CREATING MANGROVE HABITAT FOR SHORELINE PROTECTION

WORKING WITH NATURE IN THE ARABIAN GULF

Mangroves require sheltered conditions for their initial establishment, but once well established provide effective protection from shoreline erosion.

Over the past decades, there has been a growing interest in exploring innovative ways to minimise the environmental footprint of coastal developments and in nature-based approaches for shoreline protection. At Mubarraz Island near Abu Dhabi (UAE), an international oil company beneficially reused ~12 million m^3 of dredged material to protect pipelines, construct a causeway and create mangrove habitat to manage coastal erosion. This 'Working with Nature' approach has provided a cost-effective nature-based solution for shoreline protection, with added benefits for biodiversity conservation.

Mubarraz Island

Mubarraz Island is located in the Arabian Gulf, some 100 km north-west of Abu Dhabi in the United Arab Emirates. The island is surrounded by a large (165 km^2) sandy shoal (up to 5 m deep) with extensive seagrass meadows and fringing reefs. Mubarraz shoal features several oil fields (mostly situated in the northern parts of the shoal), that are under concession by a Japanese oil company, Abu Dhabi Oil Co. (Japan) Ltd since the 1970s. Mubarraz is subject to extreme climatic and environmental conditions typical of the arid Arabian Gulf region. Soils and marine sediments are predominantly calcareous sands that are poor in nutrients and organic matter. Surface water temperature on the shoal ranges from 17–21°C in winter and from 31–35°C in summer, but can locally reach up to as high as 40°C in sheltered shallow areas. Salinity is high and typically ranges from 40–48. Water levels are governed by a diurnal tide with a maximum tidal amplitude of 2.3 m. Maximum tidal currents across the shoal are generally lower than 0.5 m s^{-1}. Average wind conditions are governed by land and sea breezes with typical speeds of 7 m s^{-1} (northern wind) during the day and 6 m s^{-1} (southern wind) at night. Much stronger winds (up to 12 m s^{-1}) from the north-west direction (known locally as 'shamals') can occur during winter storms. Average annual rainfall in this arid region is 90 mm year^{-1}.

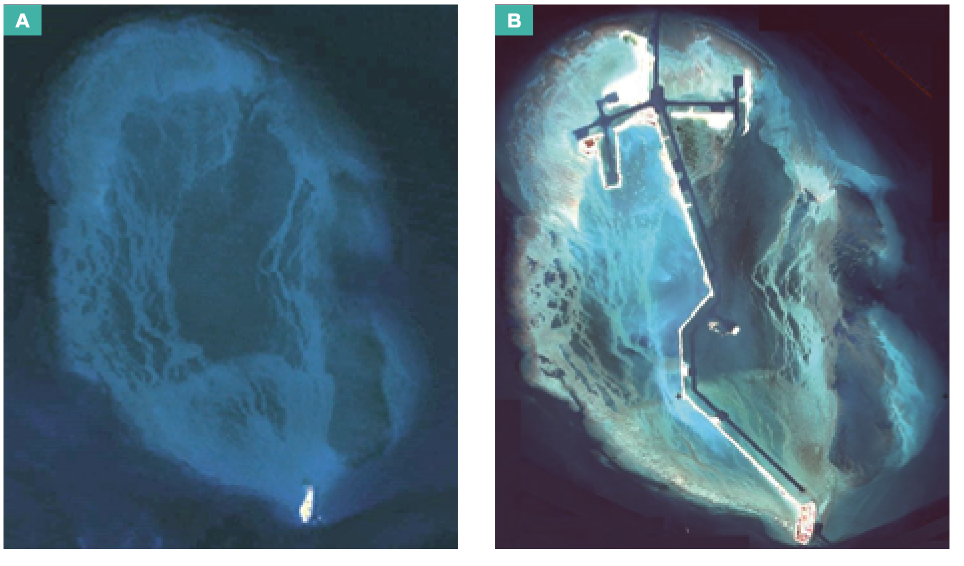

FIGURE 1

Mubarraz (Landsat satellite image) in 1972 (A) and (EOMAP satellite image) in 2018 (B).

FIGURE 2
Aerial view of the northern section of the Mubarraz causeway.

Dredging and causeway construction

During 1983–85, a navigation channel was dredged across the shoal to facilitate navigational access. The main navigation channel extends from north to south, branching out with several extensions in the north, totalling 31 km in length. The channel is 125 m wide and 6–7 m deep (i.e. some 3 m deeper than adjacent seabed), and its excavation resulted in a total volume of approximately 12 Mm^3 of carbonate sediment, consisting mostly of sand (70%), with 22% gravel and 8% fines (Aces, 2016).

Approximately 10 Mm^3 of this dredged material was used for the construction of a 17-kilometre-long causeway that protects several oil pipelines and power cables, and serves as a road connection between the oil production areas and the main island. The causeway is 50–150 m wide and has a 'height' of 5.1 m above the adjacent seabed or approximately 3.3 m above mean sea level (MSL), assuming average water depth near the causeway to be in the order of 2.8 m, and MSL being 1.2 m above Chart Datum. The remaining ~2 Mm^3 of dredged material was used for land reclamations at the production wells and along the island.

There are no historical records of environmental impacts of the construction of the causeway (early 1980s), but more recent environmental assessments describe the marine ecosystems at Mubarraz as being in good health (Deltares, 2006; DOME, 2007). Remote sensing analysis suggests that the seagrass meadows, which cover approximately 4,000 hectares of the shallow waters of Mubarraz shoal, recovered well in the years following the completion of dredging and causeway construction, having fully recovered by 1990 (DAMCO Consulting, 2018). The seagrass beds at Mubarraz support significant populations of green turtles (*Chelonia mydas*), dugongs (*Dugong dugon*) and humpback dolphins (*Sousa plumbea*). Coral reefs around Mubarraz shoal suffered multiple bleaching events in 1996, 1998, 2002 and 2017 due to thermal stress related to climate change and are now in a poor condition similar to most reefs in the southern Gulf (Burt et al., 2019). Two culvert gaps were constructed in 2007 to reduce perceived barrier effects of the causeway and enhance connectivity, providing opportunity for the exchange of water, organisms and larvae.

Mangrove planting

The first mangrove planting campaigns at Mubarraz were carried out during the start-up phase of causeway construction and oil operations during 1983–87. These plantings were conducted with seedlings of the mangrove species *Avicennia marina* obtained from a mangrove tree nursery in mainland Abu Dhabi, along with some propagules of *Rhizophora stylosa* (from Pakistan), *Rhizophora mucronata* (from Malaysia) and *Ceriops tagal* (from Thailand). The primary focus of these early planting efforts was environmental enhancement ('greening'), implemented at numerous locations, being only successful with *Avicennia marina* in sheltered corners of the causeway and island, showing very low survival with the other species and at other locations.

Following increasing shoreline erosion along the western side of the causeway in the mid-2000s, a new 'Working with Nature' approach was adopted for the mangrove planting works. A tree nursery was established under the shade of trees at the south-western edge of the main island with a capacity of 80,000 seedlings. Nursery practices followed general guidelines from international best practice manuals, further optimised over time according to what worked best under local conditions. Propagules to seed the pots in the nursery are collected annually over a two-week period in mid-September from mature mangrove stands on Mubarraz, obtaining best results with three propagules planted per pot in a soil mixture of sand, peat moss and plant potting mix. Seedlings are watered and nurtured in the nursery for approximately six months until they are large and strong enough to be planted in the field. A site survey in March 2005, assisted by satellite imagery analysis, was conducted to guide site selection for new mangrove planting efforts.

At the start of the program in the mid-1980s, most planting was done in a random fashion along the outer shorelines of the causeway and island without any specific site preparation. Although this yielded reasonable success at some sheltered locations in the north-west corner of the causeway (at West Mubarraz), most initial planting efforts along the exposed stretches of the causeway failed completely.

A tree nursery was established at the south-western edge of the main island with a capacity of 80,000 seedlings.

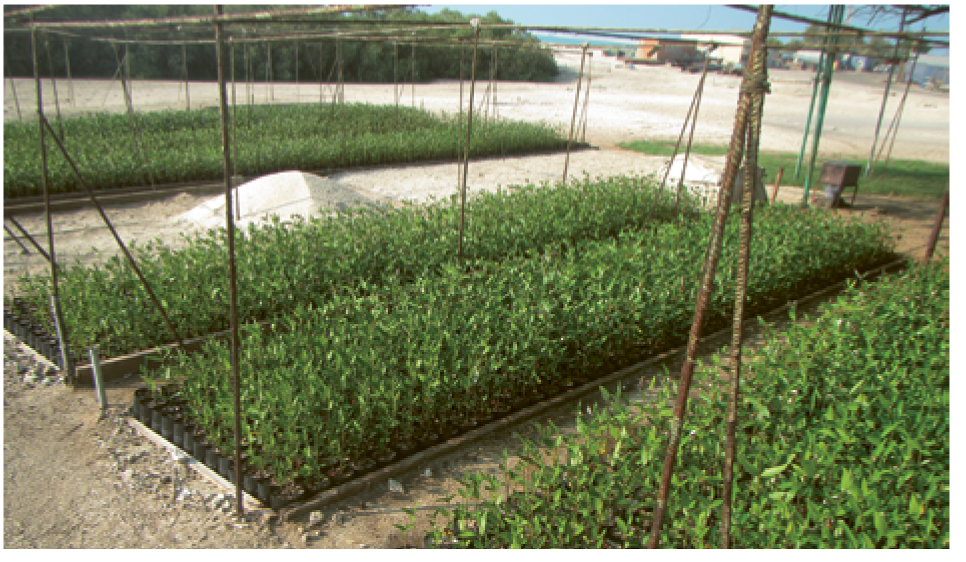

FIGURE 3

Mangrove tree nursery on Mubarraz Island.

FIGURE 4

Planting mangrove seedlings inside a tidal channel.

FIGURE 5
Excavation of tidal channels along causeway.

FIGURE 6
Completed tidal channel prior to planting.

Channels were dug to a depth considered suitable for mangrove growth.

FIGURE 7
Aerial view of causeway, tidal channels and navigation channel.
Map data: Google, image © 2020 Maxar Technologies.

Therefore, an alternative approach had to be developed here to provide the plantings with initial protection from erosion. Artificial (tidal) channels 6–9 m wide were excavated with a backhoe along the length of the causeway, leaving a protective berm or bund of dredged material between the planting site and the open sea. The channels had passages to allow for the entry and drainage of seawater with the tide and varied in length from <100 m to several kilometres. Channels were dug to a depth considered suitable for mangrove growth, generally between mean high water (MHW) and mean high water spring (MHWS) (Lewis 2005; Van Loon et al., 2016). Because these channels did not directly face the seashore, except for their intakes, the plantings were relatively protected from wave action and seagrass wrack accumulation. Compacted soil in the channels was loosened with rakes or spades to facilitate plant root penetration and soil aeration. Soil quality was further improved by the addition of peat moss prior to planting. Since 2006, the channels have been planted annually by staff from the oil company. Tens of thousands of mangrove seedlings have been planted at 1 m spacing, covering different areas each year. By 2019, a total of ~500,000 seedlings had been planted. Plans for the coming years are to continue planting more mangroves, wherever possible, until most of the shoreline of the causeway is fringed on both sides by a protective belt of mature mangrove vegetation.

A recent assessment of the overall success of the mangrove planting program at Mubarraz revealed survival rates of planted mangroves (from seedling to mature trees) to be in the order of 26% (averaged over all years), with well-established mangrove vegetation (totalling some 140,000 trees and saplings) now lining approximately 7 km of shoreline, covering 16.5 hectares (Erftemeijer et al., 2020). Successfully planted stands of mangroves were characterised by high tree density (mean: 8838 trees ha^{-1}), stunted tree height (mean: 3 m), narrow stem diameter (mean: 5 cm), moderate basal area (5–37 m^2 ha^{-1}), mean pneumatophore density of 589 m^{-2}, and healthy recruitment (>14,000 natural seedlings ha^{-1}) (Erftemeijer et al., 2020). The overall survival of 26% (or 32% if recently planted seedlings are included) of all planted seedlings at Mubarraz is comparable to natural survival rates for mangrove seedlings in the field, as reported in the general literature (see Erftemeijer et al., 2020).

FIGURE 8

Monitoring survival and growth of planted mangroves.

Colonisation by fauna

Established mangrove stands have been successfully colonised by benthic invertebrate fauna, as indicated by high densities of crab holes (up to 638 m^{-2}) and gastropod snails (up to 429 m^{-2}). Mubarraz currently supports a significant diversity of birds with 50 species recorded to date. This can be attributed almost entirely to the creation of new land, by the reuse of dredged material, and successful establishment of mangrove vegetation, previously absent from Mubarraz. At least six of these bird species have been confirmed to breed on the island, owing to the presence of the mangrove vegetation, while several others (including 12 shorebird species) visit the island during the migratory season. The oil company also facilitated the construction of 12 artificial

FIGURE 9

Impressions of various recent (A) and older (B) mangrove plantings in tidal channels behind protective berms along the causeway.

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nesting facilities for Ospreys that are being used for breeding every year by multiple pairs of this impressive fish-eating bird of prey (with maximum daily counts of 21 birds). These observations suggest a significant level of faunal colonisation of the artificially created mangrove stands on an island that did not have any vegetation before, underscoring the importance of the planted mangroves for biodiversity conservation.

Hydrological investigations and channel modification

New plantings along a further 9 km of the causeway's shoreline are currently underway. The bed levels in some tidal channels had to be adjusted in order to provide optimal tidal inundation conditions for these new plantings, based on detailed hydrological investigations in 2019 (DAMCO Consulting, 2020) following recommendations described in Van Loon et al. (2016). Using water level loggers (complemented with auto-levelling measurements), the daily duration of tidal inundation at successful and unsuccessful planting sites were measured to establish the relationship between planting success and hydrological conditions (tidal inundation as function of bed level relative to MSL). The results of these hydrological investigations indicated that mangrove planting efforts at sites that experience tidal inundation between 180–450 minutes per day, which at Mubarraz corresponds to channel bed levels of 27–42 cm above MSL, have been generally successful. Sites inundated for more than 500 minutes per day were generally unsuccessful, apparently exceeding the mangroves' tolerance limit for waterlogging, leaving them insufficient time at low tide to bring enough oxygen back into the soil through their breathing roots for survival. These site-specific findings are now being used to guide the design of new channels and modify the depth of unsuccessful (existing) channels to further optimise replanting success at Mubarraz.

Shoreline protection

The protective berms of dredged material along the mangrove channels occasionally required maintenance to repair sections affected by storm damage. Following planting, the young mangrove vegetation will not offer much shoreline protection initially, but as the mangrove stands develop and expand over the years, they can substantially reduce wave height and energy, and contribute to protection from erosion, depending on tree density, stem diameter and the density of their pneumatophores. It is expected that over the coming decade, these mangroves will have grown and established themselves sufficiently enough to withstand significant wave energy and protect these shorelines from erosion after the protective berms of dredged material separating the channels from the sea have gradually eroded away. Meanwhile, a few critical stretches of the causeway's shoreline have been protected with sheet piling. The costs of such hard engineering solutions, which require maintenance and have a limited lifespan, were six times more expensive than the costs of the mangrove planting approach. This clearly underscores the potential cost-effectiveness of nature-based solutions such as the use of mangrove vegetation over conventional engineering approaches for shoreline protection. Similar findings were reported by Winterwerp et al. (2016) who successfully restored mangroves as a cost-effective sustainable climate-adaptive solution to reverse severe coastal erosion along the north coast of Java, Indonesia, with associated socio-economic benefits for the local community.

Beneficial reuse of dredged material for mangrove habitat

There are other examples similar to the work showcased here for Mubarraz Island. The last few decades have seen a rise in such beneficial use application of dredged material for the rehabilitation and creation of coastal wetlands worldwide (Turner and Streever, 2002). Particularly in the USA (largely through the work of the US Army Corps of Engineers) there is a considerable body of well-documented experience with

FIGURE 10

Mangrove planting on Mubarraz Island photographed in 1984.

FIGURE 11

The same mangrove planting on Mubarraz Island photographed in 2009.

the establishment of 'dredged material wetlands', i.e. the intentional restoration or creation of wetlands using dredged material, both in freshwater/estuarine and coastal/marine environments (Bridges et al., 2018). It is important to note that few dredged material wetlands would be built if there was no need to dispose of material resulting from navigation-related dredging operations.

In Florida, more than 250 spoil islands (1–2 hectares each) from historic dredging operations (1930–1970) at the Indian River, Yankee Town, Pitchlacha-scotee Rover, Tampa and Caloosahatchee River, were naturally colonised by mangroves, saltmarsh and terrestrial vegetation, following processes of natural succession and are often used by waterbirds for breeding (Lewis and Lewis, 1978). Two larger dredged spoil islands south of Alafia River mouth (Florida), which initially functioned as dredged spoil disposal facilities, were later planted with marsh grass (*Spartina*) and colonised by mangroves and are now managed as a bird sanctuary, hosting more than 12,000 breeding pairs of 20 waterbird species (Robin Lewis III, pers. comm., 2017). In Singapore, two new mangrove areas encompassing a total area of 13 hectares were created on dredged material to compensate for the loss of habitat due to the construction of an offshore landfill site at Pulau Semakau (Chuan, 2009). The site was protected by a rock perimeter bund, underlain with geofabrics, and engineered to correct tidal positioning with an excavated system of artificial tidal creeks. Initial mangrove test plantings all died as the fresh mud was too acidic, but after a delay of four months to let the seawater neutralise the soil pH, the two areas were successfully planted with 400,000 mangrove seedlings (Chuan, 2009). There are similar sites at Lake Maracaibo in Venezuela (Pannier and De Pannier, 2008) and at Navachista Bay and Chiapas lagoon in Mexico (Chargoy and Hernández, 2002), all involving dredged material deposits that were either actively planted with mangroves to help stabilise the deposits or colonised naturally over time.

More recently, there is also an increasing attention to explore nature-based approaches to coastal protection from climate-change related threats worldwide (Mink and Sansoglou, 2020), including the Gulf region (Burt and Bartholomew, 2019). These form part of a wider paradigm shift in the waterborne infrastructure development industry that are inspired by larger initiatives such as 'Working with Nature' by PIANC (www.pianc.org/working-with-nature), 'Building with Nature' in the Netherlands (www.ecoshape.org; Van Eekelen and Bouw, 2020) and 'Engineering with Nature' in the USA (https://ewn.el.erdc.dren.mil; Bridges et al., 2018). A variety of innovative projects implemented under these programmes also involved the beneficial reuse of dredged material from capital or maintenance dredging operations.

FIGURE 12

Aerial view of mangroves along a channel at Mubarraz Island (protecting infrastructure).

FIGURE 13

Mangroves adjacent to oil infrastructure at West Mubarraz.

Key aspects for creating coastal habitats

Key aspects to be considered during the planning and design of beneficial reuse of dredged material for creating coastal habitats, derived from a recent review (Erftemeijer, 2019) of 39 case studies in 11 countries, including Mubarraz, are summarised in Table 1. Although many of these examples have been successful, they were not without challenges. In exposed areas, there was often a need for (temporary) protective hard engineering structures to ensure stability of fine dredged material deposits. Achieving the appropriate tidal elevation at a site to create hydrological conditions conducive for mangroves proved complex and involved patience, owing to processes of consolidation and subsidence of the dredged material following dewatering. Colonisation by vegetation, whether spontaneous or assisted, and birdlife typically took several more years. Consequently, the timescales involved were not always matching the initial expectation of developers or the general public. However, commitment to the initial vision, persistence and adaptive management in these innovative approaches are well worth the wait, as the case study of Mubarraz presented here so vividly demonstrates.

TABLE 1

Key aspects to be considered during the planning and design of beneficial reuse of dredged material for creating coastal habitats (adapted from Turner and Streever, 2002; Erftemeijer, 2019).

• **Suitability of the material:** Contaminated sediments should be avoided. Use of fines (silt/clay) generally requires the construction of confining dykes. Site suitability for mangrove growth, however, appears less dependent on soil characteristics and is probably more determined by tidal hydrology and salinity.
• **Proximity to dredging:** Sites selected for potential dredged material wetlands should be within reasonable proximity of the dredging. Moving dredged material more than a few kilometres is seldom feasible.
• **Exposure:** Sites for wetland restoration should not be exposed to high wave energy. Ideal sites would be sheltered from strong swell, wave action, extreme tidal flows and cyclones. Sites exposed to waves, swell and strong tidal flows may need protective structures.
• **Trade-off:** Some existing intertidal or shallow subtidal habitats can have environmental values that equal or exceed those of dredged material wetlands and – pending adequate evaluation – such sites should be avoided to prevent an overall net loss of environmental benefits.
• **Interference:** Potential dredged material wetland sites that will have dramatic or adverse effects on water flow, sediment transport or navigational safety should be avoided.
• **Protection:** In some cases, it may be possible to design and construct sites in a manner that affords protection of natural shorelines, port infrastructure or the navigation channel itself.
• **Availability of material:** The volume of dredged material, the expected compaction of both the dredged material and the site foundation, the initial depth of the wetland restoration site, the desired final (tidal) elevation of the wetland restoration site and the area of the wetland restoration area should all be considered to determine if adequate material is available for site construction.
• **Planting:** Dredged material wetlands located far from existing sources of plant recruitment may need to be planted (or seeded). Likewise, if rapid complete cover by plants is desired, planting may be considered. In other cases, once site conditions are conducive, natural recruitment may soon outpace any manual planting efforts, provided that there is connectivity with nearby natural wetland sites.
• **Mimic natural features:** Where appropriate, it may be desirable to construct dredged material wetlands in a manner that mimics natural landscape features. To accomplish this, an appreciation of nearby/regional wetland geomorphology is desirable.
• **Design considerations:** Various morphological (e.g. slope and shape of intertidal mudflat), hydrodynamic and eco-morphodynamic aspects should be considered in the design, as they can significantly affect the success of establishment and survival of the marsh or mangrove vegetation, affecting the hydrodynamic forcing, wave attenuation and sediment stability, affecting the overall marsh or mangrove extent.
• **Timing and access:** Availability of appropriate dredging equipment and accessibility (and ownership) of the area to be dredged and the dredged material wetland site should be considered.
• **Innovation:** Construction of special features, such as tidal creeks and tidal pools, and incorporation of structural complexity to diversify habitats and species at a site may require innovative approaches (but avoid over-engineering or trying to out-engineer nature). Extra costs for such advanced approaches may extend beyond those typically associated with dredged material wetland restoration.

FIGURE 14
'Mangrove pool', a more recent 6.7 hectare mangrove planting programme on West Mubarraz.

Conclusions

This paper describes a unique case study of beneficial reuse of dredged material from the excavation of a navigation channel in the Arabian Gulf for pipeline protection, causeway construction and creation of mangrove habitat for environmental enhancement and shoreline protection. Over a 30-year period, Abu Dhabi Oil Co. (Japan) Ltd employees planted half a million nursery-raised mangrove seedlings along the shores of the island and causeway. Initial mangrove planting success was typically highest at sheltered locations along the causeway, with little or no seedling survival at wave-exposed sites at risk of erosion. The somewhat ironical paradigm emerging here is that mangroves require sheltered conditions for their initial establishment, but once well established provide effective protection from shoreline erosion. The innovative approach adopted by the more recent mangrove planting campaigns at Mubarraz (i.e. excavating parallel tidal channels along the length of the causeway, leaving a protective berm of dredged material between the mangrove-planting site and the open sea) seems to be successful in overcoming this establishment bottleneck.

Owing to the innovative approach and continual planting at Mubarraz over many years, mangrove vegetation has been successfully established along nearly 7 km (~20%) of the causeway, with new plantings along a further 9 km underway. The resulting belts of mangroves along the shores of the causeway, once fully matured, are likely to contribute substantially to its stability and offer protection against the erosive forces of waves and storms. Well-established stands of mangroves have attracted a significant biodiversity (including benthic invertebrates and 50 bird species) previously absent from Mubarraz.

Key factors that drove the success of this program included:

- mass production of seedlings in a tree nursery;
- soil treatment – raking of hard consolidated soil to facilitate plant root penetration and addition of peat moss;
- persistent planting efforts (annually) over many years with strong commitment and support from company and staff;
- the unique design of parallel tidal channels protected by a berm of dredged material; and
- ensuring the right depth of the channels to provide appropriate tidal inundation for the mangroves.

Less successful aspects of the work included fencing to prevent ingress of plastic and debris into the mangrove plantations, planting of different mangrove species, and remote monitoring of the plantations through *in situ* (interval) camera systems, all of which were discontinued.

This case study demonstrates that planting of mangroves on dredged material is feasible, even under the extreme climatic conditions in the Arabian Gulf and offers a cost-effective nature-based solution for shoreline protection, being six times cheaper than sheet-piling or other hard engineering solutions, with added benefits for biodiversity conservation.

Summary

Beneficial reuse of dredged material from the dredging of a navigation channel in the Arabian Gulf is described. Twelve million m^3 of dredged seabed material was reused for the construction of a causeway at an offshore island to protect oil pipelines and serve as a road connection. Mangrove habitat was created along the shorelines of the causeway for environmental enhancement and protection from erosion. Over half a million nursery-raised mangrove seedlings were planted annually by company employees over a 30-year period. Initial planting focused on environmental enhancement and was only successful in sheltered corners of the causeway. Since 2006, a new 'Working with Nature' approach has been adopted in response to increasing shoreline erosion by creating artificial tidal channels that are excavated parallel along the causeway and planted annually with tens of thousands of seedlings. Owing to the innovative approach and persistent planting over many years, mangrove vegetation has been successfully established along nearly 7 km (~20%) of the causeway's shorelines, with new plantings along a further 9 km under way. Costs of mangrove planting were six times lower than the costs of sheet-piling or other hard engineering solutions. This unique case study demonstrates that planting of mangroves on dredged material is feasible, even under extreme climatic conditions, and can offer a cost-effective nature-based solution for shoreline protection, with added benefits for biodiversity conservation.

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