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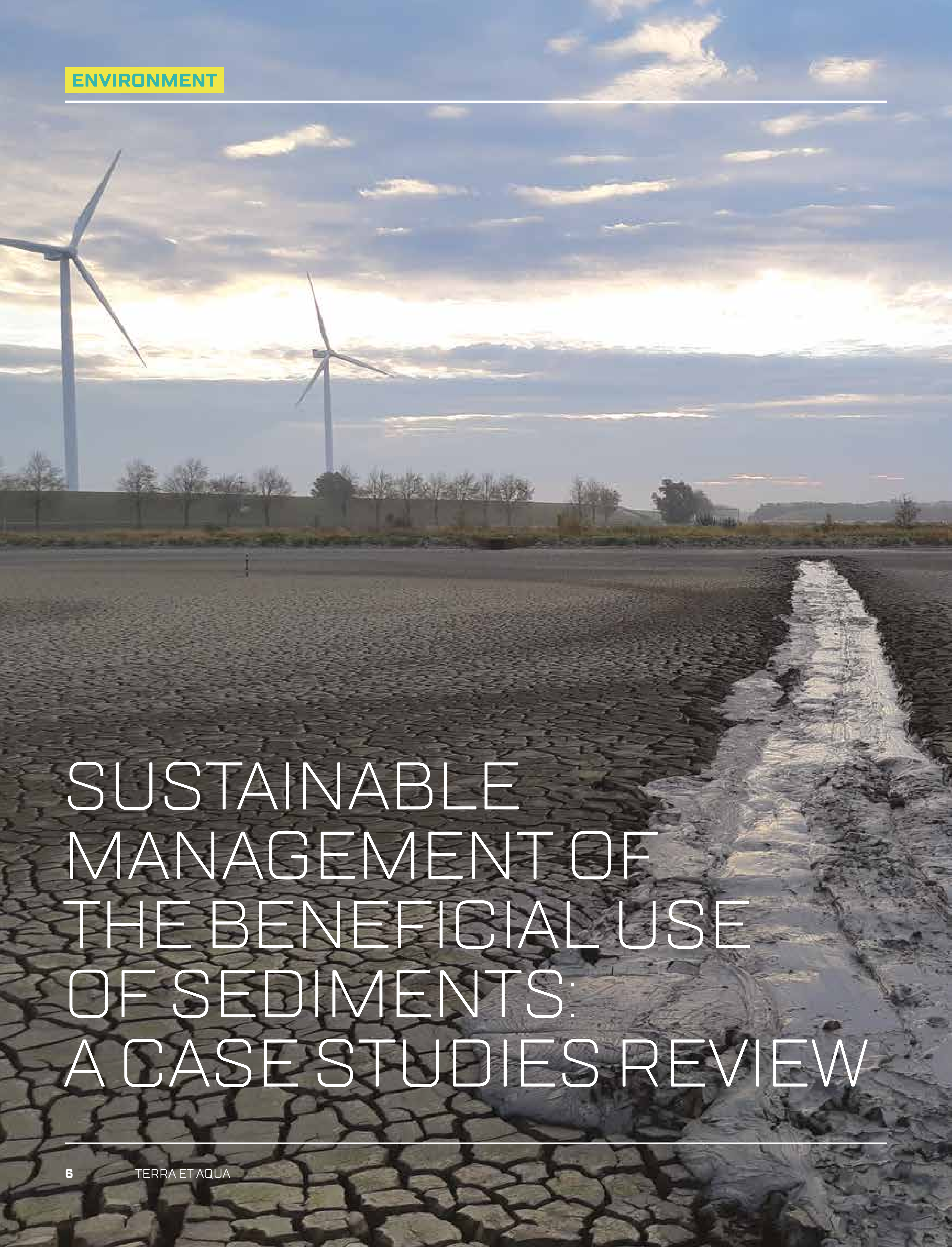

SUSTAINABLE MANAGEMENT OF THE BENEFICIAL USE OF SEDIMENTS: A CASE STUDIES REVIEW

Through its latest publication, the Central Dredging Association (CEDA) Working Group on the Beneficial Use of Sediments informs stakeholders and practitioners about the recent advances, ongoing international initiatives and programmes, and best management practices for the beneficial use and value of sediments using relevant case studies.

Over the last few decades there has been an increasing recognition that dredged sediment is a resource which should be utilised beneficially for human development activities and/or enhancement of ecological habitats.

Sediment as a resource

By describing the importance of sediments in the context of sustainable development and impact of climate change, this article aims to inspire international government agencies and policy makers, contractors, project proponents and international donors (i.e., World Bank) to encourage the implementation of sustainable sediment management strategies.

This review elaborates on previous literature and experience on this topic (e.g., PIANC 2009; IADC 2009; CEDA 2010). The Working Group on the Beneficial Use of Sediments (WGBU) researched and collated details from 38 case studies. The studies collected involved contaminated, as well as, clean sediments. These included studies that have been undertaken in 11 countries over the last 30 years, specifically focusing on the last decade. These case studies highlight many effective methods for beneficial use, supported by specific pilot and commercial project applications, assembled by an active community of practitioners with more than two decades of experience in this environmental area. This review intentionally focused on the technical aspects of these case studies to demonstrate feasibility. This article does not address legislation, economical, or governance aspects in detail. While very important, these are often country-specific, which would distract from the central scope of this article.

Based on the case studies collected, beneficial use examples range from dredged materials affected by anthropogenic sources and natural sediments, to be used for construction applications, or to help restore freshwater and marine habitats, with nature-based solutions becoming a prominent driver for sustainable sediment use in the last decade. In this article, we define beneficial use as the use of dredged or natural sediment in applications that are beneficial and in harmony to human and natural development.

While this article illustrates technical feasibility and success, to date, beneficial use of natural and dredged sediment remains below its overall potential. Technical aspects are often outweighed by country-specific legislation, policy, economics and public and industry perception (Brils et al. 2014). This complexity hampers the beneficial use of (dredged) sediments. Therefore, we recommend addressing these important aspects in a future publication in an effort to promote beneficial use practice to a level in which full potential can be realised and further in line with sustainable human development.

This article intends to demonstrate that beneficial use applications exist for clean, as well as, sediments contaminated with low-level pollutants. Dealing with contamination is perceived as challenging (both operationally and publicly); therefore, a separate complementary Position Paper by the Central Dredging Association (CEDA) was produced in 2019, by this same WGBU, that focuses on the risk management and beneficial use opportunities of sediments with various degree of contamination. For this article, case studies were made available by the WGBU members and their industrial contacts. Because the overview given in the article is not exhaustive, the authors openly invite the professional community to share their experiences with the CEDA community. The archival platform and email contact are available on the CEDA website to facilitate submission of additional and future case studies, and mutual knowledge exchange regarding the beneficial use of sediments worldwide.

Why sediment matters

The surface of the earth is being fractionised into sand, silt, and clay by the natural process of rock weathering. The fractions, or sediments, are (re)distributed over the earth's surface through erosion and sedimentation processes induced by ice, water, and air. In this way, nature shapes the landscapes of the Earth through continuous and episodic events. However, the impact of Man on these dynamic natural processes has increased tremendously in the last century, especially due to the development of (land or waterborne) infrastructural works. In 2017, *The Economist* stated 'humans now move more sediments than the natural processes of erosion'.

This likely, exaggerated, overstatement indicates that human interaction with natural processes is significant. Humans move sediment to enable and optimise:

- transport and logistics (e.g., dredging of ports and waterways for navigation);
- space for living and commercial activities (e.g., fill for land reclamation and remediation/brownfields);
- flood safety and water management (e.g., construction of dykes, breakwaters, dams); and
- natural ecosystem protection and enhancement (e.g., contaminated sites or wetland restoration, improving water clarity and quality).

Human interventions interact with the natural dynamics of sediment accumulation and erosion processes, which often disturbs the natural dynamic. Examples include: sediment trapped behind dams is not available to feed downriver floodplains or nourish a beach near the river mouth (Vörösmarty et al. 2003); sediment from river mouths, reallocated offshore, is not available to nourish a wetland anymore; excess deepening of estuaries is suspected to increase turbidity in major rivers (Winterwerp and Wang 2013; Winterwerp et al. 2013) and erosion of banks. Where disturbance to natural processes of sediment accumulation and erosion occurs, it can contribute to increase the vulnerability of natural systems and human developments, such as: coastal erosion and loss of land, flooding from sea or rivers, decrease of productivity and environmental quality of ecosystems (Winterwerp and Wang 2013; Winterwerp et al. 2013). Climate change, resulting in more frequent and more intense events (i.e., storms and hurricanes) and sea level rise, aggravates these risks and impacts further.

FIGURE 1

The restoration of an eroded coastline in Northern Java, Indonesia. Photo EcoShape

Dredging of sediments

Humans move most sediment by dredging. Unlike natural processes, like those that build and reduce shorelines seasonally, man-made infrastructure is static and less tolerant of dynamic sediment processes. The largest driver for dredging comes from the need to remove accumulated sediment from ports, harbours, and shipping channels in order to maintain their function as the backbone of our economy. Historically, the most common sediment management approach employed in many countries has been aquatic disposal of the dredged sediments at sea, or simply relocated in mid-river. This is particularly true for finer silts that are maintenance dredged from ports and harbors. In the UK alone, for example, around 22 to 44 million cubic meters (m^3) of sediment is dredged from ports and harbours every year (ABPmer 2017).

Over the last few decades there has been an increasing recognition that dredged sediment is a resource which should be utilised beneficially for human development activities and/or enhancement of ecological habitats. The need to seek beneficial use opportunities was identified as a priority within the International Maritime Organisation (IMO) (London Convention and London Protocol (IMO, 2014) and other dredged material management reviews and guidance (IADC 2009; CEDA 2010; OSPAR 2014; and HELCOM 2015). In 1992 and 2009, the World Association for Waterborne Transport Infrastructure (PIANC) established workgroups focused on preparing guidance regarding the beneficial use of dredged material (PIANC 1992; PIANC 2009). The PIANC (2009) report by the PIANC EnviCom

FIGURE 2

Dyke reinforcement underway in Hamburg, Germany. Photo Julia Gebert, TUD

Beneficial use may involve clean or contaminated sediments, when appropriately managed or treated, and when they provide added value.

Working Group 14 (chaired by CEDA) provided a forum for the development of guidance, for future consideration, of uses for dredged material on a routine basis. Since the publication of the PIANC paper, many new examples and initiatives have focused on the beneficial use of dredged sediments, as reported in this review. An appendix to this report provides wide-ranging case studies that demonstrate how dredged material has been used successfully worldwide.

Beneficial use of sediment

Beneficial use of sediment is herein defined as the use of dredged or natural sediment in applications that are beneficial and in harmony to human and natural development. Beneficial use may involve clean or contaminated sediments, when appropriately managed or treated, and when they provide added value. Considered in the context of the three pillars of sustainability (economic value, social gain and environmental benefit), many beneficial use projects typically achieve at least two of these objectives. Those projects which focus on habitat restoration have the potential to directly deliver all three. Since the mid- to late-1900s, knowledge about the natural environment – and its processes and dynamics – has advanced significantly. Environmental considerations, nature-based approaches, value engineering and win-win solutions (i.e., benefits/value for all stakeholders) are increasingly considered an integral part of dredging projects from an early stage. These advances highlight the central role of sediment management and have facilitated the development and implementation of innovative sediment uses. Several international programmes and initiatives seek to support the sustainable development of infrastructure through improved alignment and integration of engineering and natural systems.

International initiatives and programmes

There are several world-wide initiatives and programmes that are centered on sustainable, and nature-based, development of hydraulic and civil infrastructures. Beneficial use of sediment is a key, constant, theme across these programmes. Some of the most recent initiatives include:

- **Engineering with Nature (EwN)** was initiated by the US Army Corps of Engineers' Engineer Research Development Center (ERDC). The EwN programme has a specific focus on developing knowledge and practical experience regarding the use, and re-use, of dredged sediment in light of resilience and nature restoration. Their work is documented in many completed and ongoing case studies.
- **The Living Lab for Mud (LLM)** is hosted by EcoShape (EcoShape 2017). Similarly, and in partial collaboration with the EwN, the LLM is a living platform that brings together various EcoShape pilots related to sustainability, with nature (fine) sediments management to facilitate cross-pilot and international knowledge and experience exchange.
- **Working with Nature (WwN)** is similar to Building with Nature (BwN), EwN and PIANC, promoting the development of navigation-related projects based on the 'with nature' concept (PIANC 2008). Integrated and circular dredged sediment use is a central theme of this initiative.
- **SEABUDS (Precipitating a SEA Change in the Beneficial Use of Dredged Sediment)** which was led by the UK's Royal Society for the Protection of Birds (RSPB), involves reviews and meetings by key regulators and advisors to evaluate policy and practice in the field of beneficial use with a view to implementing more projects in the future (Ausden M et al., 2018).
- **Solent Forum (BUDS) Regional Strategic Review** is a project which is underway to strategically identify beneficial use project sites in the Solent (south coast of the UK) which has been underpinned by an innovative new study (by ABPmer http://www.abpmer.co.uk/buzz/cost-benefitanalysis-of-using-dredged-sediment-to-restore-andcreate-intertidal-habitat/) which reviews the costs

and benefits of using dredged sediment for marine habitat restoration, based on examples in Europe.

- **Using Sediment As a Resource (USAR)** and Promoting Integrated Sediment Management (PRISMA), are two European Union, North Sea Region initiatives covering England, France, The Netherlands and Belgium (Flanders). These programmes centre on developing alternative options, at no added cost, for the processing, treatment and beneficial use of sediments in estuaries and coastal waterways, from dredging to recycling, in lieu of the circular economy.
- **European Sediment Network (EU SedNet) Working Group on Sediment Quantity Management – Sediments on the Move From the Mountains to the Sea** (https://sednet.org/), with main objectives to increase the general awareness for sediment quantity management with the entire watershed system and to promote the sharing of experiences and best management practice in this field, in line with the CEDA WGBU.

Over the years, other beneficial use sediment programmes have contributed to the overall knowledge base, focusing on materials science (e.g., structural or geotechnical aspects) and sediment treatment (i.e., in the context of destroying or immobilising contaminants).

These include: SEDI.PORT.SIL, CEAMas, SETARMS, SEDILAB, GeDSET, the Sedimateriaux Approach and the USEPA/NJDOT New York and New Jersey Harbour Sediment Decontamination Programme. These programmes have been at the forefront of changing the perception of sediments from a 'waste' to a sustainable resource.

Several case studies and information included in this article are derived from these initiatives and therefore are concrete examples of achieving socially acceptable, economically viable and environmentally sustainable projects.

Classification of beneficial use of sediments

There are many different types of beneficial use applications, as well as different nomenclature and terminology associated with it. Therefore, adopting a unified classifying approach is not simple. For example, it is quite common to frame beneficial use potential in terms of geotechnical/structural material types (e.g., clay, rock, sand and silts). Alternatively, beneficial uses may be separated into categories based on final objective and end-use (i.e., engineering and/or environmental) or based on the dredging equipment/technique used (e.g., backhoe bucket mechanical dredge, trailing suction hopper dredge). In this article, beneficial uses are categorised according to five *end-use functions* the project fulfils (i.e., the application) and to the general operational *technique* used in the application.
Five major functions are here defined as 'the Five Rs':

1. **Raw Material**: substitution for virgin manufactured soil or building materials, such as tiles or aggregates.
2. **Remediation**: clean-up of contaminated sites, brownfields or closure of landfills and mines.
3. **Reclamation**: creating new, or expanding existing, land mainly for human/commercial development activities.
4. **Restoration**: creation of habitat to support aquatic organisms and wetlands to improve natural value.
5. **Resiliency**: shoreline nourishment and (dyke) reinforcement for defence against floods and extreme climatic events.

It is certainly recognised that some, in fact most, beneficial use applications fulfil more than one function. For example, dredged material can be a substitute for raw material, which can be used as a top layer of a landfill closure project or for dyke reinforcement; a contaminated site can be remediated as part of land reclamation for further redevelopment; a coastal nourishment can create habitat and improve flood safety and sea level rise resiliency; remediation of a mine can be part of a reclamation and restoration function to repair and mitigate a century of environmental impacts. In all these cases, the various applications are categorised following the major function, yet mentioning, and perhaps integrating, the other functions explicitly.

Furthermore, the various beneficial use applications can be divided into four broad techniques categorising the method used to implement the activity. These techniques are:

A. **On Land, Natural or Enhanced Treatment**: sediment is pumped and treated on land, such as drying/dewatering and ripening fields and dewatering plants (see Figure 3).
B. **In Water, Reallocated at a Final Location**: sediment is transported and pumped, or deposited, at final locations, such as

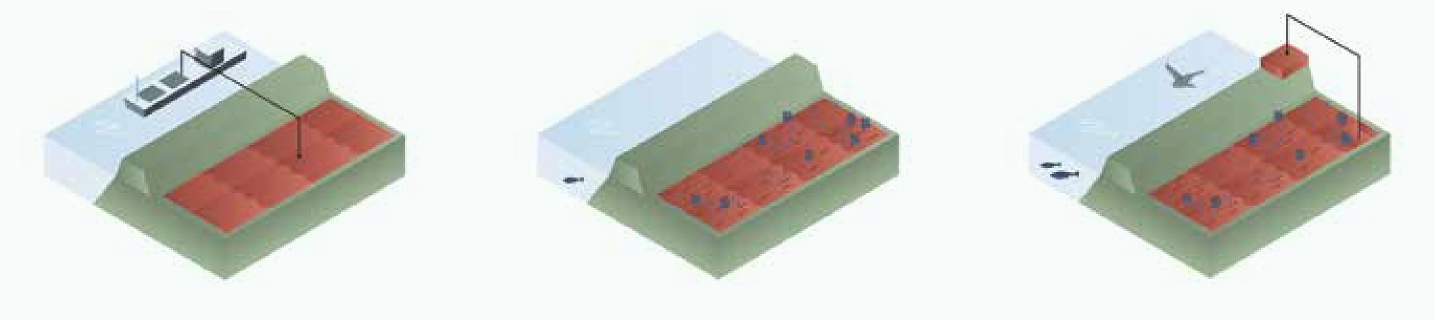

FIGURE 3
In Technique A, sediment is deposited on land, and in this illustrative case, into drying cells. Sediment is possibly treated and reclaimed for other subsequent beneficial uses such as dyke reinforcement.

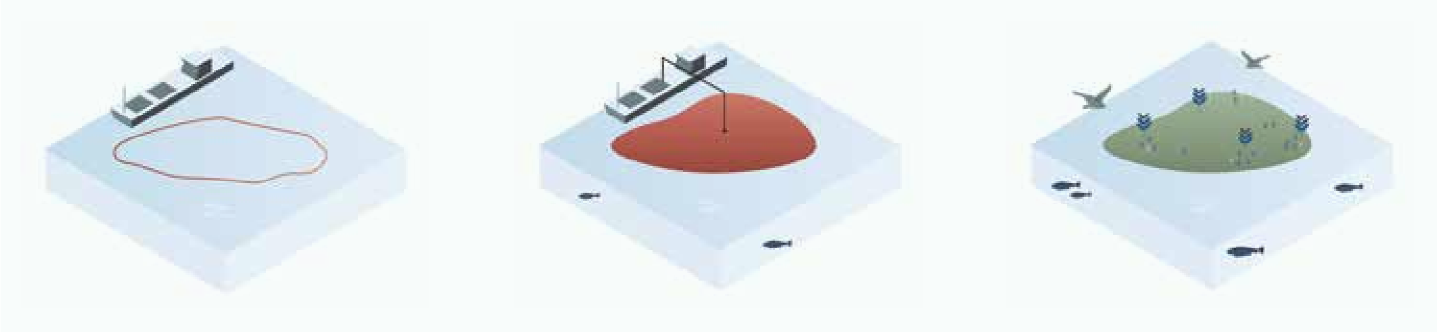

FIGURE 4

In Technique B, sediment is reallocated in water at the final location. Demonstrated in this case, the final location is an island with a major function of nature restoration.

FIGURE 5

In Technique C, sediment is reallocated in water at a strategic location. Tidal flow and waves transport the sediment to the final location. In this illustrative case, the function is wetland restoration in front of a sea dyke with a consequential reduction of flood risk.

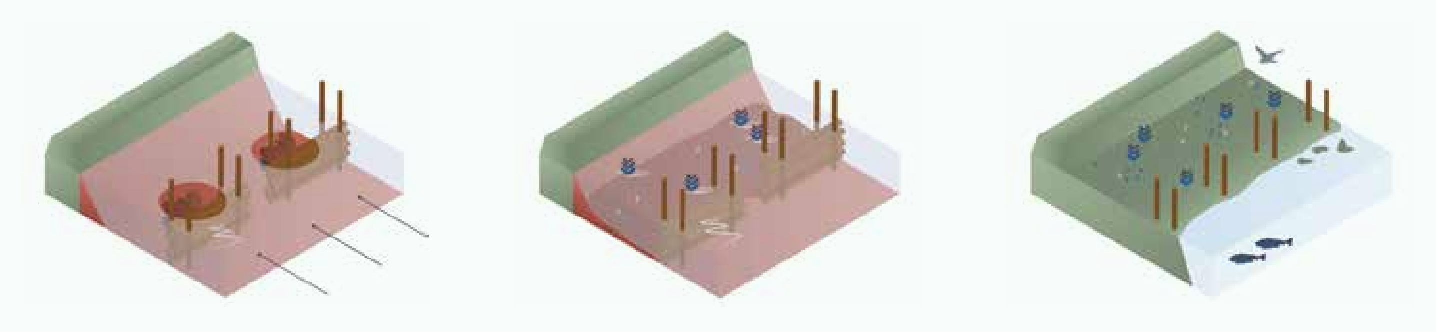

FIGURE 6

In Technique D, the trapping of sediment is enhanced. This illustrative case demonstrates the use of permeable dams to favour wetland restoration through mangroves.

It is certainly recognised that some, in fact most, beneficial use applications fulfil more than one function.

nourishments, land reclamation, waterfront redevelopment (see Figure 4).

C. **In Water, Reallocated at a Strategic Location**: sediments are disposed at a strategic location, letting the local natural processes (e.g., hydrodynamic forces) transfer and trap the sediment at the final location, such as sand or mud engine (see Figure 5).

D. **In Water, Enhanced Trapping**: improving the trapping capacity of the natural system, for example strategic mangrove or wetland restoration projects (see Figure 6). In this case sediments are not dredged or transported by humans but use natural systems and engineering tools as sediment management measures.

Human intervention decreases from techniques A through D, with techniques C and D mostly relying on nature-based approaches. Technique A often involves the use of chemical or physical treatments to sequester contaminants or improve sediment properties. Techniques A through D (Figures 3 through 6) are consistent with those proposed by the EcoShape – Building with Nature Initiative, Living Lab for Mud (EcoShape 2017). EcoShape is working with their partners on five pilot projects to develop knowledge about the sustainable use of fine sediments.

Case studies

Case studies were collected during the preparation of this article by WGBU members and associates. In total 38 case examples, undertaken in 11 countries over the last 30 years, with the focus on the last decade were collected. All case studies are described in standard two-page summaries, all of which are available on the CEDA website at: https://dredging.org/resources/ceda-publications-online/beneficial-use-of-sediments-case-studies

TABLE 1

Case studies classified after Function (Rows) and Technique (Columns). Rows 1 through 5 refer to Function and columns A through D refer to Technique. Case study nomenclature includes a reference to the Function, Technique, the year at project start, and the country location of the project. Underlining indicates contamination present. Case studies in *italics* indicate treatment (see Position Paper for details on treatment techniques).

Technique Function	A. On Land, Natural or Enhanced Treatment	B. In Water, Reallocated at Final Location	C. In Water, Reallocated at Strategic Location	D. In Water, Enhanced Trapping
1. Raw Material	R1A_1985_DE *R1A_1993_DE* *R1A_1996_DE* R1A_2006_DE R1A_2006_NL *R1A_2012_FR* *R1A_2015_US* *R1A_2017_IT* *R1A_2018_US*			
2. Remediation	*R2A_1988_DE* *R2A_1995_NL* *R2A_2015_DE*			
3. Reclamation	R3A_2016_US R3A_2018_NL	*R3B_2006_NZ* *R3B_2010_NO* *R3B_2018_SE*		
4. Restoration	R4A_2010_NL	R4B_2002_US R4B_2005_US R4B_2008_US R4B_2016_NL R4B_2016_UK(A) R4B_2016_UK(B)	R4C_1999_NL R4C_2002_US R4C_2007_US R4C_2016_NL	
5. Resiliency	*R5A_2004_DE* *R5A_2005_BE* *R5A_2013_FR* R5A_2018_NL *R5A_2019_BE*	R5B_1990_UK R5B_2006_NL R5B_2010_US	R5C_2008_US	R5D_2015_ID

TABLE 2

List of case studies by title and classification code.

Classification Code	Case Study Title
R1A_1985_DE	*Production of raw material through dewatering fields, Hamburg – DE*
R1A_1993_DE	*Production of raw material through a dewatering plant, Hamburg – DE*
R1A_1996_DE	*Use in ceramic industry through industrial treatment, Hamburg – DE*
R1A_2006_DE	*Use as agricultural soil after dewatering, Ihrhove – DE*
R1A_2006_NL	*Reclamation of clean sand through sand separation, Rotterdam – NL*
R1A_2012_FR	*Use in road construction after immobilisation and stabilisation, Dunkirk – FR*
R1A_2015_US	*Use in civil and environmental applications after stabilisation via Pneumatic Flow Tube Mixing, New Jersey – US*
R1A_2017_IT	*Use in civil and environmental applications after multiple phase cleaning and sorting process, Palermo – IT*
R1A_2018_US	*Production of grade cement after thermo-chemical high temperature treatment and immobilisation,New Jersey – US*
R2A_1988_DE	*Use as sealing material after dewatering, Hamburg – DE*
R2A_1995_NL	*Use as landfarming through bioremediation, Oostwaardhoeve – NL*
R2A_2015_DE	*Use as substitute for sand to backfill former harbour-basins, Hamburg – DE*
R3A_2016_US	*Raise elevation of near-shore agricultural fields after natural dewatering, Ohio – US*
R3A_2018_NL	*Raise elevation of low-lying peatlands and production of high value soil through blending with local organic waste, Krimpenerwaard – NL*
R3B_2006_NZ	*Use in expansion of port terminal after blending with cement, Auckland – NZ*
R3B_2010_NO	*Use in expansion of port terminal after blending with cement and stabilisation contaminated sediments, Oslo – NO*
R3B_2018_SE	*Use in civil applications after testing with various binders, Gothenburg – SE*
R4A_2010_NL	*Raise elevation of low-lying peatlands after natural dewatering in confined facilities, Jisperveld – NL*
R4B_2002_US	*Creation of natural habitat and morphological stabilisation through strategic deposition, New Jersey – US*
R4B_2005_US	*Counter subsidence and creation of natural habitat through strategic deposition, California – US*
R4B_2008_US	*Habitat restoration through creation of islands, Wisconsin – US*
R4B_2016_NL	*Habitat restoration through creation of islands, Lelystad – NL*
R4B_2016_UK(A)	*Habitat and wetland restoration through strategic deposition, Brightlingsea – UK*
R4B_2016_UK(B)	*Habitat and wetland restoration in three locations through strategic deposition, Hampshire – UK*
R4C_1999_NL	*Feeding the natural system through natural dispersive processes, Wadden Sea – NL*
R4C_2002_US	*Creating islands through natural dispersive processes, Louisiana – US*
R4C_2007_US	*Beach replenishment and lagoon restoration through natural dispersive processes, California – US*
R4C_2016_NL	*Wetland enhancement through of natural dispersive processes, Harlingen – NL*
R5A_2004_DE	*Use in dyke construction reinforcement to enhance flood resilience after industrial dewatering, Hamburg – DE*
R5A_2005_BE	*Use in dyke construction reinforcement to enhance flood resilience after dewatering and treatment, Dendermonde – BE*
R5A_2013_FR	*Use in breakwater components to enhance flood resilience after dewatering and treatment, Dunkirk – FR*
R5A_2018_NL	*Use in dyke construction reinforcement to enhance flood resilience after natural ripening, Delfzijl – NL*
R5A_2019_BE	*Use in dyke construction reinforcement to enhance flood resilience after dewatering and treatment, Waasmunster – BE*
R5B_1990_UK	*Coastal defence and habitat restoration through strategic disposal, Essex - UK*
R5B_2006_NL	*Making room from rivers through various beneficial uses, various location in NL*
R5B_2010_US	*Use for coast defence and nature restoration through strategic placement, Mississippi – US*
R5C_2008_US	*Use for coast defence and nature restoration through strategic placement and use of natural processes, California – US*
R5D_2015_ID	*Use for coast defence and local economy enhancement through natural trapping, Demak – ID*

These case studies include general information about a specific project, technical information of the beneficial use application, and illustrations. Should the reader be interested in more information, a contact reference is also provided. All case studies were classified after function and technique, as described in the previous section of this article, uniquely named, and included in the summary table (see Table 1). The nomenclature of the case studies includes the year of project initiation and the country.

This table also identifies those case studies that involved contaminated sediments and (chemical/physical) treatment. For further clarity, Table 2 provides a list of the case studies by title and cross-referenced against their classification.

Historical and enhanced beneficial use case studies

Table 1 shows that beneficial sediment use is not a new concept but began in the 1960s with the flushing fields at the Port of Hamburg, Germany, and updated in the 1980s with dewatering fields being an iconic example. In the 1990s, the Port of Hamburg built a large-scale facility for the Mechanical Treatment of Harbour Sediments (METHA plant) for enhanced dewatering and treatment of the (mildly) contaminated portion of the dredged sediment in the harbour (5%-20% of the total – depending on annual sedimentation behaviour). The beneficial use output, of the METHA plant, was used for reclamation and restoration projects as well as for the manufacturing of bricks and ceramics. The remaining clean sediment is reallocated downstream of the Elbe river. Two decades later, the Port of Antwerp followed with a similar plant, the AMORAS. In France similar sediment output is utilised as a sub-base material for road construction. Sediment treatment, such as mixing with Portland cement and/or other binders, has been successfully implemented for the stabilisation of contaminants and modification of the geotechnical properties of the dredged material, mostly fines, in order to meet geotechnical specifications for specific project applications in remediation, and redevelopment projects (including port development) in the United States, Norway and Sweden. Stabilisation focuses on minimising segregation of different grain sizes, increasing strength and reducing water content and permeability. Stabilisation is not only used to stabilise contaminated sediments, but also has a role in coastal resiliency in the construction of seawalls, levees and dykes. For dredged materials not suited for aquatic placement, upland stabilisation for geotechnical construction purposes, mine reclamation, road subbase, landfill and brownfield caps, are examples of routine value-added beneficial use applications.

FIGURE 7

Depositing dredged sediment to enhance wetlands. Photo Exo Environmental

Nature-based case studies, the focus of the 21st century

Since the early 2000s more case studies implement nature-based techniques and focus on restoration and resilience functions (see Table 1). Nature-based solutions (NBS) rely on natural processes (i.e., currents, waves, the deposition and erosion of sediment, and plant growth) that are directly incorporated in the design and construction methods (Borsje et al. 2011; De Vriend and van Koningsveld 2012; De Vriend et al. 2015). This requires an understanding of the specific natural system, its main forces, their variation, the ecosystem, and the societal and governance structure.
For this reason, there is not a 'one solution fits all' but instead an appropriate solution needs to be strategically considered for each site, river basin, estuary, coastal system, community and country. Nature-based projects must therefore be integrated in the large-scale, long-term development of the social and physical (eco)system. NBS does not mean green or nature-based only but are often a combination of green and grey (i.e., conventional approaches) with the proportion of each depending on the project objective, specific environment, the (natural and social) ecosystem and the potential for sustainable outcomes. The beneficial results of nature-based sediment use are often to be achieved and appreciated in the longer term and larger scale. Design, planning, construction, testing, long-term monitoring, and adaptive management should account for appropriate time and spatial scales.

Given the scarcity and cost of sand, many case studies begin to explore the effective implementation of soft fine sediments (or mud). These case studies are often brought forward by the international initiatives mentioned before (i.e., Building/Engineering/Working with Nature, USAR, PRISMA). These initiatives rely heavily on NBS and fine sediments management. Sediment and beneficial use are critical considerations for all types of NBS, and the link between NBS and beneficial sediment (re-)use is intrinsically strong. Examples of nature-based projects, based on beneficial use, collected during this study are varied in scope. They include:

- using natural products and processes such as manure, vegetation and ripening, to stabilise sediments (e.g., Kleirijperij or Krimpenerwaard in The Netherlands);

- using stabilised sediment directly or indirectly for land reclamation, raising subsiding land or strengthening dykes (e.g., Vlassenbroek in Belgium, Auckland in New Zealand, Sandvika in Norway, Hamburg in Germany, and Lowlands in The Netherlands, see Figure 2);
- depositing of dredged sediments in thin or thick layers on marine wetlands and retreating or vulnerable coastlines (e.g., at Horsey Island, Lymington, or Brightlingsea in the UK, see Figure 7);
- creation of artificial nature islands to improve flood safety and/or improve the habitat biodiversity and the natural value of the specific area (e.g., Marker Wadden Restoration Project in The Netherlands, Cat Island and Deer Island in the United States);
- attempting to extend coastal wetlands by depositing dredged material at a strategic location and relying on coastal processes for transport (e.g., Koehoal in The Netherlands); and
- implementation of old Dutch techniques to trap sediments (i.e., permeable dams) in front of eroding coastlines, to trap sediment and restore mangrove forest, so improving the resilience against flooding of rural communities (e.g., Demak in Indonesia, see Figure 1).

Given their integration with natural processes, the selection of the location of nature-based solutions is critical. Strategic reviews are being carried out to actively explore where projects can be best located. One recent example includes the UK Solent Forum Study, which identified economic criteria for site selection. An online map for potential project locations, in the Southampton area, was developed (ABPmer 2018). These sites should be taken forward to affirm economic and ecological merits.

Conclusions

This article demonstrates that dredged sediment is a valuable resource, reinforcing the findings from past reviews on this subject. Sediments can be used to support the sustainable development of many important human activities in harmony and in integration with nature. Vice versa, failure to do so will likely reduce resiliency and increase the vulnerability to natural forces. The numerous case studies provided in this article demonstrate that technical knowledge and experience with beneficial use of sediment is significant.

The practice of beneficial use is well-established, particularly in relation to production of alternative raw material to support civil infrastructural projects. More recently, innovative applications and pilot projects have been explored on how to best use natural forces and processes, implementing NBS, that incorporate beneficial use of sediment. Successful projects include wetland restoration and coastal nourishment studies to improve resilience against coastal flooding and extreme climatic events. A community of practitioners lies behind these numerous successful applications, with over two decades of experience to draw upon. The collected case studies unequivocally demonstrate that applications of beneficial use of sediments, contaminated by low-level pollution, are implementable. A parallel Position Paper is produced that describes how to evaluate and mitigate risk, to successful beneficial use, when contamination is present.

This number of applications demonstrate that many possibilities for beneficial use exist, offering the opportunity for its prioritisation in dredging and sediment management activities. In some instances, the benefits of beneficial use applications may only be realised long after project implementation, or may be less directly quantifiable, such as indirect ecosystem service benefits. Successful applications may also require long-term maintenance or adaptive management approaches. This is the logical consequence of implementing NBS, where natural processes intrinsically need time to respond and adapt to changes.

This article focused on technical feasibility, only indirectly touching on legislation or economic components (which are often country-specific). However, case studies did generally discuss these project aspects, and non-technical challenges critical for the success of a beneficial sediment use project, especially when implementing NBS. These are, for example: definition of beneficiaries and funding mechanism; clear policy and legal framework to regulate, permitting design, implementation and maintenance; and managing institutional and public perception. In early 2019 PIANC, initiated WG 214 on the same topic of beneficial sediment use. WG 214 includes various CEDA members who worked on this article, which serves as a solid technical baseline. It is the ambition of the PIANC WG to include a wider analysis of the non-technical success or failure factors, to provide a broader perspective on how to consistently implement beneficial sediment use in large scale applications.

Finally, as a call for ongoing collaboration, the authors invite the reader and the professional community to share their experience, knowledge and further case studies by sending them to ceda@dredging.org. As identified in Murray (2008), ongoing active communication on this subject is vital in order to see more and larger projects achieved. Therefore, CEDA will provide a platform for ongoing knowledge and experience exchange on the subject of beneficial sediment use.

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Summary

This article is based on a paper which has been prepared by the Central Dredging Association (CEDA) Working Group on the Beneficial Use of Sediments (WGBU). The WGBU was initiated by CEDA's Environmental Commission in 2017. This article intends to inform sediment stakeholders and practitioners about the recent advances, on-going international initiatives and programmes, and best management practices regarding the beneficial use of sediments and the value of sediments as a natural resource in the context of sustainable development using relevant case studies.

This article was first published as an Information Paper presented by the Central Dredging Association (CEDA), an independent, international organisation with an extensive professional network, a centre of expertise on dredging and reclamation, and an easy-to-access forum for knowledge exchange. The article has been prepared by a working group of international experts of broadly diverse backgrounds and range of expertise, under the remit of the CEDA Environment Commission.

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Some members from the CEDA BU WG are concurrently participating in the ongoing PIANC EnviCom WG 214 on Beneficial Sediment Use.

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