goals, some aspects such as the method of placement can affect project costs and are included as critical decision points. If the benefits are not included as part of optimization, the framework can be used to identify only least-cost placement options that do not violate any identified constraints, treating all restoration options as equally beneficial per unit volume of sediment moved. However, using cost alone to optimize within the framework may bias the analysis and lead to certain sites being favored over others without regard to the true value of other BUDS sites.

One available tool to deterministically optimize a system of dredging, transfer, and placement sites is the USACE software package Dredged Material Management Decisions (D2M2). The D2M2 has been applied to existing dredging and placement sites including BUDS sites in relatively large estuaries such as Long Island Sound (Bridges et al. 2015). In the framework proposed here, the D2M2 is paired with tools to estimate sediment need and availability at the regional level towards a systematic approach to BUDS.

FRAMEWORK APPLICATION: To apply the framework, the user must first define and characterize the system of interest. The system refers to the geographic area in which the framework will be applied. System boundaries can be physical boundaries such as the shoreline of an embayment or the extent of tidal influence; geopolitical boundaries defined by state, county, or locality boundaries; or ecological boundaries such as the landward extent of coastal vegetation communities. These boundaries define the spatial domain within which sediment is being moved from sources to placement locations and may be determined in part by project constraints such as the maximum acceptable transport distance.

The coastal ecological systems of interest should be identified so the sediment need can be assessed for those areas. The framework is flexible and can consider any number of ecological system types in which BUDS is applied. The principal requirement is that the sediment need of a system can be quantified over time either through (1) the use of ecological or geomorphic modeling tools or (2) adaptive management plans that can anticipate future sediment need and placement frequency and volume. Herein, consideration is limited to the following: beach-dune systems, wetlands, tidal and sub-tidal flats (mud or sand with or without submerged aquatic vegetation/macroalgae), and islands. The navigation channels within the system boundaries should be identified since, in some cases, the system boundaries will be defined by the channel network. Navigation channels are maintained and operated by a variety of entities such as Federal and local governments as well as port authorities and private individuals in some cases. The BUDS framework can be applied to a subset of those sediment sources such as only Federally maintained channels or, if a whole-system approach is desired, to any or all channels, harbors, or disposal areas such as Ocean Disposal Sites. Once such boundary conditions are defined, methods and tools are applied to quantify sediment needs for the ecological systems of interest and the sediment available from the navigation dredging (Figure 1).

1. **Sediment needs.** Sediment needs are divided into main categories: needs for current and future planned BUDS projects and needs for maintenance of existing BUDS projects and

natural ecological systems of interest (Figure 2). Sediment needs will be driven largely by planned restoration and resiliency projects rather than maintenance of existing natural ecological systems and BUDS projects, as maintenance actions typically require lower sediment volumes per unit area.

Planned BUDS projects. Application of the BUDS framework should utilize regional planning efforts whenever possible to identify sediment needs for upcoming restoration and resiliency projects. These efforts may be Federal, state-led, or organized by any number of non-governmental organizations. These planned BUDS projects may be captured in regional restoration plans already in place with past, current, and future restoration sites (or at a minimum, restoration criteria) already identified. One goal of regional restoration planning is to create a network of ecological systems that provide enough patches of habitat and connectivity between patches to maintain regional ecosystem function. Such plans are crucial to support populations of organisms with highly mobile life stages such as oysters that are planktonic during larval stages. Coastal managers and planners have active restoration goals that may require conversion of some ecological systems to other types (for instance restoring an impounded open water area to a wetland) and as sea levels rise, some sites may be allowed to degrade intentionally as their functions become more difficult to maintain. Several critical estuaries in the US have enacted regional restoration plans including coastal Louisiana, the Maryland reaches of the Chesapeake Bay (see section on application sites), and Narragansett Bay. Ideally, Federal, state, and local navigation managers are already engaged with such efforts and the use of this Framework will facilitate better linkages between planned restoration and navigation dredging.

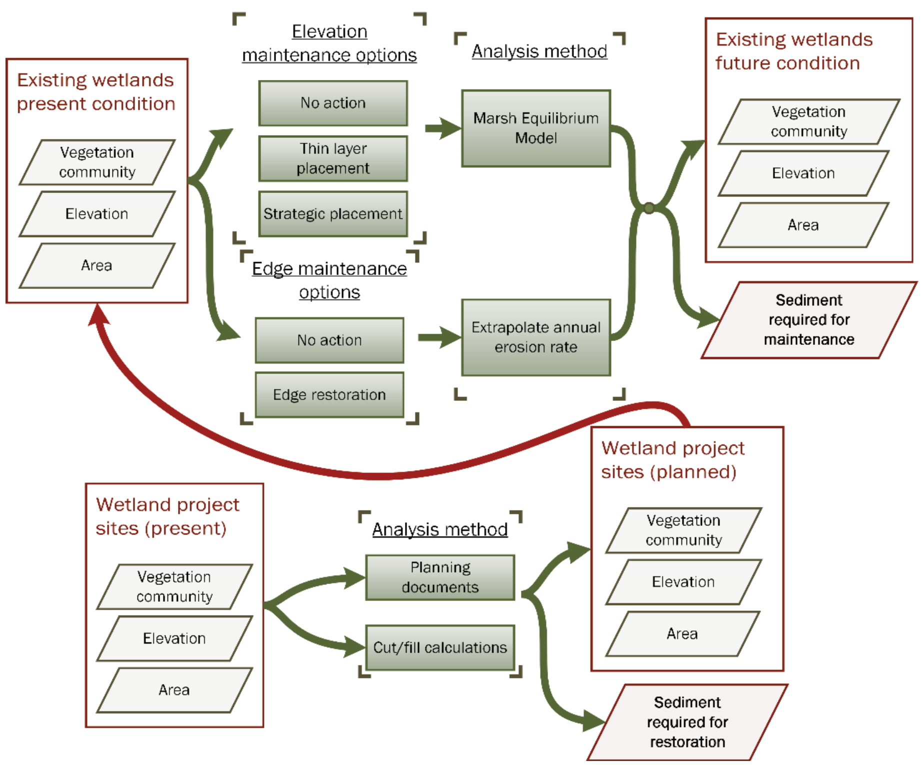

Figure 2. Example of how sediment needs will be calculated for maintenance and restoration of wetland BU sites.

However, in some areas, restoration efforts are not coordinated at a regional level and identifying planned restoration and resiliency projects will require coordination with more groups. Many coastal BUDS projects occur on public lands so planners and managers of those lands must be contacted to determine what the sediment requirements are for any planned projects. In other cases, private landowners including private conservancies may also have planned restoration. In one such case, the SediMatch tool hosted by the San Francisco Estuary Institute (SFEI 2017) can help navigation managers find potential BUDS sites although such tools may not help synchronize dredging and restoration efforts as well as regional restoration master planning that considers more projects over a longer timeline.

Once planned restoration and resiliency projects are identified, they must be assessed to determine sediment quantities required. Planned projects will likely have determined sediment volumes required to achieve the project requirements; however, if no data are available, a rough estimate of the sediment volume required for a project can be determined using basic assumptions informed by the ecological and site characteristics, e.g., “Existing Wetlands Present Conditions” (Figure 2).

Maintenance of existing BUDS projects and natural ecological systems. Since the framework incorporates both current and future conditions, the evolution of BUDS projects and natural ecological systems over time should also be examined to determine sediment needs for these projects should they require restoration or maintenance in the future. In some cases, the extrapolation of historical trends in ecosystem condition may suffice to estimate future sediment needs for maintenance, but in others, appropriate models must be identified and utilized to estimate the magnitude of sediment needs into the future by predicting the morphological response of the ecological system in response to future stressors (e.g., storms, SLR, or development; Figure 2).

Beach–dune systems. Beach-dune systems commonly utilize BUDS as part of routine maintenance, and sediment nourishment requirements are estimated as part of project planning. When beach-dune systems are designed as part of a coastal and flood risk management approach, the minimum acceptable geometry is defined. However, not all beach-dune systems in an area are used for FRM, and the geometry of these beaches and dunes should be more appropriately linked to the desired ecological function. Common condition metrics for beaches and dunes to determine if maintenance is required include beach width, slope, dune toe and crest elevation, and dune base width. Other indicators of appropriate ecological function may include vegetation type and cover density and alongshore variability of cross-sectional geometry and vegetation cover, for example.

For beach-dune systems included as part of a FRM system, determining required maintenance actions is a matter of comparing current cross-sectional geometry to the minimum acceptable geometry as described by design specifications. Condition surveys occur periodically and after major storm events and navigation operations managers are often in close contact with individuals responsible for maintaining the beach-dune system to identify locations where sediment is required. Local coastal managers can also be utilized to identify current sediment needs and determine how to utilize sediment resources in the future. Beaches and dunes considered critical habitat for threatened, endangered, and other species of concern may have additional considerations that will affect how sediment is used to support those systems.

Beach and dune response to storm conditions can be predicted using coastal morphology models (Roelvink et al. 2009; Johnson et al. 2012) on per storm basis or on a multi-year time scale. However, mid- to long-term predictions of beaches and dune morphology change remains difficult and uncertainty is high due in part to an incomplete understanding of nearshore sediment transport. Recent erosion rates can be used to estimate shoreline erosion in the near term but the impact of multiple large storm events on beach and dune maintenance requirements over many years is not always feasible without large scale modeling efforts and may be beyond the means of sediment management in some systems.

Wetlands. Wetlands can confer FRM benefits, but they are not widely implemented in the US for that function. Required FRM attributes such as elevations and cross-sections for wetlands are not as common as in many beach-dune systems. While sustained wetland function depends on many factors, maintenance actions requiring sediment are designed to address deficiencies in area or elevation, or both. Therefore, accurate elevation data in and around the wetland restoration site is critical to adequately estimate sediment need. Wetland BUDS projects are relatively stable through time (Berkowitz et al. 2021) but maintenance is most likely to be required for wetlands with high erosion rates, high ratios of unvegetated to vegetated areas, and net accretion rates less than the rate of SLR (Ganju et al. 2015). Wetlands degraded due to other issues such as constrained tidal flow, soil biogeochemical issues, increased wave exposure, or invasive species, should only be considered for restoration with sediment if the other issues can also be addressed through restoration design or continued maintenance.

Future changes in environmental conditions may necessitate future maintenance actions. Many wetlands have adapted to rising sea levels through biogenically-mediated accretion processes. However, as sea level rise accelerates in many areas, biogenic accretion may not be able to keep up, necessitating restoration action (Ganju 2019; Morris et al. 2016). Future maintenance actions that address edge erosion can be estimated by extrapolating current erosion rates into the future as recent studies indicate relatively steady erosion rates for marsh shorelines since the 1970s (Leonardi et al. 2016). However, changes in the system such as sudden loss of land area, breaches of sheltering islands, or increases in boater traffic could increase the erosion rate along some wetland shorelines. Wetland accretion processes are dynamic and should be estimated using models unless accretion rates are well understood. Several wetland accretion models exist (Morris et al. 2002; Swanson et al. 2014) and have been used to determine if sediment additions would be required to maintain wetland elevation. Several one- and two-dimensional models of wetland evolution (Kirwan et al. 2016; Best et al. 2018; Mariotti 2020) have also been developed but their use in the context of sediment management has not been assessed. Whatever model is chosen, it should be parameterized for the wetland type and species of interest as well as the environmental drivers critical to the wetland (e.g., tidal versus meteorologically driven water levels).

Tidal flats. Tidal flats can be comprised of mud or sand and are intertidal or shallow subtidal mostly unvegetated areas. Since tidal flats are important habitat areas for many aquatic organisms as well as foraging and loafing areas for birds, maintenance and restoration of these areas may be prioritized. While there are fewer examples of BUDS to restore tidal flat habitat as compared with beaches and wetlands, subaquatic habitat benches have been constructed in freshwater areas such as Duluth Harbor, MN. The appropriate elevation of tidal flats to be maintained is dependent on the biotic zones for the targeted ecological system of interest. For instance, subtidal flats constructed to restore submerged aquatic vegetation (SAV) habitat must be in the photic zone to ensure sites receive enough light to support plants should they establish.

Like wetlands, tidal flat elevations depend on accretion and erosion processes. Accretion on tidal flats is controlled by inorganic deposition and can be estimated using empirical methods to estimate the flux of sediment delivered per tide cycle if no data on accretion rates are available for the sites. However, the capture efficiency of sediments that deposit on tidal flats will vary with the site energy and re-suspension of sediments can occur. In higher energy environments, coastal morphology models such as the ones used for beach environments may be more applicable.

Islands. Island BUDS projects are becoming more common as interest in restoration of eroding and subsiding islands, as well as barrier islands damaged during coastal storms, is increasing. Examples of island restoration utilizing BUDS include Battery and Barren Islands, MD, Ship Island, MS, and Mordecai Island, NJ. As islands are mosaics of different habitats, the design of the island is largely dictated by the desired ecological outcomes. For example, island restoration for Mordecai Island was designed as low and high salt marsh, requiring final elevations in the upper intertidal zone whereas Barren Island included tidal flat, wetland, and upland shrub and forest habitat requiring a range of elevations. No single tool exists to predict island evolution; while some models of barrier island evolution (Nienhuis and Lorenzo-Trueba 2019) have been developed, their utility for addressing sediment management questions has not been determined. Instead, the tools previously described for the other ecological systems can be applied to relevant parts of the island based on the forces to which it is subjected. For instance, islands in relatively sheltered embayments would not require the implementation of coastal morphology models but may require the implementation of a wetland accretion model if most of the island is comprised of wetlands. Modeling tools that predict the evolution and migration of wetland habitats due to SLR (e.g., Kirwan et al. 2016) may be applicable to islands that contain wetland and upland areas.

2. **Sediment availability.** The framework assumes available sediments will come from maintenance and planned new work dredging. Dredging histories provide details on timing, frequency, and funding levels of past maintenance dredging projects, equipment used, and type, quality and quantity of sediment removed, which are used to predict future dredging needs, assuming conditions remain the same. Additionally, these data are used to determine constraints associated with dredging activities. The Corps Shoaling Analysis Tool (CSAT) can be used to determine the volume of source material available within Federal Navigation Channel (FNC) reaches by analyzing shoaling rates from historical channel surveys (Dunkin et al. 2018). However, changes to the FNC, such as channel deepening, new channels, or planned realignments can affect the amount of sediment available from dredging in the future and need to be identified to determine the impacts to future BUDS projects. Changes in baseline conditions that may affect future dredging requirements such as SLR and changing sediment transport patterns should also be considered.

3. **MCDA.** The key criteria and constraints governing dredging and placement sites are incorporated into the framework using a MCDA process. MCDA is often used in project planning to transparently formalize the decision-making process by prioritizing investments that reflect the goals, objectives, and preferences of disparate stakeholder groups. The criteria included in the MCDA will vary by region and perhaps even by site but should be clearly

established for each application of the framework. Criteria may reflect the restoration or conservation missions of non-governmental organizations, policies put in place to promote BU placement, and regulatory policies that limit placement in certain environments, among others. Criteria included in the MCDA can be associated with the sediment source and DM transportation method, the BUDS site, or related to jurisdictional areas if special requirements prohibit dredging or placement in some areas. Key criteria and constraints related to the sediment source and DM transportation method include transport distances for sediment transport and pumping, equipment type and size requirements, and associated limitations on water depths that may limit transport to a site. Additional considerations may include the long-term sustainability of the BUDS site since sites likely to deteriorate even with the addition of sediments would not be a wise investment in cases where sediment resources are limited.

Dredging and transport criteria. Local factors affect maintenance dredging and disposal operations and methods. Some projects are governed by regulations that limit the type and/or size of dredging equipment used while others may have limited availability of dredge types or size classes, affecting the transport methods used. Dredging equipment choices affect the transportability of DM between the sediment source and the BUDS site as well as the placement methods.

Hydraulic pipeline dredges are most used in USACE dredging projects (USACE 2015), and transport sediment-water slurry to the placement site directly via a pipeline. Transport distance from the dredging to the placement site is limited by the pump power, although additional booster pumps can be used at added costs. Hydraulic hopper dredges with pump-off capabilities can also be used to transfer DM from the dredge to the placement area but depending on the distance between the dredging and placement sites, the dredge may need to transit to a location where pump-off to the placement site can occur. Since hopper dredges are ocean-going and draft more when loaded, navigation channels to the placement area must be adequate to allow the loaded dredge to safely transit. Alternatively, mechanical and hydraulic dredges can load DM onto barges which will transport DM from the dredging to the placement locations using mechanical or pump off capabilities to distribute the DM to the placement site.

Certain types of dredging equipment make placement in intertidal and shallow water areas difficult or impossible and specialty equipment may be required to physically transport the sediment to the BU site, increasing placement costs. Additional constraints may arise if the dredging equipment produces DM at a rate far in excess to the rate at which it can be placed at the BU site. Some BU sites require relatively precise and/or thin lifts of sediment across large areas, limiting the rate at which it can be applied. If dredging is slowed or forced to shut down to accommodate site placement requirements, the dredging and placement cost per unit volume of sediment will increase. Transfer or stockpile areas, where DM is moved from one vessel to another or stored at a location until a BUDS project begins, can potentially alleviate a mismatch between dredging and placement requirements, but will also incur additional costs due to re-handling.

Placement criteria. Key criteria applicable to sediment placement depend on ecological system type but may include minimum and maximum sediment capacity per placement event, time of year restrictions for construction activities (which affect dredging and placement logistics), sediment grain size requirements, and regulatory considerations such as turbidity standards or other discharge regulations that may affect placement methods. The DM characteristics such as the available volume and physical properties should be consistent with the intended purpose of the BUDS. For instance, if a tidal flat BUDS site is intended to support oyster reefs, the sediment available should both be of sufficient quantity to produce a tidal flat of adequate size and elevation and the bearing capacity of the sediment after consolidation should be adequate to support the weight of the reef structure.

The sediment placement method is also critical to include in the MCDA, since the method used can dictate equipment, timing, placement efficiency, and may require additional regulatory oversight. BUDS restoration methods can be categorized as direct and strategic placement. Direct sediment placement involves sediment being moved from a navigation channel or transfer location and being placed directly onto a BUDS site using a variety of placement techniques (e.g., thin layer placement). Direct placement has been used for beach nourishment and wetland/island restoration and includes placement thicknesses ranging from a few centimeters to many meters. After placement, the sediment can be reworked as needed but generally nearly all the sediment is conveyed to the restoration site. Strategic sediment placement involves putting the sediment near the restoration site and allowing natural processes, either hydrodynamic or aeolian, to move it into the site. Strategic placement does not generally require reworking after construction. Strategic placement may be subject to similar thickness or elevation constraints as direct placement to prevent adverse impacts to the physical or ecological environment.

The placement method selected depends on local physical processes and environment, BUDS project goals, the acceptable level of construction-related impacts, environmental regulations, the relative amount of sediment required for restoration, and logistics and budget constraints. Since not every location experiences sediment transport at a frequency to effectively transport sediment into a restoration site, strategic placement may not be a viable option, especially for sites that require large volumes of sediment to meet restoration goals. Likewise, if sediment resources are relatively scarce, the relatively low efficiency of strategic placement methods may not provide the required amount of sediment required at a site. However, if the BUDS site is sensitive to construction impacts, direct placement may cause too much damage or require expensive specialty equipment to prevent damages. Special placement considerations may take additional time, which may disrupt dredging schedules. Strategic placement may be able to reduce construction-related impacts at the restoration site but impacts at the placement site may still be of concern as are elevated levels of suspended sediment in the vicinity of the placement.

Generally, direct placement is more time and resource intensive as (1) pumps and pipeline may be required to deliver sediment slurry, (2) hydraulic dredge flow rates must be controlled to ensure placement thicknesses or elevations are not exceeded, and (3) adequate residence time must be allowed for sediments to settle. Additional equipment may be required to move pipeline or to place and rework sediments. For small restoration sites, specialty dredging equipment with smaller pipelines or spray nozzles may be required to effectively construct the site.

4. **Optimization.** While MCDA will identify which sediment sources are compatible with which placement sites based on the site constraints and identified goals, objectives, and preferences, optimization is required to identify which solution sets are the most beneficial and cost-efficient over time. D2M2 uses multi-objective optimization (MOO) as a cost-benefit analysis

method that uses a linear programming algorithm to identify optimal links between the dredging and placement sites based on user-defined preferences, costs, and constraints. The MOO framework is flexible, allowing multiple users to define costs and benefits in ways that make sense to the area and project and balance potentially competing interests. Since placement areas for USACE dredging operations are defined by the Federal standard, "optimal" solution sets in this context are those that best satisfy dredging requirements as well as the sediment needs of the potential BU site for the least cost in an environmentally acceptable and engineering-sound manner. Per the Federal standard, the non-Federal sponsor would be responsible for additional costs over the base costs.

Given the various requirements associated with BUDS placement, unit costs for BUDS projects can vary widely. Distance between the dredging and placement site is a significant driver of unit dredging costs. When pipeline and/or transit distances between the dredging and placement sites are calculated, the network distance should be used rather than the straight-line distance. Hopper dredges and barges must utilize navigation channel networks to transport the DM while pipeline routes must be carefully planned to prevent damage from vessel traffic and to stage BUDS construction such that placement requirements are met. Cost engineering methods should also consider additional costs BUDS requirements may impose. In some cases, these costs may be similar to or even less than the transit costs associated with moving the DM to permitted disposal sites. But in some cases, additional costs may be incurred, requiring the local sponsor to pay the incremental cost above the base cost. While these costs may be significant, the incremental cost for transportation of DM to the restoration site may be less than sourcing sediment from other borrow or upland areas. To achieve effective cost-sharing in association with maintenance dredging, early engagement between dredging and restoration parties is required, especially in cases where separate permits and/or certifications for the dredging and placement are required.

Optimization also depends on the methods by which BUDS benefits are determined and may include the preference for type of BUDS site, benefit quantification metric (e.g., area of ecological system restored, habitat quality of ecological system restored), the minimum and maximum volume of sediment required to realize benefits (which may be different from minimum and maximum site capacity constraints), and if benefits per unit volume of sediment accrue at a constant rate or if there is an optimal volume of sediment for a site. Some benefits can be determined in a semi-quantitative manner using expert or stakeholder opinion as to which sites would provide the greatest benefit while other benefits, such as area or predicted habitat quality change, can be directly modeled or calculated.

POTENTIAL USES AND APPLICATIONS: Some areas of the country have attempted to use a more structured approach to BUDS to support restoration activities. The framework proposed here could be applied in combination with existing efforts to further realize BUDS to support ongoing restoration activities in these areas and plan for future activities. While these applications are coastal in nature, the framework can be customized to inland applications as many of the boundary conditions are identical or similar. The following are examples of areas in which this framework would be applicable.

1. **San Francisco Bay Estuary (SFBE).** Concerns over the future extent and condition of current wetland and mudflat areas in the SFBE, collectively referred to as baylands, have

resulted in large restoration efforts. Stakeholder groups in the region have restored and identified many baylands for future restoration. This information can be used to determine placement areas, frequencies, and volumes using the BUDS framework. Restoration advocacy has also led to a parcel tax to fund bayland restoration. Economic resources from mitigation, taxes, or stewardship are incorporated in the framework and will likely be a necessary component of large-scale restoration planning. A collaborative partnership amongst stakeholder groups in the SFBE developed the SediMatch web-tool to help maximize BUDS in the SFBE by matching projects with sediment needs with sediment providers (SFEI 2017). SediMatch relies on users to determine the most likely pairing of restoration and dredging projects using a snapshot of current and near-term restoration needs. However, the framework presented here can utilize SediMatch data to determine how to systematically match dredging and restoration locations based on current and future sediment needs.

2. **Galveston Bay.** Galveston Bay is fringed with a variety of ecosystems including oyster habitat, tidal marshes, and beach-dune complexes, which provide valuable habitat and nursery areas for the region's fisheries and reduce erosion and attenuate waves in an embayment frequently impacted by tropical storms and hurricanes. Since 1990, the interagency Beneficial Use Group has successfully implemented many high-profile BUDS projects including Evia Island, Bolivar Marsh, and a series of BUDS islands adjacent to the Houston Ship Channel (Koening 1997; Aspelin and Krueger 2007). The framework described here could be used to optimize placement as part of such an approach by incorporating future sediment needs, stakeholder preferences, and wetland valuation.

3. **Chesapeake Bay, Maryland.** The State of Maryland has long recognized the value of BUDS in promoting shoreline and coastal community resilience while reducing dredging costs, passing the Dredged Material Management Act in 2001 with the goal of promoting BUDS. The Maryland Department of Natural Resources developed the Beneficial Use: Identifying Locations for Dredge (BUILD) tool to identify coastal BUDS opportunities with special consideration given jointly to restoration and dredging needs (Specht 2019). The framework presented herein could be paired with BUILD to consider future needs and optimize the most logistically and economically practical opportunities.

CONCLUSIONS: The framework presented here is designed to promote systematic use of BUDS for the support of restoration and long-term maintenance of ecological systems of interest including beaches and dunes, wetlands, and mudflats in coastal areas. The framework leverages several existing spatially- and temporally-explicit models to develop the required data for decision and optimization tools that allow managers to better align required dredging activities with system-wide ecological system management. Operationalizing BUDS at a systems-level will help minimize restoration and management costs by providing an expansive and necessary sediment resource while also keeping DS within estuarine systems, promoting regional sediment management principles. To illustrate how the BUDS optimization framework could be applied as a planning and operations tool, three applications are described for the SFBE, Galveston Bay, and Maryland Chesapeake Bay. The workflow that describes the application of the framework within a geographic information system is described in a second forthcoming report.

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REFERENCES

Arkema, K. K., R. Griffin, S. Maldonado, J. Silver, J. Suckale, and A. D. Guerry. 2017. "Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities." *Ann. NY Acad. Sci* 1399(1), 5-26.

Aspelin, S., and D. Krueger. 2007. Houston Ship Channel Beneficial Use Project: Lessons Learned in Building Thousands of Acres of Habitat with Dredge Material. In P*roceedings of the Western Dredging Association*.

Best, Ü. S., M. Van der Wegen, J. Dijkstra, P. W. J. M. Willemsen, B. W. Borsje, and D. J. Roelvink. 2018. "Do salt marshes survive sea level rise? Modelling wave action, morphodynamics and vegetation dynamics." *Environmental modelling & software* 109: 152-166.

Bridges, T. S., K. A. Burks-Copes, M. E. Bates, Z. A. Collier, J. C. Fischenich, C. D. Piercy, and J. D. Rosati. 2015. *Use of natural and nature-based features (NNBF) for coastal resilience*. SR-15-1. Vicksburg, MS: US Army Engineer Research and Development Center, Environmental Laboratory, Coastal and Hydraulics Laboratory.

Dunkin, L. M., L. Coe, and J. J. Ratcliff. 2018. *Corps shoaling analysis tool: Predicting channel shoaling*. ERDC/CHL TR-18-16. Vicksburg, MS: US Army Engineer Research and Development Center. https://erdc-library.erdc.dren.mil/jspui/handle/11681/30382

Ganju, N. K., M. L. Kirwan, P. J. Dickhudt, G. R. Guntenspergen, D. R. Cahoon, and K. D. Kroeger. 2015. "Sediment transport-based metrics of wetland stability." *Geophys. Res. Lett.* 42, 7992– 8000, doi:10.1002/2015GL065980.

Ganju, N. K. 2019. "Marshes are the new beaches: Integrating sediment transport into restoration planning." *Estuaries and Coasts 42*(4): 917-926.

Johnson, B., M. B. Gravens, and N. Kobayashi. 2012. *Cross-Shore numerical model CSHORE for waves, currents, sediment transport and beach profile evolution*. ERDC/CHL TR-12-22. Vicksburg, MS: US Army Engineer Research and Development Center. https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/4558/

Kirwan, M. L., D. C. Walters, W. G. Reay, and J. A. Carr. 2016. "Sea level driven marsh expansion in a coupled model of marsh erosion and migration." *Geophys. Res. Lett.* 43, 4366– 4373, doi:10.1002/2016GL068507.

Leonardi, N., Z. Defne, N. K. Ganju, and S. Fagherazzi. 2016. "Salt marsh erosion rates and boundary features in a shallow bay." *J. Geophys. Res.: Earth Surf.* 121 (10): 1861–1875.

Mariotti, G. 2020. "Beyond marsh drowning: The many faces of marsh loss (and gain)." *Advances in Water Resources* 103710.

Morris, J. T., P. V. Sundareshwar, C. T. Nietch, B. Kjerfve, and D. R. Cahoon. 2002. "Responses of coastal wetlands to rising sea level." *Ecology* 83(10): 2869-2877.

Morris, J. T., D. C. Barber, J. C. Callaway, R. Chambers, S. C. Hagen, C. S. Hopkinson, and C. Wigand. 2016. "Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state." *Earth's future* 4(4): 110-121.

Nienhuis, J. H., and J. Lorenzo-Trueba. 2019. "Can barrier islands survive sea-level rise? Quantifying the relative role of tidal inlets and overwash deposition." *Geophysical Research Letters* 46(24): 14613-14621.

Ouyang, Z., C. Song, H. Zheng, S. Polasky, Y. Xiao, I. J. Bateman, and G. C. Daily. 2020. "Using gross ecosystem product (GEP) to value nature in decision making." *Proceedings of the National Academy of Sciences 117*(25): 14593–14601. https://doi.org/10.1073/pnas.1911439117

Roelvink, D., A. Reniers, A. P. Van Dongeren, J. V. T. De Vries, R. McCall, and J. Lescinski. 2009. "Modelling storm impacts on beaches, dunes and barrier islands." *Coastal engineering* 56(11-12): 1133-1152.

San Francisco Estuary Institute (SFEI). 2017. SediMatch Web Tool. https://sedimatch.sfei.org/. [Web tool].

Specht, J. 2019. BUILD User Manual Beneficial Use: Identifying Locations for Dredge. Maryland Department of Natural Resources. https://gisapps.dnr.state.md.us/CoastalAtlas/StepbyStep_Guides/BUmanual/BUILDUserManual.pdf

Swanson, K. M., J. Z. Drexler, D. H. Schoellhamer, K. M. Thorne, M. L. Casazza, C. T. Overton, and J. Y. Takekawa. 2014. "Wetland accretion rate model of ecosystem resilience (WARMER) and its application to habitat sustainability for endangered species in the San Francisco Estuary." *Estuaries and Coasts* 37(2): 476-492.