

A MULTI-DECADAL ASSESSMENT OF DREDGED SEDIMENT BENEFICIAL USE PROJECTS PART 2: ECOSYSTEM FUNCTIONS, GOODS, AND SERVICES

Jacob F. Berkowitz†[1], Nia R. Hurst[1], Nathan R. Beane[1], Kevin D. Philley[1], and Jacob F. Jung[1]

ABSTRACT

Data and observations made at > 40-year-old dredged sediment beneficial use project sites were used to link ecosystem functions (e.g., maintenance of floral and faunal habitat, energy dissipation) with an established ecosystem goods and services framework (e.g., navigation channel maintenance, hazard reduction, ecosystem sustainability). This approach works toward quantifying the full suite of positive outcomes dredged sediment beneficial use projects provide to the environment and society. Ecological functions are derived from physical, biogeochemical, and habitat processes which occur on different timeframes and to varying magnitudes, and these functional drivers control the delivery of ecosystem goods and services. For example, physically dominated ecological functions are typically delivered more quickly (weeks to months) after project implementation than functions requiring the maturation of plant communities or other biologically mediated processes (years to decades). As a result, coupling ecological functions with the resulting ecosystem goods and services informs dredged sediment beneficial use decisions by communicating the relative influence of specific design features or management actions on project outcomes. These analyses also support the development of conceptual ecological benefits trajectories across decadal timelines. Future research will be needed to improve the quantification of ecological functions, and the resulting goods and services in a dredged sediment beneficial use context. The need for better quantification tools is expected to increase with implementation of Working with Nature, Engineering With Nature, and natural and nature-based feature initiatives. A companion paper evaluates the long-term ecological outcomes of dredged sediment beneficial use project implementation, demonstrating the capacity of beneficial use projects to sustainably deliver a variety of ecosystem functions over multiple decades.

Keywords: Natural and nature-based features, ecological functions, ecosystem goods and services, restoration trajectory curves

INTRODUCTION

There is a paucity of data on the long-term outcomes of dredged sediment beneficial use projects from an ecological function, goods, and services perspective. The lack of studies linking dredged material beneficial use initiatives with ecosystem functions, goods, and services is two-fold. First, few beneficial use projects were implemented more than 30 years ago, limiting the capacity to conduct long-term analyses. Second, the ecosystem function, goods, and services typologies evolved relatively recently, and are only now being incorporated into engineering and environmental management practices (Bouwma et al. 2018). In this paper, we utilize data and observations made at six historic (> 40-year-old) dredged sediment beneficial use projects to evaluate multi-decadal ecosystem function, goods, and services outcomes. This is accomplished by 1) providing a background of ecosystem functions, goods, and services within a dredged sediment beneficial use context, 2) describing the ecosystem functions occurring at each study location, 3) and linking them to the ecosystem goods and service framework described in Waigner et al. (2020). Additionally, the ecological trajectory of beneficial use sites is discussed to highlight the relative timing of

---

[1] US Army Engineer Research and Development Center, 3909 Halls Ferry Rd, Vicksburg, MS, 39180, USA

ecosystem functions, goods, and services delivery as well as the impact that specific project design features can have on environmental and societal outcomes.

BACKGROUND

Ecological functions are defined as the normal activities or actions that take place in an ecosystem, such as the maintenance of habitat for flora and fauna, detention of floodwater and reduction of storm surges, and the biogeochemical cycling of nutrients and other compounds (Novitski et al. 1996). These functions result from complex interactions between the structural components in an ecosystem (e.g., plants, animals, soil, water, and the atmosphere), the surrounding watershed and landscape (e.g., geomorphic setting), and the processes that link these structural components such as overbank flooding, evapotranspiration, chemical reactions in the soil, predation, and primary productivity (Smith et al. 2013). In general, ecological functions can be grouped into three broad categories (physical, biogeochemical, and habitat functions) based upon the underlying processes predominantly driving the function. These functions work in concert to maintain ecosystem integrity and sustainability. The hierarchy demonstrating the relationship between ecological indicators (or structural elements), processes, functions, and suites of functions is shown in Figure 1.

In addition to providing for ecosystem integrity, ecological functions also deliver benefits for society known as ecosystem goods and services that help to sustain or enhance human life (Brown et al. 2007). Ecosystem goods and services include the opportunity to harvest fish or other species for human consumption, reduced flood risk damages to infrastructure, improved water quality, and other beneficial outcomes (Gómez-Baggethun et al. 2010). As such, ecosystems represent capital assets, whose benefits and services can be assessed and quantified in a variety of frameworks, including economic and engineering contexts (Daily et al. 2000). Many studies have evaluated the complex ecosystem functions, goods, and services associated with different ecosystems, and an array of approaches to assess these outcomes have been applied across the United States and internationally (De Groot et al. 2002). In a dredging context, Wellman and Gregory (2002) discussed the incorporation of ecosystem goods and services into a coastal management trade-off analysis, suggesting the consideration of these metrics can help to achieve both economic and ecosystem integrity objectives.

Recently, an ecosystem goods and services framework was developed in support of U.S. Army Corps of Engineers project planning activities (Table 1; Waigner et al. 2020). The framework identified ecosystem goods and services categories that can be applied to a number of disciplines, including the management of dredged sediment (Kolman 2014). The Central Dredging Association (2013) described ecosystem goods and services as a new way of thinking, a tool for decision-making about sustainable development, and capable of re-focusing discussions about dredging and the environment to identify proactive, opportunity driven, win-win situations. That report highlighted the beneficial use of dredged sediment as a mechanism to increase the delivery of ecosystem goods and services, but also identified challenges for assessing, valuating, and incorporating goods and services into the design of dredging projects.

The following example examines how dredging and the beneficial use of dredged sediment can alter ecosystem functions, goods, and services in both positive and negative ways. The dredging of canals through wetlands and the placement of dredged sediments adjacent to the canals (known as spoil banks) in Louisiana, USA, has contributed to the conversion of large wetlands areas to open water features (Britsch and Dunbar 1993). The extirpated wetlands no longer provide ecological functions such as flood water retention and the reduction of storm surges, exacerbating coastal land loss in the region (Turner and McClenachan 2018). Additionally, the conversion of wetlands to open water decreased the delivery of ecosystem goods and services such as the capacity of the system to naturally reduce storm impacts to infrastructure (hazard mitigation), provide a sustainable fishery (food provisioning), and improve water quality by removing excess nitrogen which contributes to hypoxia (water purification; ecosystem

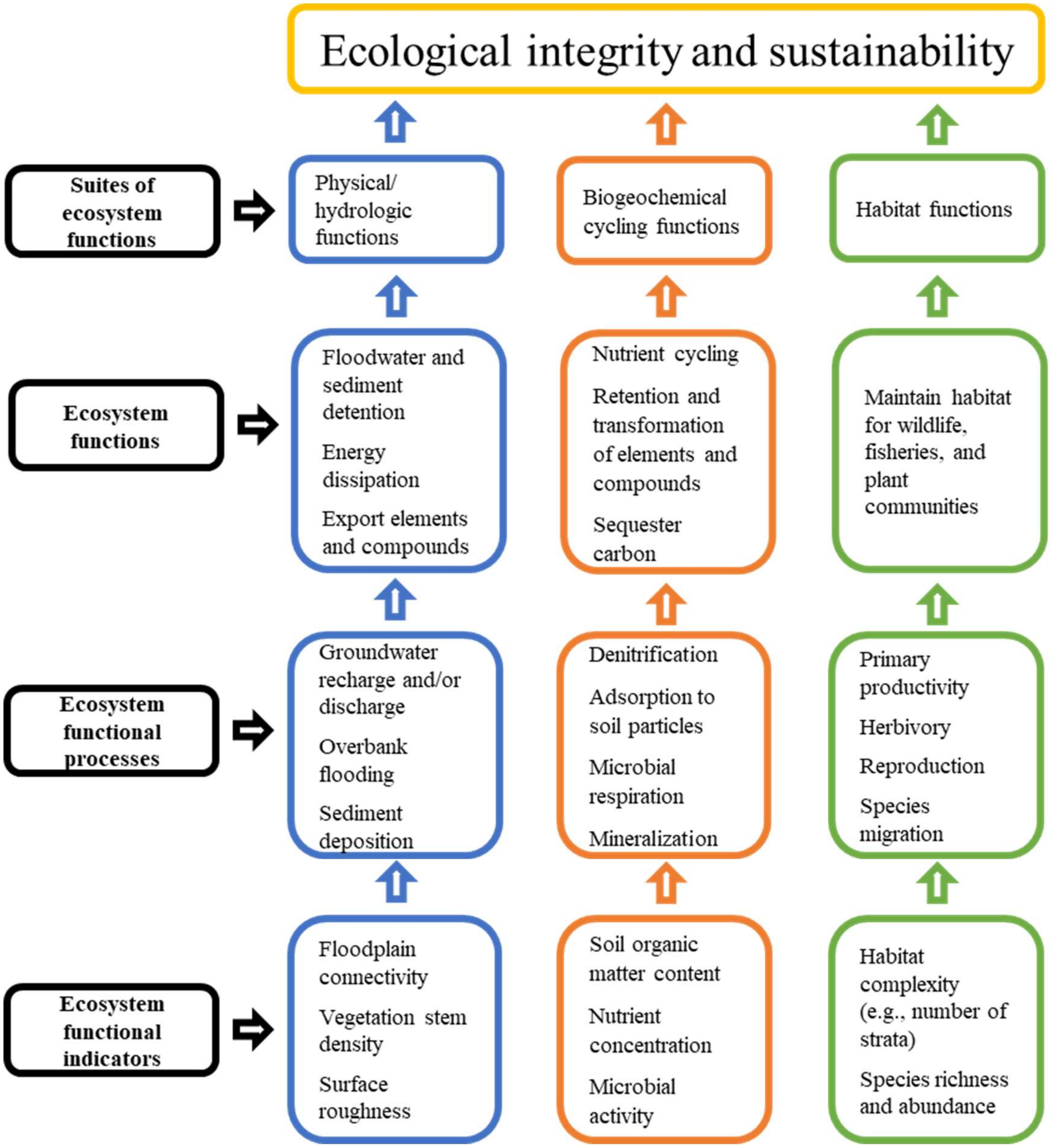

Figure 1. Hierarchy of ecological functions.

sustainability) (Bianchi et al. 2010; Chesney 2000). Conversely, dredged sediments have been used to restore and improve ecological functions in the degraded areas. In the case of the Louisiana canals, Baustian and Turner (2006) measured increases in ecosystem indicators related to habitat, hydrologic, and biogeochemical functions after canals were re-filled with dredged sediment. While not directly measured, restoring the impacted wetlands with dredged sediment appears to have increased the delivery of a number of ecosystem goods and services, including ecosystem sustainability, hazard mitigation, water purification, and climate regulation. Evidence that ecosystem functions, goods, and services have been enhanced using dredged sediments includes observed increases in soil organic matter (an ecological indicator) following canal restoration which shows that carbon sequestration (a biogeochemical functional process) and climate regulation (an ecosystem service) resulted from the dredged sediment placement.

Table 1. Framework of ecosystem goods and services categories, associated definitions, and examples related to dredged sediment beneficial use (adapted from Waigner et al. 2020).

Category	Definition	Beneficial use example
Ecosystem sustainability	Maintenance of ecosystems' structural and functional qualities and resilience to adapt to change over time.	Sediment placement to increase habitat in support of population viability for threatened species.
Hazard mitigation	Ecosystem-induced reduction of risk of or vulnerability to floods and storms that threaten property, infrastructure, safety, or natural resources.	Using dredged sediment to restore coastal marshes to decrease storm surges and reduce flood damages to infrastructure.
Navigation maintenance	Provision of unobstructed waterborne transport as supported by sediment reduction and water regulation by functioning ecosystems.	Use of dredged sediment to construct projects that improve hydrodynamics and prevent channel infilling.
Cultural, spiritual and educational support	Maintenance of sites and landscapes with spiritual or religious significance, contribute to a sense of place, or sustain cultural heritage, including traditional ways of life. Also includes opportunities for scientific discovery and education.	Use of dredged sediment to protect important archeological or indigenous sites such as shell middens from erosion or other threats.
Recreation and aesthetics	Quantity and quality of recreational opportunities and the aesthetic enjoyment provided by the condition and relative placement of landscape and ecosystem features pleasing to one or more of the five senses. This may also include property value enhancement.	Development or maintenance of beaches, wetlands, or other features using dredged sediment that provides for tourism, recreational hunting and fishing, camping, and attractive scenery for landowners and the public.
Food, raw goods, and materials provisioning	Provisioning of commercial or subsistence production of food and raw goods and materials.	Dredged sediment placement that supports hunting, fishing, and foraging opportunities; or supports timber harvest and aggregate re-use.
Water purification	The filtration and removal of excess nutrients or pollutants by ecosystems.	Constructing wetlands using dredged sediment naturally removes of excess nutrients and retains/detoxifies pollutants.
Climate regulation	Ecosystem moderation of adverse climate effects via greenhouse gas sequestration.	Construction or maintenance of wetlands and seagrass beds using dredged sediment.

The incorporation of ecosystem goods and services into dredged sediment management aligns with a recent paradigm shift elevating the concept that beneficial use projects can deliberately align engineering and environmental stewardship missions to maximize outcomes for both navigation and the ecosystem (Bridges et al. 2014). While there has been a growing recognition that incorporating measures of ecosystem functions, goods and services into dredged sediment management programs can help achieve both engineering and environmental objectives (International Association of Dredging Companies 2013; Kolman 2014), few studies have holistically evaluated these metrics in a dredged sediment beneficial use context. For example, Jenkins et al. (2010) estimated the monetary value of restoring wetland habitats in the Mississippi River Valley, focusing on greenhouse gas reductions and recreation. While valuable, that study did not consider other functions and benefits such as flood risk reduction or navigation channel maintenance. Foran et al. (2018) linked ecological functions with navigation channel maintenance, greenhouse gas dynamics, and water quality improvements at one beneficial use study site in Louisiana, providing an example of the integration of ecosystem services into the quantification of favorable outcomes. This study takes another step forward toward holistically communicating beneficial use project benefits by evaluating the long-term (>40 year) delivery of ecosystem functions, goods, and services at six geographically and ecologically dredged material management sites constructed to improve habitat while supporting sustainable navigation.

STUDY LOCATIONS AND APPROACH

Six historic dredged sediment beneficial use projects designed to improve habitat were developed between 1974 and 1977, and post construction monitoring data was collected until 1987 (Landin et al.1989). These project locations represent some of the earliest beneficial use sites with monitoring data in the United States. The data collected provide a unique opportunity to evaluate the mid- to long-term outcomes of dredged sediment beneficial use initiatives within an ecosystem function, goods, and services context. Additionally, the projects represent a range of geographic locations and target habitat types (e.g., marsh, meadow, dune), allowing for the evaluation of beneficial use outcomes in a variety of ecological settings (Figure 2). Table 2 provides a brief description of each project sites' characteristics. Additional details about the study sites and beneficial use activities are available in Berkowitz et al. (2021). To assess the multidecadal ecosystem functions, goods, and services delivered by the projects a four-tiered analysis was conducted as described below:

Tier 1 - The monitoring data from each of the historic projects summarized by Landin et al. (1989) and others was reviewed to identify direct measures and indicators of ecosystem functions. For example, throughout the 1976-1987 monitoring period, high bird species abundance and diversity and robust plant communities were recorded, demonstrating that habitat functions were occurring as a result of the dredged sediment placement activities.

Tier 2 - A field sampling campaign was completed in 2019 at each of the six historic dredged sediment beneficial use sites to assess vegetation community structure, avian community composition, and soil

Figure 2. Location of the historic beneficial use projects.

Table 2. Brief description of historic dredged sediment beneficial use projects.

Location	Year	Size (ha)	Beneficial use activity	Target habitats
Bolivar Peninsula, TX	1976	11.1	Historic pile of unvegetated dredged sediment adjacent to the Houston ship channel contoured using construction equipment to create elevation and inundation gradients for floral and faunal habitat improvements. The site was then planted with a range of flora based on elevation, salt tolerance, and inundation frequency.	Low marsh High marsh Herbaceous upland Woody upland
Drake Wilson Island, FL	1976	5	Hydraulically pumped fine grained silty dredged sediment from the Gulf Intercoastal Waterway deposited onto older course sandy dredged sediment. The area was planted with a range of flora based on elevation, salt tolerance, and inundation frequency.	Low marsh High marsh Woody upland
Buttermilk Sound, GA	1975	2.1	Converted a ~5 m high unvegetated dredged sediment sand mound adjacent to the Atlantic Intracoastal Waterway to a gradient of intertidal elevations. The area was planted with a range of flora based on elevation, salt tolerance, and inundation frequency.	Low marsh High marsh Unvegetated upland
Nott Island, CT	1974	3.2	Re-contoured an unvegetated, steeply sloped dredged sand mound adjacent to the Connecticut River. Soils were amended with fine grained dredged sediment and fertilizer, then planted.	Upland meadow
Pointe Mouillee, MI	1979	148	Strategically situated area diked to protect degraded adjacent marsh and reestablish habitat using dredged sediments, establish a visitors' center and recreational opportunities, and store Lake Erie shipping channels and harbor dredged sediments.	Freshwater marsh
Miller Sands, OR	1974	94.7	Regraded historic dredged sediment mound adjacent to the Columbia River navigation channel to develop elevation and inundation gradients. Disked and amended upland areas with fertilizer, deposited fine dredged sediments in marsh areas, and placed sand (with sand fencing) to establish dunes. The area was planted with a range of flora based on elevation, salt tolerance, and inundation frequency.	Tidal marsh Upland meadow Dune

physicochemical properties (Berkowitz et al. 2021). During the site visits and upon subsequent analysis of field and laboratory data, measurements and observations of multiple ecological functional indicators were identified within each target habitat (e.g., low marsh, vegetated upland, dune). The ecosystem functional indicators considered include both direct measures of function (e.g., avian community habitat usage) and proxy measures indicative of ecosystem functions (e.g., documented field indicators of hydric soils provide indirect, but diagnostic evidence of nutrient cycling) (Figures 1 and 3).

Tier 3 - Based on ecosystem functional indicators documented during the assessment, the ecosystem functions being delivered at each project site were identified. For example, the presence of sediment deposits and stratified soil layers (i.e., repeating layers of mineral and organic soil materials) provides

Figure 3. Examples (from left) of ecological indicators linked with ecosystem functions including direct observations of faunal habitat use at Pointe Mouillee, MI; stratified soil layers indicate floodwater and sediment detention functions at Drake Wilson Island, FL; and field indicators of hydric soils (e.g., iron translocation) signify the retention and transformation of elements and compounds function at Bolivar Peninsula, TX.

evidence that energy dissipation and floodwater and sediment functions are occurring (USACE 2012). Similarly, the presence of organic-rich soil horizons and field indicators of hydric soils demonstrate that carbon sequestration, retention and transformation of elements and compounds, and nutrient cycling functions are occurring (USDA-NRCS 2018).

Tier 4 - The identified ecosystem functions were linked with ecosystem goods and services that benefit society using the framework described in Waigner et al. (2020). This approach has been used before, and ecological functional indicators have proven valuable for quantifying ecosystem functions (Berkowitz and White 2013) and allowing them to be coupled with ecosystem goods and services (McLaughlin and Cohen 2013).

RESULTS AND DISCUSSION

The historic habitat improvement projects constructed with dredged sediment successfully established each of the target habitats (Landin et al. 1989), and in general the target habitats have persisted for the past four decades (Berkowitz et al. 2021). While monitoring occurred for approximately 10 years following project construction, it focused on habitat improvement and the historic studies failed to evaluate the full suite of ecosystem functions occurring at the beneficial use sites. However, data from those studies in conjunction with the 2019 assessment of ecological indicators was used to document the wide array of ecosystem functions occurring at each project location (Table 3).

Results suggest that the beneficial use of dredged sediment yields positive ecological outcomes that are sustainable over periods exceeding 40 years at the study locations. This is significant because prior to construction of the dredged sediment beneficial use projects, the study locations provided very limited ecosystem functions with regard to habitat (Landin et al., 1989). As a result, the improvements induced by the projects represent a significant 'lift' in ecosystem functions (Yan et al., 2021). Further, this is one of the first studies to document the long-term delivery of ecosystem functions by dredged sediment beneficial use projects across a multi-decadal period. The ecosystem functions identified were assigned based on the various target habitats documented during the ecological assessment because different landforms are subject to different processes that induce ecological functions (Table 4; Berkowitz et al. 2021). For example, areas that do not come into contact with runoff and floodwaters lack the capacity to detain significant amounts of water and suspended sediments.

Table 3. Ecological functions observed at the six historic dredged sediment beneficial use projects and associated ecological indicators used to document each function.

Ecological functions	Ecological indicators
Physical functions	
Floodwater and sediment detention - the capacity of the ecosystem to temporarily store water and sediment following rain events, overbank flooding, & high tides.	Inundation and soil saturation, microtopographic relief, vegetation stem density, sediment deposits, stratified soil layers, soil bulk density
Energy dissipation - the capacity of the ecosystem to attenuate and decrease energy from wind and waves	Inundation and soil saturation, vegetation stem density, roughness, sediment deposits, water marks, drift deposits, algal mats
Export elements and compounds - the capacity of the ecosystem to export dissolved and particulate organic carbon, nutrients, sediment, and other materials to down-stream or down gradient areas	Inundation and soil saturation, water-stained leaves, soil organic matter content, drainage patterns, field indicators of hydric soils
Biogeochemical functions	
Nutrient cycling - The capacity of an ecosystem to convert nutrients from inorganic forms to organic forms and back through biogeochemical processes such as photosynthesis and microbial decomposition	Organic material production and storage, inundation and soil saturation, soil organic matter accumulation, field indicators of hydric soils
Retention and transformation of elements and compounds - the capacity of an ecosystem to temporarily or permanently store and transform metals, organic chemicals, and other substances through processes such as adsorption to soil particles, oxidation, reduction, and microbial degradation	Inundation and soil saturation, soil organic matter accumulation, field indicators of hydric soils, presence of reduced iron, oxidized rhizospheres along living roots
Sequester carbon - The capacity of an ecosystem to accumulate soil organic matter and store carbon, providing a long-term sink for greenhouse gases	Inundation and soil saturation, soil organic matter accumulation, below ground biomass, field indicators of hydric soils
Habitat functions	
Maintain habitat for wildlife, fisheries, and plant communities - the capacity of an ecosystem to provide the environment necessary to support the characteristic fish and wildlife species during part of their life cycles	Direct observations of faunal utilization, vegetative structural complexity, species richness and abundance, evidence of succession

The observed ecosystem functions occurring in each habitat type documented at the study locations (Table 4) were linked with ecosystem goods and services provided by the dredged sediment beneficial use projects using the relationships shown in Figure 4. Results indicate that the number and type of ecosystem functions, goods, and services delivered by each project depends on the distribution of habitats components created and the ecosystem functions occurring at those landforms (Table 5; Swanson et al. 1988). For example, the Bolivar Peninsula, TX project created four distinct target habitats that each provide for the maintenance of plants and animals habitats (functions) that contributes to ecosystem sustainability (goods and services). However, the herbaceous and shrubby uplands at that study location lack the soil organic matter characteristics and patterns of frequent inundation associated with the carbon sequestration and energy

Table 4. Summary of ecological functions occurring at each beneficial use project location.

Ecological functions	Study locations and target habitat types														
	Bolivar Peninsula, TX				Drake Wilson Island, FL			Buttermilk Sound, GA			Nott Isla., CT	Pointe Mou., MI	Miller Sands, OR		
	Low marsh	High marsh	Herbaceous upland	Woody upland	Low marsh	High marsh	Woody upland	Low marsh	High marsh	Unvegetated upland	Upland meadow	Freshwater marsh	Upland meadow	Tidal marsh	Dune
Floodwater and sediment retention	X	X			X	X		X	X			X		X	X
Energy dissipation	X	X			X	X		X	X			X		X	X
Export elements & compounds	X	X			X	X		X	X			X		X	
Nutrient cycling	X	X	X	X	X	X	X	X	X		X	X		X	X
Retention and transformation of elements and compounds	X	X			X	X		X	X			X		X	
Sequester carbon	X	X			X	X		X	X			X		X	
Maintain habitat for wildlife, fisheries, and plant communities	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

dissipation functions as well as the associated climate regulation and hazard mitigation ecosystem goods and services categories (amongst others).

This highlights the interplay between landforms, ecosystem functions, and the delivery of ecosystem goods and services within a single project area. Additionally, the distribution of functions, goods, and services varied across beneficial use sites. For example, the results of the assessments at Bolivar Peninsula, TX and Miller Sands, OR indicate that projects designed to create a variety of landscape features, elevation, and patterns of inundation promote a higher diversity of ecosystem functions, goods, and services than projects that only contain a single geomorphological feature (e.g., the upland meadow at Nott Island, CT).

Results suggest that the establishment of marshes and wetlands using dredged sediment yielded a larger number of ecological functions than transitional or upland landscape features, and therefore deliver more categories of ecological goods and services. This occurs because wetlands are very productive ecosystems, subject to a higher degree of ecological dynamism (fluctuating water tables, floods) than other landforms, providing additional opportunities to confer positive societal outcomes (Costanza et al. 1989; Nyman 2011). Our findings align with the existing literature which reports that wetlands and other aquatic resources supply ecosystem functions, goods, and services at levels that exceed those of other habitats (Barbier 2013; Gunderson et al. 2016). The differences in the number of ecosystem functions, goods, and services should

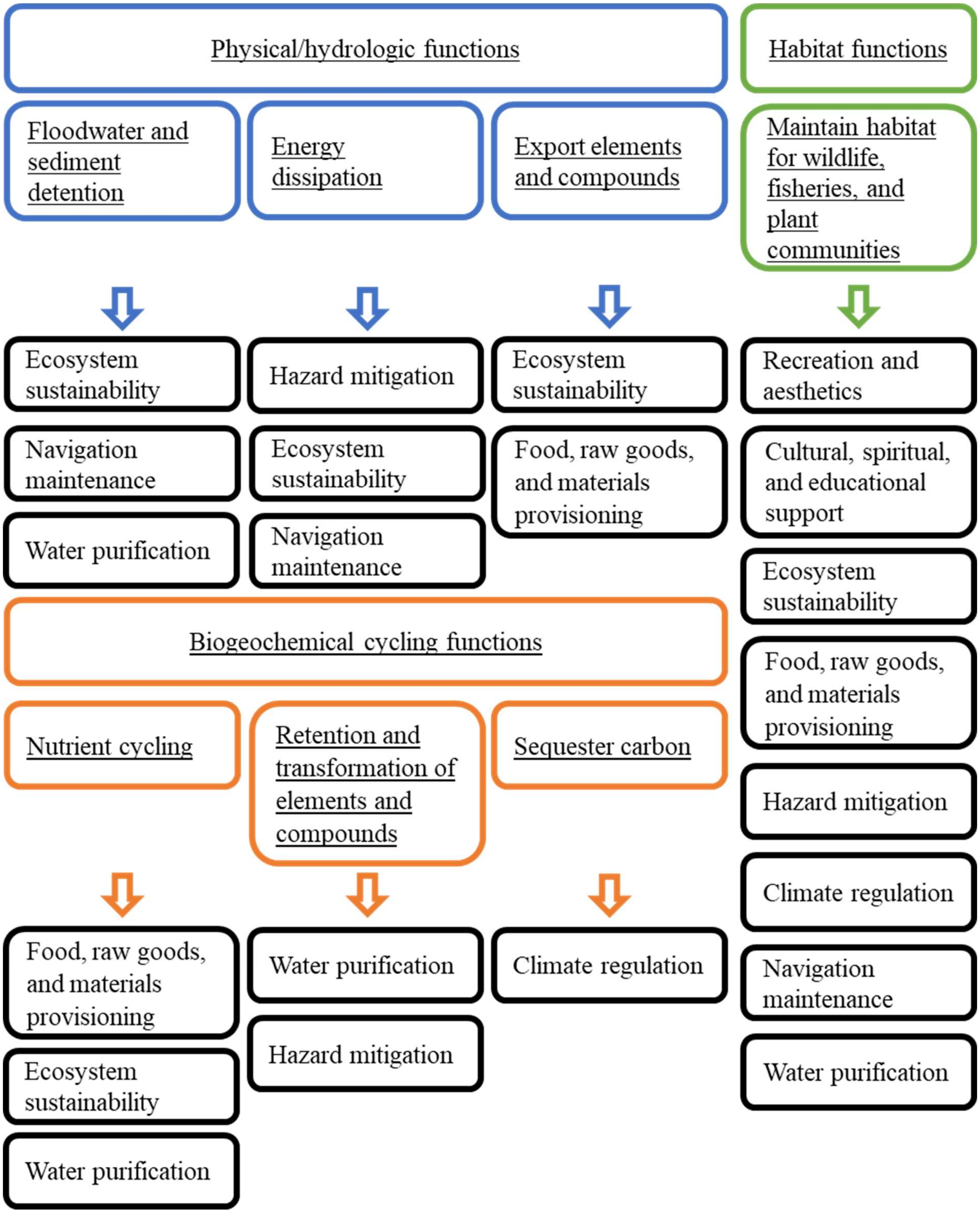

Figure 4. Relationship between ecological functions (underlined text in colored boxes) and resulting ecosystem goods and services (black boxes) that benefit society.

Table 5. Summary of ecosystem goods and services categories being delivered by each beneficial use project location.

Ecosystem goods and services categories	Study locations and target habitat types														
	Bolivar Peninsula, TX				Drake Wilson Island, FL			Buttermilk Sound, GA			Nott Isla., CT	Pointe Mou., MI	Miller Sands, OR		
	Low marsh	High marsh	Herbaceous upland	Woody upland	Low marsh	High marsh	Woody upland	Low marsh	High marsh	Unvegetated upland	Upland meadow	Freshwater marsh	Upland meadow	Tidal marsh	Dune
Ecosystem sustainability	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Hazard mitigation	X	X			X	X		X	X			X		X	
Navigation maintenance	X	X			X	X		X	X			X		X	
Cultural, spiritual, and educational support												X			
Recreation and aesthetics	X	X					X			X	X	X	X		
Food, raw goods, and materials provisioning	X	X						X	X			X		X	
Water purification	X	X			X	X		X	X			X		X	
Climate regulation	X	X			X	X		X	X			X		X	

not be interpreted to suggest that wetlands are 'better' than other landscape features in terms of potential beneficial use project outcomes, but instead highlights the fact that recognizing how ecosystem functions, goods, and services differ across the landscape can inform project design and management. Additionally, ecosystem components are not isolated and conditions or activities occurring in upland environments can impact the delivery of ecosystem functions, goods, and services in adjacent areas, including wetlands (Jones et al. 2018). As a result, management activities that apply regional or watershed perspectives (including dredging operations) are needed to maximize the delivery of ecosystem functions, goods, and services (Boerema and Meire 2017).

Notably, the observed relationships between the landforms created using dredged sediment and the delivery of ecosystem functions, goods, and services not only document beneficial use project outcomes, but also provides a mechanism to deliberately incorporate project design features that achieve specific environmental and societal objectives. For example, Berkowitz et al. (2016) demonstrated that biogeochemical and nutrient cycling (functions) and the associated improvements to water quality (goods and services) were maximized in dredged sediment beneficial use project features exposed to frequent inundation with carbon rich substrates. As such, projects seeking to remove excess nutrients for improved water quality should incorporate habitat components that mimic these environmental conditions. Similarly, Davis et al. (2021) linked ecosystem processes (i.e., sediment retention, habitat) with ecological goods and services (erosion, flood hazard mitigation) to quantify the flood risk reduction benefits of constructing barrier islands with dredged sediments, suggesting that specific ecological targets (surface elevation, percent cover of rooted vegetation) be incorporated into project designs and used to guide future management activities including additional dredged sediment deposition.

Finally, the results of the historic dredged sediment beneficial use assessment can also be used to develop conceptual ecosystem function trajectory curves to inform project life cycles (Figure 5; top panel). Previous studies demonstrate that the rate of ecological function delivery differs across functional categories, with physically derived functions delivering positive outcomes faster than biologically mediated processes (Meyer et al. 2008). For example, projects yield physical-process derived functions (energy dissipation)

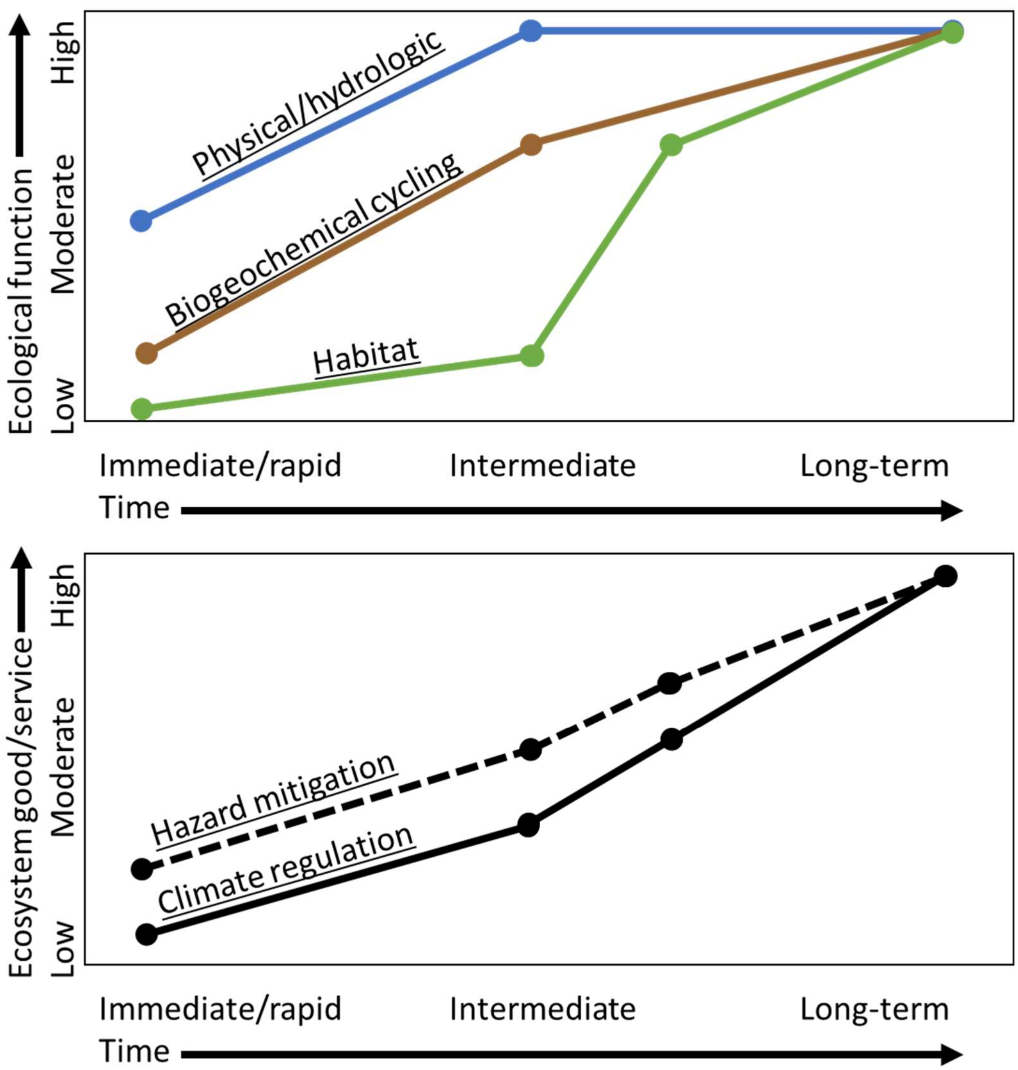

Figure 5. Conceptual trajectories for suites of ecological function (top panel) and two ecosystem services (bottom panel) following beneficial use project implementation.

immediately after construction, while most biogeochemical cycling and habitat functions require the accumulation of labile nutrients, microbial communities, and vegetative structures to become established (Berkowitz and White 2013). For example, dunes constructed using dredged sediment can dissipate energy immediately, while the development of mature forested habitats requires several decades (Davis et al. 2021; Berkowitz 2013).

Feedback loops alter the magnitude and rate of ecological functional trajectories over a project life cycle, especially with regard to biologically mediated process which experience threshold effects such as the establishment of woody vegetation or canopy closure. For example, the initial benefits delivered by dune establishment are enhanced with the expansion of beach grasses that fortify the features and help to entrap additional sediment over time (Feagan et al. 2015). Additionally, the shape of the trajectories differs across landform and habitat types as ecological succession occurs. For example, while unvegetated dredged sediment deposits provide valuable habitat for shore-nesting birds following project construction, habitat for those species declines as vegetation becomes established and forest growth induces a habitat shift toward species that require woody plants (Soots and Parnell, 1975).

Conceptual ecosystem goods and services trajectory curves can also be generated using the assessment results (Figure 5; lower panel). These curves are derived from the relative proportion of functional drivers depicted in the functional trajectory diagram, providing an example of how ecosystem functions, goods, and services are inter-related and can be linked to estimate anticipated changes over time. This approach provides a relative scale to estimate when, and to what extent, environmental and societal project objectives are likely to be realized. This has value because goods and services predominantly derived from physically driven ecosystem functions are likely to be delivered more rapidly and to a greater extent than outcomes associated with biologically mediated habitat and biogeochemical functions that take additional time to mature. For example, the hazard mitigation service is derived from a combination of physical, biogeochemical, and habitat functions (Figure 4) while the climate regulation service is predominantly associated with biogeochemical and habitat functions. As a result, the delivery of hazard mitigation benefits occurs faster and to a larger extent because of the influence of physical functions compared with climate regulation via soil carbon accumulation which is inherently biologically mediated (Berkowitz et al. 2021). Understanding and communicating these effects to practitioners and stakeholder groups can improve the perception of dredged sediment beneficial use projects by coupling ecological processes with societal objectives. While conceptionally derived, these curves provide a mechanism to link ecological functions and ecosystem goods and services in a systematic way that can be used to further promote specific project objectives, support alternatives analysis, and address uncertainties related to dredged material beneficial use project outcomes.

CONCLUSIONS

In order to address the economic and environmental challenges facing society in the coming decades, practitioners must focus on maximizing the available ecosystem functions, goods, and services that dredged sediment beneficial use projects can provide. Evaluating historic dredged sediment beneficial use projects is valuable because it provides a platform to document long-term project outcomes. Our findings suggest that linking ecological functions with an established ecosystem goods and services framework provides a mechanism to document the full suite of positive project environmental and societal outcomes provided by dredged sediment beneficial use projects. This approach will further promote continued innovation and help to offset increasing project construction costs, manage risk and uncertainty related to the use of natural processes and natural infrastructure, support holistic project life-cycle analysis, and effectively communicate project benefits to a variety of stakeholders. These analyses also assist with the quantification of the relative benefits delivered by specific design features or management activities and the trajectory of those benefits over time. As a result, we recommend that practitioners incorporate the concepts described herein into their projects. We anticipate that the proposed approach will be revised and improved iteratively as additional research quantifies and parameterizes models and other tools linking project features and management activities with changes in ecological functions, goods, and services.

REFERENCES

Barbier, E.B. (2013). "Valuing ecosystem services for coastal wetland protection and restoration: Progress and challenges," Resources, 2(3):213-230.

Baustian, J.J. and Eugene Turner, R. (2006). "Restoration Success of Backfilling Canals in Coastal Louisiana Marshes," Restoration Ecology, 14: 636-644. https://doi.org/10.1111/j.1526-100X.2006.00175.x

Berkowitz, J.F. (2013). "Development of restoration trajectory metrics in reforested bottomland hardwood forests applying a rapid assessment approach," Ecological indicators 34:600-606.

Berkowitz, J.F., and White, J.R. (2013). "Linking wetland functional rapid assessment models with quantitative hydrological and biogeochemical measurements across a restoration chronosequence." Soil Science Society of America Journal, 77(4):1442-1451.

Berkowitz, J.F., Green, L., VanZomeren, C.M. and White, J.R. (2016). "Evaluating soil properties and potential nitrate removal in wetlands created using an engineering with nature based dredged material placement technique," Ecological Engineering 97:381-388.

Berkowitz, J.F., Beane, N.R., Hurst, N.R., Jung, J.F., and Philley, K.D. (2021). "An assessment of Long-Term, Multipurpose Ecosystem Functions and Engineering Benefits Derived from Historical Dredged Sediment Beneficial Use Projects," Vicksburg, MS: US Army Engineer Research and Development Center Technical Report ERDC/TR-21-4.

Bianchi, T.S., DiMarco, S.F., Cowan Jr, J.H., Hetland, R.D., Chapman, P., Day, J.W. and Allison, M.A. (2010). "The science of hypoxia in the Northern Gulf of Mexico: a review," Science of the Total Environment 408(7):1471-1484.

Boerema, A. and Meire, P. (2017). "Management for estuarine ecosystem services: a review," Ecological Engineering, 98:172-182.

Bouwma, I., Schleyer, C., Primmer, E., Winkler, K.J., Berry, P., Young, J., Carmen, E., Špulerová, J., Bezák, P., Preda, E. and Vadineanu, A. (2018). "Adoption of the ecosystem services concept in EU policies," Ecosystem Services 29:213-222.

Bridges, T.S., Lillycrop, J., Wilson, J.R., Fredette, T.J., Suedel, B., Banks, C.J., and Russo, E.J. (2014). "Engineering with Nature Promotes Triple-Win Outcomes," Terra Et Aqua. 135:17-23.

Britsch, L. D., & Dunbar, J. B. (1993). "Land loss rates: Louisiana coastal plain," Journal of Coastal Research, 324-338.

Brown, T.C., Bergstrom, J.C. and Loomis, J.B. (2007). "Defining, valuing, and providing ecosystem goods and services," Natural Resources Journal 47(2):329-376.

Central Dredging Association. (2013). "Ecosystem Services and Dredging and Marine Construction," CEDA Information Paper, May 2013.

Chesney, E.J., Baltz, D.M. and Thomas, R.G. (2000). “Louisiana estuarine and coastal fisheries and habitats: perspectives from a fish's eye view,” Ecological Applications, 10(2):350-366.

Costanza, R., Farber, S.C., and Maxwell, J. (1989). "Valuation and management of wetland ecosystems," Ecological economics 1(4):335-361.

Daily, G.C., Söderqvist, T., Aniyar, S., Arrow, K., Dasgupta, P., Ehrlich, P.R., Folke, C., Jansson, A., Jansson, B.O., Kautsky, N. and Levin, S. (2000). “The value of nature and the nature of value,” Science 289(5478):395-396.

Davis, J., Whitfield, P., Szimanski, D., Golden, B.R., Whitbeck, M., Gailani, J., Herman, B., Tritinger, A., Dillon, S.C. and King, J. (2022). “A framework for evaluating island restoration performance: A case study from the Chesapeake Bay. Integrated Environmental Assessment and Management,” 18(1):42-48.

Davis, J., P. Whitfield, D. Szimanski, B. R. Golden, M. Whitbeck, J. Gailani, B. Herman, A. Tritinger, S. C. Dillon, and J. King. (2021). “A Framework for Evaluating Island Restoration Performance: A Case Study from the Chesapeake Bay.” Integrated Environmental Assessment and Management. https://doi.org/10.1002/ieam.4437.

De Groot, R.S., Wilson, M.A., and Boumans, R.M. (2002). “A Typology for the Classification, Description and Valuation of Ecosystem Functions, Goods and Services,” Ecological Economics 41(3):393–408.

Feagin, R.A., Figlus, J., Zinnert, J.C., Sigren, J., Martínez, M.L., Silva, R., Smith, W.K., Cox, D., Young, D.R. and Carter, G. (2015). “Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion,” Frontiers in Ecology and the Environment, 13(4):203-210.

Foran, C.M., Burks-Copes, K.A., Berkowitz, J., Corbino, J. and Suedel, B.C. (2018). “Quantifying Wildlife and Navigation Benefits of a Dredging Beneficial-Use Project in the Lower Atchafalaya River: A Demonstration of Engineering with Nature®,” Integrated environmental assessment and management 14(6):759-768.

Gómez-Baggethun, E., De Groot, R., Lomas, P.L. and Montes, C. (2010). “The history of ecosystem services in economic theory and practice: from early notions to markets and payment schemes,” Ecological economics 69(6):1209-1218.

Gunderson, L. H., Cosens, B., and Garmestani, A.S. (2016). “Adaptive governance of riverine and wetland ecosystem goods and services,” Journal of environmental management, 183:353-360.

International Association of Dredging Companies. (2013). “Facts About Ecosystem Services & Dredging,” An Information Update from the IADC, 4.

Jenkins, W.A., Murray, B.C., Kramer, R.A., and Faulkner, S.P. (2010). “Valuing ecosystem services from wetlands restoration in the Mississippi Alluvial Valley,” Ecological Economics 69(5):1051-1061.

Jones, C.N., McLaughlin, D.L., Henson, K., Haas, C.A. and Kaplan, D.A. (2018). “From salamanders to greenhouse gases: does upland management affect wetland functions?” Frontiers in Ecology and the Environment, 16(1):14-19.

Kolman, R. (2014). “Introducing ecosystems services for port development,” Environment and Sustainability, 62:181-183.

Landin, M.C., Webb, J.W., and Knutson, P.L (1989). "Long-Term Monitoring of Eleven Corps of Engineers Habitat Development Field Sites Built of Dredged Material, 1974–1987," Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station Technical Report D-89-1.

McLaughlin, D.L. and Cohen, M.J. (2013). "Realizing ecosystem services: wetland hydrologic function along a gradient of ecosystem condition," Ecological Applications, 23(7):1619-1631.

Meyer, C.K., Baer, S.G. and Whiles, M.R. (2008). "Ecosystem recovery across a chronosequence of restored wetlands in the Platte River Valley," Ecosystems, 11(2):193-208.

Novitski, R.P., Smith, R.D. and Fretwell, J.D. (1996). "Wetland functions, values, and assessment," National Summary on Wetland Resources, USGS Water Supply Paper, 2425:79-86.

Nyman, J.A. (2011). "Ecological functions of wetlands". Wetlands:115-128. Springer, Dordrecht.

R. Daniel Smith, Chris V. Noble, and Jacob F. Berkowitz (2013). "Hydrogeomorphic (HGM) Approach to Assessing Wetland Functions: Guidelines for Developing Guidebooks (Version 2)," ERDC/EL TR-13-11, Environmental Laboratory, Engineer Research and Development Center, Vicksburg, MS.

Soots Jr, R.F. and Parnell, J.F. (1975). "Ecological succession of breeding birds in relation to plant succession on dredge islands in North Carolina," University of North Carolina Sea Grant Publication UNC-SG-75-27.

Swanson, F.J., Kratz, T.K., Caine, N. and Woodmansee, R.G. (1988). "Landform effects on ecosystem patterns and processes," BioScience, 38(2):92-98.

Turner, R.E. and McClenachan, G. (2018). "Reversing wetland death from 35,000 cuts: Opportunities to restore Louisiana's dredged canals," PloS one, 13(12).

United States Army Corps of Engineers (USACE). (2012). "Regional supplement to the Corps of Engineers wetland delineation manual: North Central and Northeast region (Version 2.0), ed. J.F. Berkowitz, R. Lichvar, C.V. Noble, J.S. Wakeley. Vicksburg, MS: US Army Engineer Waterways Experiment Station Technical Report ERDC/EL TR-12-1.

United States Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). (2018). "Field Indicators of Hydric Soils in the United States, Version 8.2". L.M. Vasilas, G.W. Hurt, and J.F. Berkowitz (eds.). USDA-NRCS, in cooperation with the National Technical Committee for Hydric Soils.

Wainger, L.A., McMurray, A., Griscom, H.R., Murray, E.O., Cushing, J.A., Theiling, C.H. and Komlos, S.B. (2020). "A proposed ecosystem services analysis framework for the US Army Corps of Engineers," Vicksburg, MS: US Army Engineer Research and Development Center Technical Note ERDC/El SR 20-2.

Wellman, K., and Gregory, R. (2002). "Trade-off Analysis for the Use of Environmental Windows," Journal of Dredging, 4(2).

Yan, N., Liu, G., Xu, L., Deng, X. and Casazza, M. (2021). "Energy-based eco-credit accounting method for wetland mitigation banking," Water Research, 210.

ACKNOWLEDGEMENTS

Funding for this study was provided by the U.S. Army Corps of Engineers Dredging Operations Environmental Research Program. We thank the following USACE collaborators who made this study possible by assisting with site access and laboratory analysis: Mr. Jose Vargas (Galveston District); Mr. Richard Allen (Mobile District); Mr. Glenn Bacon (Savannah District); Dr. Kyle Tidwell (Portland District); Mr. Todd Randall (New England District); and Ms. Christina Saltus and Ms. Sydney Bufkin (Engineer Research and Development Center). The authors also thank three peer reviewers and the handling editor for providing insightful and valuable feedback.

AIMS AND SCOPE OF THE JOURNAL

WEDA's peer-reviewed papers in this practice-oriented journal present solutions to dredging, dredged material placement, and related issues. Submissions on all related topics are of interest to our readers. Examples include, but are not limited to, dredging techniques, hydrographic surveys, dredge automation, dredge safety, instrumentation, design of dredging projects, dredged material placement, transport of sediment through pipes, design of dredging equipment, dredging software, physical modeling of equipment and processes, cost estimating, environmental dredging, beneficial uses, Engineering with Nature®, contaminated sediments, litigation, economic aspects, and case studies.

The *Journal of Dredging* is published by the Western Dredging Association (WEDA) to disseminate technical and project information on all dredging-related topics to the broadest possible audience. In addition to the Journal, WEDA sponsors annual technical conferences covering the Western Hemisphere and smaller regional conferences focused on more geographically relevant topics. WEDA collaborates with the Central Dredging Association (CEDA) and Eastern Dredging Association (EDA) to hold the World Dredging Congress (WODCON) every three years. Historical conference proceedings are available at http://westerndredging.org.

NOTES FOR CONTRIBUTORS

The Journal of Dredging welcomes technical papers from all prospective authors regardless of employment or location. Editorials and commentaries will be considered provided they are fact-based and of interest to the Journal readership. Published manuscripts will not contain evident commercialism or promote private or political interests.

Submission of a manuscript implies that it is not under consideration for publication elsewhere and that original, previously unpublished work is being presented. Authors should obtain all necessary approvals for publication from employers or others involved before submitting a paper.

Papers should be concisely written in U.S. English, free of grammatical and spelling errors, and contain appropriate illustrations, figures, and equations. Papers must be appropriately cited to show that the work is scientifically sound and based upon previously published scientific literature. Published manuscripts will not exceed 20 total pages. Appendices are not allowed.

Manuscript preparation information, formatting requirements, and submission information can be found at https://www.westerndredging.org/journal. Authors are encouraged to use the Microsoft Word template provided on that webpage to facilitate proper manuscript formatting.

Authors will be responsible for producing the final, print-ready versions of the paper and providing them to the journal in PDF format unless other arrangements are made in advance with the Editor. The journal will be reproduced directly from the camera-ready manuscripts supplied by the authors.

Copyright of published papers will be the property of the Western Dredging Association. Authors are granted permission to reprint the paper, provided the copyright information is retained.

Send all manuscript and journal-related questions to journal@westerndredging.org.