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Challenges and Innovations in Sand Dredging and Sustainable Management of Dredged Material: A Comprehensive Review

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ABSTRACT: Sand dredging is a crucial activity for maintaining navigable waterways, replenishing beaches, and supporting coastal development, but it also poses significant environmental challenges due to its impact on marine ecosystems and coastal stability. The management of dredged material from these activities is essential for balancing economic development with environmental conservation. This review paper explores the various aspects of sand dredging and the management of dredged materials, highlighting both the benefits and the potential risks associated with these practices. The paper begins by outlining the importance of sand dredging for maintaining waterway access and replenishing eroded coastlines, emphasizing its role in coastal protection and economic development. It then delves into the environmental impacts of sand dredging, including habitat disruption, sedimentation, and alteration of coastal dynamics. Additionally, the review discusses regulatory frameworks and best practices for sustainable sand dredging, focusing on minimizing adverse effects on marine ecosystems. Furthermore, the management of dredged material is examined, encompassing disposal options such as beach nourishment, beneficial reuse, and offshore placement. The paper evaluates the challenges and opportunities in implementing effective dredged material management strategies, emphasizing the need for integrated approaches that consider ecological, economic, and social factors. In conclusion, this review synthesizes current knowledge on sand dredging and the management of dredged materials, highlighting key issues, innovative solutions, and future directions for sustainable coastal development.

KEYWORDS: Sand dredging, Dredged material, Coastal management, Environmental impacts, Sustainable development

I. INTRODUCTION

Sand dredging is an essential part of managing riverine and coastal resources since it shapes the terrain and facilitates a range of human endeavours. The growing need for this necessary building material is what propels the removal of sand from riverbeds and coastal regions. Sand dredging, however, poses serious environmental risks, including destruction of habitats, erosion, and deterioration of water quality. Maintaining the biological integrity of aquatic ecosystems while satisfying the demands of society for building materials requires effective management of dredged material. This entails putting into practise environmentally friendly dredging procedures, using cutting-edge technology, and creating solid plans for the advantageous reuse of dredged material. Understanding and resolving the environmental effects of sand dredging is essential for the appropriate and sustainable use of this essential natural resource as societies work towards economic growth. Managing dredged material requires balancing a number of intricate factors, including economic, regulatory, and environmental ones. If dredged debris is not disposed of carefully, it may have a significant impact on aquatic and terrestrial ecosystems. Innovative solutions are being used, such as the advantageous repurposing of dredged material in land reclamation, building, and restoration projects. These methods lessen the environmental impact of dredging operations while supporting sustainable development by turning what was before thought of as garbage into a useful resource.

Social and economic aspects are just as important to the efficient handling of dredged debris as environmental ones. The lives of local residents often depend on water bodies, and the repercussions of sand dredging might go beyond the

immediate ecological implications. Sand extraction has economic advantages, but maintaining the integrity of ecosystems is also important. To achieve this, a complete strategy that includes community involvement, environmental impact assessments, and strict regulatory compliance is needed. The accuracy and effectiveness of sand dredging operations are also greatly enhanced by technological developments in dredging machinery and monitoring instruments. Operators can optimise dredging procedures and reduce disruption to aquatic environments by using real-time data gathering and analysis. Furthermore, a step in the right direction towards reducing the negative environmental effects of sand extraction is the development of environmentally friendly dredging technology, such as suction dredgers that lessen sediment resuspension.

1.1 Challenges and Concerns in Sand Dredging

Ecological Consequences: Assessing the Impact on Marine Ecosystems

An essential operation for many sectors, sand dredging presents a number of difficulties and worries, especially with regard to its environmental effects. The process of sand mining has a significant impact on marine ecosystems, particularly as demand for the material rises. Dredging activities may generate disturbances that change the topography of the seabed, which can result in the loss of habitat for a variety of marine species. Furthermore, sediment discharge into the water may have a detrimental effect on the quality of the water, harming aquatic life and upsetting the fragile ecosystem's equilibrium. Ensuring sustainable sand dredging practises that minimise damage to marine habitats requires an understanding of and commitment to minimising these ecological impacts.

Regulatory Frameworks: Navigating the Complexities of Dredging Laws

The intricate regulatory frameworks that govern the sand dredging sector provide additional difficulties for the operation. A thorough awareness of environmental, social, and economic aspects is necessary to navigate the complexities of dredging rules and regulations at the local, national, and international levels. Sustainable and ethical sand mining depends on legal compliance; nevertheless, due to the heterogeneous and sometimes incompatible character of these frameworks, regulatory agencies and industry players may encounter difficulties. Developing and enforcing effective dredging legislation requires striking a balance between promoting economic growth and protecting environmental concerns. In order to promote a responsible and transparent sand dredging sector that is in line with environmental conservation objectives, it is imperative to address these legislative complications.

1.2 Dredged material management categories

In 1987, a national workshop was held for beneficial use of dredged material in inland waterways (Landin 1988). The national workshop included the USACE-HQ Dredging Division Chief (Bill Murden), various district personnel, USACE Researchers, U.S. Environmental Protection Agency (USEPA), Environment Canada, federal and state resource agencies, and academia. This workshop emphasized the importance of continuity between navigational dredging and the relocation of sediment for beneficial purpose. Projects in need of sediment will benefit from navigation dredging projects; and, sustainable navigation is dependent on finding cost-efficient opportunities for beneficial use of the dredged sediment. Today's navigation managers clearly consider beneficial use of sediment as a dredged material management alternative based on responses from the questionnaire survey. However, consistent dredged material management terminology which differentiates disposal from beneficial use is not yet available. The USACE and others in the dredging industry have many examples of successful projects that have relocated sediment for beneficial purpose, yet an accurate account is not currently available. Terminology that differentiates disposal of dredged sediment from the beneficial use of dredged sediment is obviously needed.

1.3 Environmental impacts

Sand dredging and the management of dredged material can have significant environmental impacts, affecting various aspects of aquatic ecosystems and coastal environments. Here are some key environmental impacts associated with these activities: Sand dredging alters the natural substrate and physical features of riverbeds, lakes, and coastal areas. The removal of sand can disrupt and destroy important habitats for aquatic plants, invertebrates, and fish, affecting biodiversity. Dredging stirs up sediment from the bottom, increasing turbidity in the water column. This reduces light penetration, which can harm submerged vegetation that depends on photosynthesis. Suspended sediment can also smother bottom-dwelling organisms and affect water quality. Dredging can modify natural water flow patterns, particularly in rivers and estuaries. Changes in flow velocity and direction can impact sediment transport, erosion, and deposition processes, leading to further habitat alterations downstream.

The noise and vibrations generated by dredging equipment can disturb or displace aquatic species, including fish, shellfish, and marine mammals. Additionally, dredging operations may inadvertently capture and harm non-target species. Dredged material often contains pollutants such as heavy metals, pesticides, and hydrocarbons, which can be released into the water during dredging operations. This can result in water and sediment contamination, posing risks to aquatic life and human health. Changes in sediment composition due to dredging can influence nutrient cycling and the availability of food resources for aquatic organisms. This can trigger cascading effects throughout the food web, potentially leading to shifts in species composition and ecosystem functioning. Excessive or poorly managed sand extraction can exacerbate coastal erosion by removing sediment that would naturally contribute to shoreline stability. This can increase vulnerability to storm surges and sea-level rise, impacting coastal communities and habitats.

After dredging, the ecosystem may struggle to recover naturally. Re-establishment of native vegetation and habitat structure can be slow, particularly if the dredged area experiences continued disturbances or if the dredged material is not properly managed. Efforts to mitigate these impacts include careful site selection, use of sediment traps and barriers to minimize sediment dispersal, adoption of environmentally friendly dredging techniques, and proper disposal or beneficial reuse of dredged material. Comprehensive environmental impact assessments and monitoring programs are essential to minimize the adverse effects of sand dredging and ensure the sustainable management of aquatic environments.

1.4 Economic aspects of sand dredging

Sand dredging, the process of removing sand from the seabed or riverbed, has several economic aspects that influence its practice and management. The economic considerations of sand dredging encompass both the benefits derived from the extracted sand and the costs associated with the dredging process and its impacts. Firstly, sand dredging is economically significant due to the vital role of sand in construction and infrastructure development. Sand is a crucial raw material used in making concrete, and its availability impacts construction costs and timelines. Therefore, a steady and affordable supply of sand, facilitated by dredging, supports the construction industry's growth and infrastructure projects, thus contributing to economic development. The economic impact of sand dredging extends to job creation and local economies. Dredging operations require skilled and unskilled labor for extraction, transportation, and processing activities. This generates employment opportunities in coastal regions or near riverbanks where dredging activities are concentrated. Moreover, the sale and distribution of dredged sand contribute to local economies by stimulating trade and commerce related to construction materials.

However, the economic benefits of sand dredging must be balanced against its costs and associated environmental impacts. One critical aspect is the cost of dredging operations, including equipment maintenance, fuel, and labor costs. The profitability of dredging projects depends on market demand for sand, regulatory constraints, and operational efficiencies. Furthermore, the management of dredged material adds economic dimensions to sand dredging activities. Dredged sand often requires proper disposal or reuse to minimize environmental impacts and optimize economic value. Effective management strategies involve identifying suitable disposal sites, exploring options for recycling or repurposing dredged material, and adhering to regulatory requirements—all of which have cost implications for dredging operators. In summary, the economic aspects of sand dredging are multifaceted, influencing construction industries, local economies, and environmental management. While sand dredging supports economic growth through its contributions to infrastructure development and job creation, careful consideration of costs and environmental impacts is essential for sustainable and responsible dredging practices.

II. RELATED WORK

Fulvio Onorati et.al (2013) describes the application of LSQGs to the harbour of Fiumicino (Rome, Italy). The aims were to evaluate the quality of dredging sediments through an integrated chemical–ecotoxicological approach and to define suitable management options. Thirty-eight sediment cores, covering the planned dredging depth, were collected in the study area and sliced into 92 sediment samples. Chemical analyses, including inorganic and organic contaminants as well as microbiological parameters, were carried out for all the samples. A bioassay battery composed by the bacterium *Vibrio fischeri*, the sea urchin *Paracentrotus lividus* and the alga *Dunaliella tertiolecta* was applied on one third of the samples. LSQGs were derived from chemical and ecotoxicological data of the harbour area, and were integrated with those from the identified dumping site. The Baseline Chemical Level, corresponding to an absent or unlikely ecotoxicological hazard, and the Limit Chemical Level, corresponding to a probable ecotoxicological hazard, were the LSQGs derived for each chemical.

G. Cevikbilen et.al (2015) presents the construction, expansion or deepening, and maintenance stages of a port generate tons of dredged sediments. Dumping the dredged sediments in nearby marine waters is the most commonly preferred method. The non-hazardous dredged material can be assessed as a resource and therefore a raw material that will not be wasted. The use of these sediments as construction fill materials might be one of the beneficial usage alternatives. This study illustrates the preliminary findings of geotechnical evaluation of dredged sediments recovered from six port sites placed at Black Sea, Marmara Sea, Aegean Sea and Mediterranean Sea of Turkey. The grain size distribution and the consistency limit tests were performed to classify the samples according to AASHTO and Unified Soil Classification system.

Pembe Ozer-Erdogan et.al (2016) describes the potential beneficial use of untreated and treated marine dredged material (DM) in ready-mix concrete (RMC) as a fine aggregate. DMs collected from four Turkish ports/harbours were characterized, assessed according to the National Legislation and transformed into one composite DM. Silica sand was replaced with untreated- and treated-composite-DM (COMP-U/COMP-T) at five ratios (0%, 25%, 50%, 75%, 100%), respectively. Mechanical, durability, leaching, mineralogical/micro-structural properties of DM-based-RMCs were analysed. Concretes having 50% COMP-U and 100% COMP-T met the minimum requirement for C25/30 class RMC. Marine DM can be beneficially used in RMC production; however, DM pre-treatment should be applied.

Omran Frihy et.al (2016) present study is the first attempt in Egypt to assess feasibility of using of dredging material from Damietta Harbor in the northwestern Nile Delta for erosion control. The study also provides an economic evaluation for the shoreline management alternatives selected to mitigate for the effects of coastal erosion at two pilot eroding areas (namely, A and B) located near the Damietta Harbor. Results of compatibility analysis reveal that the dredging material is fairly compatible with the native sand of the nearby eroding beaches. In addition to soft nourishment by dredged sand, other types of coastal engineering measures which are often used in erosion management area were also evaluated as alternatives for erosion control and mitigation solution. Economic feasibility assessment by means of cost-benefit analysis of direct and indirect items has been carried out to facilitate comparison between these alternatives.

C. Sheehan et.al (2012) examines the main aspects of the Irish dredging industry with comparison to international practice and standards, including the source of the dredge material and volumes generated annually, the dredging plant employed and the management processes currently practised. Relevant European and Irish legislation governing dredging, disposal at sea and waste licensing are presented. The potential impacts of disposal at sea are discussed with the implications for the Irish dredging industry of recently introduced European Directives assessed. Beneficial use rates for dredge material and the techniques implemented in Ireland are examined and compared with international practice. Recent notable beneficial use projects for dredge material and proposed innovative dredge material management techniques for specific dredging projects in Ireland are presented.

M. Bahgat et.al (2018) studied Coastal zone of Egypt Nile Delta is exposed to an extensive changes due to natural and artificial influences. These changes have induced erosion problems along coastlines of Nile Delta. Near or foreshore replenishment is an alternative approach in many areas instead of hard structures to avoid negative impact of coastal structures. The frequent maintenance dredging works of ports approach channels could be considered as possible sources of sand, which may be used to address sediment budget and to help overcome coastal erosion at key strategic locations. Two-dimension morphological numerical model (2DH) was developed using Delft3D to study and predict the effect of using dredged sediment from the approach channel on minimizing the retreat of shoreline at the area subjected to erosion.

Zachary A. Collier et.al (2014) investigate Dredging and disposal issues often become controversial with local stakeholders because of their competing interests. These interests tend to manifest themselves in stakeholders holding onto entrenched positions, and deadlock can result without a methodology to move the stakeholder group past the status quo. However, these situations can be represented as multi-stakeholder, multi-criteria decision problems. In this paper, we describe a case study in which multi-criteria decision analysis was implemented in a multi-stakeholder setting in order to generate recommendations on dredged material placement for Long Island Sound's Dredged Material Management Plan. A working-group of representatives from various stakeholder organizations was formed and consulted to help prioritize sediment placement sites for each dredging center in the region by collaboratively building a multi-criteria decision model. The resulting model framed the problem as several alternatives, criteria, sub-criteria,

and metrics relevant to stakeholder interests in the Long Island Sound region. An elicitation of values, represented as criteria weights, was then conducted.

Pranshoo Solanki et.al (2023) examined dredged materials from various aspects, including their sources, the volume generated annually, beneficial uses, and the management processes currently practiced. In addition, this paper presents the relevant policies governing the dredging, reuse, and disposal of dredged materials in the United States. A summary of various sources, types/classifications, and the physical and chemical properties of dredged materials used by various researchers are presented. This paper also summarizes the innovative techniques for the beneficial reuse of dredged materials in a wide range of applications in concrete materials, construction products, roadway construction, habitat building, landfill liner/cap, agriculture soil reconstruction, and beach nourishment. Further, limitations and corresponding solutions related to the beneficial use and management of dredged materials were provided in the end.

Md. Motiur Rahman et.al (2020) presents Dredging is the relocation of earth which is mainly under or with water. This operation normally done to create or improve waterways and sometimes to improve the environment. There are several types of dredger such as cutter suction dredger, trailing suction hopper dredger, grab dredger, backhoe dredger, bucket dredger etc. Types of dredgers selected based on the location and soil properties. Dredged material normally disposed in open water or confined area. In some cases management of dredged material is a very complicated issue. Mongla Port is situated on the left bank of Pussur River at about 130 km upstream of Bay of Bengal. At establishment time of the port depths of Pussur River at present location were satisfactory for average 8.5 m draft ships. But, since 1970 the depths in this area started to deteriorate rapidly. Since then, regular maintenance dredging has been required to provide sufficient depth alongside the berths and in the approaches to the berths. Till now Mongla Port has carried out 172.28 lac cu.m dredging which is about 4.30 lac cu.m/year. In the year 2019-20, Mongla Port is implementing the 117 lac cu.m dredging at outer bar and food silo area. In 2020-2022, Mongla Port is planning to dredge the approach channel upto 8.5 m CD and the quantity will be about 216 lac cu.m

Katherine E. Brutsche et.al (2017) Nearshore placement is becoming an increasingly utilized method for the beneficial use of dredged material from operations and maintenance dredging of navigation channels. It is important to have an understanding of what happens to sediment once it is placed in the nearshore. To that end, the U.S. Army Engineer Research and Development Center created the Sediment Mobility Tool (SMT) to estimate frequency of sediment mobility and general transport direction. During the summer of 2015, sediment dredged from the St. Augustine Inlet ebb and flood shoals and the Atlantic Intracoastal Waterway was placed in the nearshore of Vilano Beach, Florida. The site was monitored using topo-bathymetric surveys, the Radar Inlet Observing System (RIOS), and camera arrays to help quantify morphologic evolution of the nearshore berms. The Coastal Modeling System was used to qualitatively evaluate changes in the hydrodynamic conditions of the study area due to the placement of the material in the nearshore.

V. Kapsimalis et.al (2013) The selection of the best site for the placement of dredged sedimentary material (~7,000 m³) from the Aliveri coastal area in the adjacent South Euboean Gulf (Greece) was accomplished through a screening procedure. The initial stage comprised the determination of physical, chemical, and biological characteristics of the dredged sediment before the commencement of any dredging operation. Grain size measurements, geochemical analyses together with the use of pollution/toxicity indices and empirical sediment quality guidelines, and the conduct of an acute toxicity test showed that the dredged material consisted of “unpolluted to slightly polluted” silty sands and sandy silts. However, the local authorities planned to place this sediment in the neighboring open sea area, i.e., the South Euboean Gulf, due to the absence of any beneficial use or alternative dumping option (i.e., dumping on public lands).

BRIAN C. MCFALL et.al (2019) In 2015, 115,000 m³ of material was dredged from St. Augustine Inlet and placed in the nearshore of Vilano Beach, Florida. Material was placed into two separate nearshore berms. To understand changes in the berms, one pre-construction survey and two post-construction surveys were conducted. The Radar Inlet Observing System (RIOS) was also deployed to illustrate morphologic changes in the berms between surveys. The Coastal Modeling System (CMS) and Sediment Mobility Tool (SMT) were used to illustrate and predict morphologic changes and impacts to the hydrodynamic conditions in the nearshore. Overall, the nearshore berms were observed by surveys and RIOS to move onshore and diffuse in the alongshore direction as correctly predicted by the SMT.

Remigiusz Duszyński et.al (2017) the supporting structure inside a coastal dike is often made of dredged non-uniform sand with good compaction properties. Due to the shortage of natural construction material for both coastal and river

dikes and the surplus of different processed materials, new experiments were made with sand-ash mixtures and fine-grained dredged materials to replace both dike core and dike cover materials resulting in economical, environmentally friendly and sustainable dikes. Ash from EC Gdańsk and dredged sand from the Vistula river were mixed to form an engineering material used for dike construction. The optimum sand-ash composites were applied at a field test site to build a large-scale research dike. Fine-grained dredged materials from Germany were chosen to be applied in a second full-scale research dike in Rostock. All materials were investigated according to the standards for soil mechanical analysis. This includes basic soil properties, mechanical characteristics, such as grain-size distribution, compaction parameters, compressibility, shear strength, and water permeability.

Assane Luis Pena et.al (2017) This work intends to access the sediments quality and to suggest potential uses of dredged material off the mouth of Figueira da Foz Harbor, at a frequently dredge area in order to keep port accessibility. Thirty-six sediment samples collected at an area of about 4 km² were submitted to textural, mineralogical (X-Ray Diffraction techniques) and geochemical (ICP-MS) analyses. Results evidenced that bottom sediments in the study area are composed mainly of sand. Fine fraction increases with distance to the FFH mouth. The mineralogical and geochemical analyses performed in 14 samples (with enough fine fraction for both analyses) indicate that the sediments sources are mostly related to the littoral drift and Mondego River, which flows into the region.

Que.1 Literature Review Summary and Comparison

Study Reference	Key Focus and Findings	Methodology/Approach	Application/Implication
Fulvio Onorati et al (2013)	Integrated chemical-ecotoxicological evaluation of dredging sediments; defined suitable management options.	Sediment core collection, chemical analyses, bioassay battery application.	Development of LSQGs for quality assessment and management decisions.
G. Cevikbilen et al (2015)	Geotechnical evaluation of dredged sediments for construction fill materials.	Grain size distribution, consistency limit tests.	Exploration of reuse options for dredged material in construction applications.
Pembe Ozer-Erdogan et al (2016)	Beneficial use of marine dredged material in ready-mix concrete; impact of material replacement on concrete properties.	Characterization of dredged materials, concrete testing.	Potential incorporation of marine dredged material into concrete production.
Omran Frihy et al (2016)	Feasibility assessment of using dredging material for erosion control in Egypt; economic evaluation of shoreline management.	Compatibility analysis of dredged material with eroding beaches.	Exploration of dredged material as a resource for coastal erosion mitigation.
C. Sheehan et al (2012)	Overview of Irish dredging industry; comparison with international standards; examination of beneficial use rates.	Analysis of dredging processes, legislative framework.	Assessment of Irish dredging practices against international standards.
M. Bahgat et al (2018)	Study on using dredged sediment for coastal erosion mitigation in Egypt;	Numerical modeling, morphological analysis.	Utilization of dredged material for erosion control using advanced modeling techniques.

	2DH morphological modeling.		
Zachary A. Collier et al (2014)	Implementation of multi-criteria decision analysis for stakeholder collaboration on dredged material placement.	Multi-stakeholder decision analysis approach.	Framework for collaborative decision-making on dredged material management.
Pranshoo Solanki et al (2023)	Examination of sources, volume, uses, and management practices of dredged materials; summary of policies in the US.	Review of dredged material properties and applications.	Compilation of dredged material information and limitations for various uses.
Md. Motiur Rahman et al (2020)	Overview of dredging operations at Mongla Port, Bangladesh; necessity and volume of maintenance dredging.	Description of dredging operations and volumes.	Insight into ongoing maintenance dredging requirements at Mongla Port.
Katherine E. Brutsche et al (2017)	Evaluation of nearshore placement of dredged material; morphologic and hydrodynamic impacts.	Monitoring of sediment placement, modeling of morphological changes.	Understanding of nearshore sediment placement effects for coastal management.
V. Kapsimalis et al (2013)	Screening procedure for selecting dredged material placement site; assessment of sediment quality.	Physical, chemical, and biological characterization of dredged sediment.	Decision-making framework for appropriate placement of dredged material.
BRIAN C. MCFALL et al (2019)	Monitoring of morphological changes in nearshore berms post-dredging; hydrodynamic impact assessment.	Pre- and post-construction surveys, hydrodynamic modeling.	Assessment of nearshore sediment placement effects on coastal morphology.
Remigiusz Duszyński et al (2017)	Experimentation with sand-ash mixtures and dredged materials for sustainable dike construction.	Investigation of sand-ash composites and dredged materials for dike construction.	Development of alternative materials for environmentally friendly dike construction.
Assane Luis Pena et al (2017)	Quality assessment and potential uses of dredged material for port accessibility; sediment source analysis.	Textural, mineralogical, and geochemical analyses of sediment samples.	Evaluation of sediment properties for reuse in port maintenance and development.

III. CONCLUSION

The management of sand dredging and the handling of dredged material are critical aspects of coastal and marine environmental management. Sand dredging, while essential for various human activities like construction and beach

nourishment, has profound impacts on ecosystems and coastal dynamics. It alters sediment transport patterns, affects biodiversity, and can lead to erosion and habitat loss if not properly managed. Effective management of sand dredging requires a balanced approach that considers both economic demands and environmental sustainability. Regulation and enforcement of dredging activities are essential to minimize adverse impacts. This includes implementing guidelines for sustainable dredging practices, such as using adaptive management strategies, employing sediment tracing technologies, and promoting ecosystem-based approaches. Furthermore, the management of dredged material is equally important. Dredged material can be reused beneficially for purposes like habitat restoration, land reclamation, and infrastructure projects. However, it often contains contaminants that must be carefully managed to prevent adverse effects on water quality and ecosystems. Collaborative efforts involving government agencies, researchers, industry stakeholders, and local communities are vital to developing effective dredging management strategies. Public awareness and engagement are key components for ensuring transparency and accountability in dredging operations. In conclusion, sustainable sand dredging and effective management of dredged material are essential for maintaining healthy coastal ecosystems and supporting coastal communities. By implementing science-based regulations and innovative management practices, we can minimize the negative impacts of dredging while maximizing its benefits for society and the environment.

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