

# TERRA ET AQUA

MANGROVE HABITAT

## WORKING WITH NATURE IN THE ARABIAN GULF

### 10 YEARS ON

Advances in case law with respect to adverse physical conditions

### SEABED MANAGEMENT

First-of-a-kind demonstration plant that prevents harbour silting



# WORKING HAND IN HAND SHORELINE PROTECTION AND BIODIVERSITY CONSERVATION

At Mubarraz Island near Abu Dhabi (UAE), an international oil company beneficially reused ~12 million m<sup>3</sup> of dredged material to protect oil pipelines, construct a causeway and create mangrove habitat to manage coastal erosion. 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 this innovative approach and persistent planting, mangrove vegetation has been successfully established along nearly 7 km (~20%) of the causeway's shorelines. This unique case study demonstrates that the 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. Read the full article on page 16.





## CONTRACTS

### Adverse physical conditions: legal development and changes in risk profiles

Over the past 10 years, there have been noteworthy advances in case law with respect to adverse physical conditions, as well as the development and use of digital ground models that have become more widespread. This article looks at the development and changes in risk profiles that may result due to these two developments.



## PROJECT

### Sustainable marine and coastal seabed management plan

The LIFE MARINAPLAN PLUS project is an innovative and sustainable technology that, thanks to submerged devices called 'ejectors' installed on the seabed, avoids sedimentation of solids at the entrance of small ports and harbours. Read the preliminary assessment of results after 15 months of operation of the first-of-a-kind demonstration plant installed in the harbour of Marina di Cervia in Italy.

## ENVIRONMENT

### Creating mangrove habitat for shoreline protection

The unique case study of Mubarraz Island in the Arabian Gulf 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.



## SAFETY

### IADC Safety Awards 2021

Do you have the most innovative and original work in safety in the dredging industry? Find out how you can register your nominations for the awards, granted to one dredging contractor and one supply chain organisation.



## EVENTS

### Cultivate new skills and share knowledge

Attend IADC's Dredging and Reclamation Seminar, WEDA's Virtual Dredging Summit or IADC and CEDA's one-day online course Dredging for Sustainable Infrastructure.



# IN ADAPTING TO CLIMATE CHANGE FINANCING IS PARAMOUNT



**Frank Verhoeven**  
President, IADC

The Climate Adaptation Summit (CAS) 2021, hosted by the Netherlands government and in collaboration with the Global Centre on Adaptation (GCA), tackled some of the core issues of adapting our society to the threats of climate control, with the overall aim of raising ambition, unlocking finance and leveraging broad-based partnerships.

United Nations Secretary-General António Guterres's call for 'more concrete plans, more ambition from more countries and more businesses' to make the world more climate-resilient, is clear and simple. It speaks to governments, companies and individuals alike. The overriding message that came out of CAS 2021 is that the need for financing is paramount. Significant financial resources are essential to adapt to the adverse effects and reduce the impacts of a changing climate.

**At IADC, we know that sustainable behaviour and working is a pre-requisite for future development. It is essential that we inform the outside world about the results of our efforts – past, present and future.**

IADC will publish its joint study to explore financing of green coastal, river and port projects in Q1. Despite the success of implemented green projects, the financial sector is insufficiently aware of the contributions of sustainable waterborne infrastructure projects. One conclusion is that more detailed information needs to be presented to enable financial agencies and investors to better understand the potential and develop ideas to bring this to mainstream asset classes. This study is a result of this quest and provides content for further dialogue to foster the uptake of green marine and freshwater concepts.

The importance of sustainable dredging practices is a core value held throughout the industry. In keeping with our focus on sustainability, IADC has created an internship to help develop an industry sustainability report based on the

most commonly used practices already implemented by member companies. A second intern has been engaged to make an inventory of methodologies for sustainable marine infrastructure project assessments, taking into account the societal and environmental elements that assess a project to be sustainable. By comparing these methodologies, the aim is to advise which method(s) is most suitable for the dredging industry.

Hand in hand with sustainability is safety. Recognising the growth of safety innovations in the dredging industry, IADC is calling for nominations for its 2021 Safety Awards, which encourage diverse innovations and support the multi-faceted nature of the dredging industry's operations.

This issue also features articles on sustainability: creating mangrove habitat to provide shoreline protection and how an innovative technology can prevent harbour silting. Also in this issue, David Kinlan addresses advances in case law with respect to adverse physical conditions.

**António Guterres's call for 'more concrete plans, more ambition from more countries and more businesses' to make the world more climate-resilient, is clear and simple.**



# ADVERSE PHYSICAL CONDITIONS

LEGAL DEVELOPMENT AND  
CHANGES IN RISK PROFILES



**In marine infrastructure contracts, adverse physical conditions are physical conditions that could not be readily identified by the contractor at the time of tender.**

In the past decade, there have been noteworthy advances in case law with respect to adverse physical conditions as well as the development and use of digital ground models that have become more widespread. This article looks at the development and changes in risk profiles that may result due to these two developments.

A decade ago, I co-authored an article in *Terra et Aqua* (Autumn 2005) titled 'Adverse Physical Conditions and the Experienced Contractor Test'. The article examined the relationship between site inspection, foreseeability and adverse physical conditions and their incorporation in standard contracts and their evolution over the years. The article also looked at site investigation techniques and the issues arising due to incomplete or inaccurate data.

**What constitutes adverse physical conditions?**

To recap from the original article, in marine infrastructure contracts, adverse physical conditions are physical conditions that could not be readily identified by the contractor at the time of tender. When a contractor encounters an adverse physical condition during the execution of the project, they may be entitled to an extension of time or additional payments. The inclusion of an adverse physical conditions clause in most standard forms of contract is to reallocate the risk for the consequence of encountering such unforeseen adverse physical conditions from the contractor to the employer. The rationale for this approach is that the employer only pays for those conditions actually encountered and does not have to pay any contractor's price contingency for conditions that may not be encountered.

Geological/Physical	Anthropogenic	Natural/Hydrological Event
Cobbles, boulders	Anchors, wires, debris	Wave shoaling
Clay balls	Ship wrecks	Flash flooding
Rock/cap rock/duricrust	Unknown foundations, jet-ties, etc	Earthquake liquefaction
Particle size distribution	Archaeological finds	Tsunami
Internal angle of friction	Submarine cables	Mudflows
Density/unit weight	Pipelines	Scour
UCS/point load index	Pollutants	Coastal erosion
RQD/fracture index	Unexploded ordnance	
Mineralogy		
Compactness		
Carbonate/shell content		
H2S		
Groundwater levels		
Ground settlement/consolidation		

**FIGURE 1**

Extract from *Adverse Physical Conditions and the Experienced Contractor* (Kinlan, 2014).

The definition of 'unforeseeable', as stated in the Federation Internationale des Ingenieurs-Conseils (FIDIC) Red and Yellow Book (1999), is 'not reasonably foreseeable by an experienced contractor by the date for submission of the tender'. Some examples of adverse physical conditions are shown in Figure 1.

**Experienced contractor test**

In determining whether a condition is adverse and unforeseen, the 'experienced contractor

test' is applied. Variations of the principle of a 'test' can be found in many standard form construction contracts. Essentially, it is a comparison of what adverse physical conditions were encountered and whether they differ materially from those which could reasonably have been foreseen by an experienced contractor. The marine construction industry has a significant risk profile when compared to the wider sections of the construction industry. The *CRUX Insight 2020* investigation of





**FIGURE 2**  
Gibraltar with its original runway crossing.

131 infrastructure projects worldwide confirms a nexus of entrenched causation factors behind disputes. Notably, restrictions on access to worksites and unforeseen physical – typically ground conditions being key infrastructure claims.

At the time of the author's original article in 2010, there was very little guidance in the way of case law, literature and publications on the vexing issue of the risk allocation for foreseeability of adverse physical conditions in marine infrastructure projects. John Uff QC reported in 2012, 'It is indeed unfortunate that there is virtually no authority on the application of this difficult test.' Contract users were left to fend for themselves when it came to the nuances of how site inspection, foreseeability and the entitlement to claim for adverse physical conditions interacted and to what extent they interrelated.

**Contract developments in the intervening years**

Luckily, time does not stand still both in the development of contracts and applicable case law as well as reporting on such matters. There is much more reporting of disputes now and claims have been taken to the courts and the decisions are made public for industry participants to consider. A key issue for the marine infrastructure industry remains the type and quality of the available geotechnical information.

In 2016, FIDIC released the *Form of Contract for Dredging and Reclamation Works, Second Edition*, known industry-wide as the FIDIC Blue Book. In the notes for guidance, which at 19 pages is longer than the contract itself, it states in particular, that the employer should supply the following information: Soils information: good quality and adequately

distributed information on soils to be dredged, disposed of (including disposal areas), used as reclamation materials and underlying the proposed reclamation area. A detailed investigation should be carried out before going out to tender.

It goes on to state: When considering the time allowed for tendering and when considering the time and cost of carrying out site investigations, particularly marine investigations, the employer should note that in their own interests, compliance with this requirement is strongly advised.

It is the authors' observation that these sort of recommendations are either not fully acted on or are given lip service as the lack of good quality and adequately distributed information on the site make-up still give rise to disputes. However, case law over the past decade has shown that the contractor should not just accept blindly the information it is given and totally rely on it to the exclusion of its own independent assessment.

**Court cases over the past decade**

This article examines two decisions of the English Technology and Construction Court in 2014 and 2015, firstly *Obrascon Huarte Lain SA v Her Majesty's Attorney General for Gibraltar* [2014] EWHC 1028; [2014] BLR 484 (*Obrascon*) as well as *Van Oord UK Ltd and SICIM Roadbridge Ltd v Allseas UK Ltd* (OSR), in which the court applied the experienced contractor test. In addition, in 2011 there was also an Australian case on the application of the obligation to inspect the site, being the Supreme Court of New South Wales' decision in *Walton Construction Pty Ltd v Illawarra Hotel Company Pty Ltd* NSWSC 534 (*Walton*).

**Obrascon case**

The *Obrascon* case in 2014 has been widely reported on. It involved a contract (using FIDIC's 1999 Yellow Book) for the design and construction of a tunnel under the runway of the Gibraltar airport.

*Obrascon* brought an adverse physical condition claim when the Government of Gibraltar terminated their contract. *Obrascon* claimed the extent and amount of contaminated materials was not reasonably foreseeable by an experienced contractor at the time of tender.

**A key issue for the marine infrastructure industry remains the type and quality of the available geotechnical information.**

The site investigation report contained a number of borehole log and trial pit results, which indicated 'made ground' (i.e. man-made ground) of varying depths between 1.0 m and 5.4 m, and non-uniform soil contamination results.

In their claim for unforeseen adverse physical conditions, Obrascon relied on details in the environmental statement provided in the tender documents, which estimated that the work would require removal of some 10,000 m<sup>3</sup> of contaminated material. Obrascon claimed that the removal of much more contaminated material than that described in the environmental statement was not foreseeable.

When rejecting Obrascon's claim, Justice Akenhead stated: 'The contractor cannot simply accept someone else's interpretation of the data and say that is all that was foreseeable.'

Akenhead noted that an experienced contractor would not limit itself to the soil investigation report and volume of contaminated material in the environmental statement. Rather a contractor would have referred to the environmental statement containing references to the history and various historical maps (including the contaminated land desk study showing 'earthwork rifle butts' present in 1869 along

the tunnel alignment), and foreseeably there would have been lead within the made ground.

Similarly, he referred to aircraft fuelling activities on the site for over 70 years and the location of a previous fuel farm and oil pipes close to the works, with such information leading experienced contractors to have appreciated that there 'could well be' hydrocarbon or other oil derivatives in the soil.

Akenhead stated that if these factors were coupled with the tender requirement to allow for 10,000 m<sup>3</sup> of contaminated material, in his judgment, any experienced contractor tendering for the works would foresee that there would or at least could realistically be substantial quantities of contaminated material, and that the allowance of 10,000 m<sup>3</sup> was only a 'say' figure. In terms of quantities, Akenhead did not put a precise figure on what should have been foreseen, but commented that it would be 'very substantially above 10,000 m<sup>3</sup>'.

Akenhead determined that an experienced contractor would have not just blindly accepted the volume of contaminated material mentioned in the environmental statement but would have also looked at the history of the site. The site had previous been a runway, a fuel farm and a rifle range and the material to be excavated was all made ground. Therefore, an experienced contractor could reasonably

expect considerable contamination at the site and therefore made a greater allowance in removal of such material.

With respect to the estimate of 10,000 m<sup>3</sup> of contaminated materials contained in the environmental statement, Akenhead stated that this was one person's interpretation of the data and tenderers were bound to take that assessment into account, but they remained under a duty to make their own independent assessment of the physical conditions likely to be encountered.

### OSR case

This particular case refers to the claimants, a joint venture (JV) formed by Van Oord UK Ltd and Sicim Roadbridge Ltd (together OSR), which made an adverse physical conditions claim against Allseas UK Ltd. The claim was brought in the name of the JV but only concerned the onshore work element in respect of the gas export pipeline, carried out by the civil partner, Sicim Roadbridge Ltd (Sicim). Allseas was the head contractor for construction of gas pipelines for a gas field development that formed part of the Total Laggan-Tormore gas field development at Sullom Voe in the Shetland Islands, Scotland.

The proposed route of the gas export pipeline onshore was from the Shetland Gas Plant on the north-western coast to Firths Voe on the eastern coast. The total length of the gas export pipeline onshore was ~5.7 km.

Sicim contended that it originally intended to construct part of the pipeline by forming an 8-metre-wide stone road and laying the pipe in a trench excavated into the adjacent untreated ground. OSR claimed that because peat was encountered at greater depths than it could reasonably have foreseen, it was obliged to build a 13.5-metre-wide stone embankment and lay the pipe within the embankment.

Sicim relied on a Mackintosh probe survey report. The Mackintosh probe is a test used to measure the depth of soft soils, including peat. The report was not a contract document. It showed similar depths of peat along the pipeline, varying up to 2 m in depth. Sicim claimed that in cases where the actual conditions were different to the survey results, it was entitled to an adverse physical conditions claim under the subcontract.



**FIGURE 3**

Total E&P UK Laggan-Tormore gas field development. Photo © Total



**Increasingly, both employers and contractors are turning to digital ground models to aid them in their understanding of their particular site and its unique characteristics.**

The head contractor had also carried out pre-contract trial pit logs, which showed peat at various depths at various locations, with some of greater depth than the Mackintosh survey. Shortly after the contract was concluded the head contractor provided a full topographic and geophysical survey, including a resistivity survey, the results of which were consistent with the pre-contract trial pit information.

With respect to the requirement that subsurface conditions must be different from those described in the subcontract documents, Justice Coulson found that the only subcontract documents that referred to the subsurface conditions were the contract drawings, the purpose of which was to identify the path of the pipeline. However, the drawings also referred to 'the approximate depth of peat strata' and showed many areas of peat greater than 1 m or 1.5 m, and an area of peat 140 m in length of depth between 3 m and 5 m. Coulson concluded the subsurface conditions were not different from those described in the contract documents and therefore, Sicim's adverse physical conditions claim failed.

Coulson rejected the supposition that Sicim was entitled to treat the Mackintosh report as a type of 'guarantee'. Further stating that it is a matter for contractors' judgment as to the extent to which they rely on the information, referring to the decision in *Obrascon*, and as a matter of common sense that 'every contractor knows that ground investigations are only 100% accurate in the precise locations in which they are carried out, and that it is for an experienced contractor to fill in the gaps.' Coulson added that it was reasonable to take an informed decision as to depths greater than 1.5 m in depth.

**Walton case**

There is an Australian case that is noteworthy, this being *Illawarra Hotel Company Pty Ltd (Illawarra) and Walton Construction Pty Ltd (Walton)*. Illawarra entered into a contract for Walton to carry out the renovation and refurbishment of its hotel. A number of matters were referred for determination by a referee one of which was on account of variations to the scope of work.

One of Walton's variations concerned the unexpected discovery of a deep void in the foundation to the floor slab, which required the construction of a suspended floor slab, rather

than a slab on ground, as indicated on the drawings. The referee found that the void was an unforeseen condition under the terms of the contract. Illawarra challenged the referee's finding on this issue.

Justice Einstein set out the terms of the contract that had an adverse physical conditions clause similar to that in the FIDIC contract suite, and was of the view that the provision did not require an investigation of all potential aspects of physical conditions on the site, but is limited to an inspection of the site and its surroundings. He was of the view that what is reasonable in terms of inspection of the site is to be informed by the degree of information otherwise available to the tenderer, which in this case, included the engineering drawings prepared by Illawarra's structural engineer, depicting a slab on ground. Illawarra's evidence was that Walton inspected the site, but did not get under the building and inspect the subfloor conditions, since they believed that the architect and the engineer would have done this, resulting in the selection of the slab on ground design.

Einstein found that Walton did precisely what was required, examined the drawings and inspected the site, and that the drawings did not show the void, rather, to the contrary. He concluded that an experienced contractor would not expect to find physical conditions in the nature of the void, having regard to the very drawings that the adverse physical conditions clause requires a contractor to examine.

Einstein, in referring to Walton, was of the view that an experienced contractor's inspection of the site is to be 'informed by the degree of information otherwise available to the builder'. Einstein reasoning that he considered an experienced contractor would not have accessed below the building and inspected the subfloor conditions, in light of having examined the employer's drawings showing a slab on ground.

How such a decision would be interpreted for a marine infrastructure project throws up some interesting points. The author considers that this particular contractor's failure to fully 'inspect' is inconsistent with the terms of most adverse physical conditions clauses such as in FIDIC (1999 Red and Yellow Book) clause 4.10, which specifies as an independent requirement that the experienced contractor

shall, to the same extent as the contractor, 'be deemed to have inspected and examined the site, its surroundings and other available information', with the term 'surroundings' not containing any limitation as to distance. The author submits that the decision in Walton should not therefore be relied upon by contractors as authority for the principle that the experienced contractor test does not involve a complete and thorough inspection of the entire site and its surroundings, and that 'surroundings' in a marine environment, whether immediate or in the area, need to be considered when assessing the likelihood of encountering adverse physical conditions.

With respect to 'other available information' mentioned in FIDIC (1999 Red and Yellow Book) it should be readily available and not buried away somewhere in an inaccessible archive. In the NEC4 ECC contract (2017) under clause 60.2 when judging physical conditions, it refers to 'publicly available information referred to in the site information' as well as 'other information which an experienced contractor could reasonably be expected to have or to obtain'. So, for the

latter, the contractor may have information that the employer may not have provided, which has a bearing on the expected physical conditions at the proposed site.

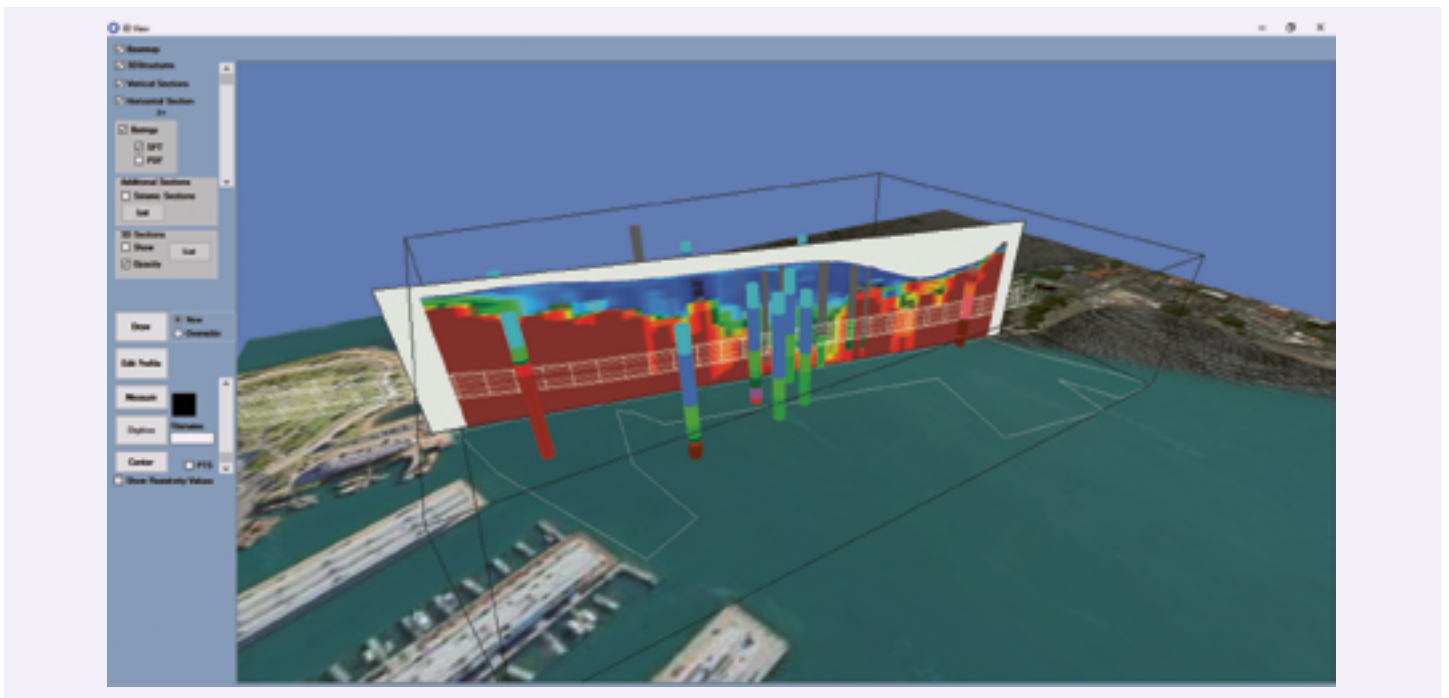
When the tenderer compiles all the available data it needs to make sense of it all in order to make an assessment of the likely physical conditions and materials that may be encountered. Increasingly, both employers and contractors are turning to digital ground models to aid them in their understanding of their particular site and its unique characteristics.

### Geomodels and digital ground models

Geomodelling is the applied science of creating computerised representations of the Earth's crust based on geophysical and geological observations and physical sampling of materials both on and below the surface. A geomodel is the numerical equivalent of a three-dimensional geological map complemented by a description of physical properties of the ground in the area of interest. Geomodelling was developed with main applications to oil and gas, and mining fields as

well as the study of groundwater aquifers and ore deposits.

The spin-off from the use of geomodels in the resource industry was their development and application in other fields such as civil engineering where various proprietary digital ground model software has been developed. Many geological survey organisations worldwide have started to implement varying software systems and methodologies to facilitate a migration, from a 2D paper-based survey to a 3D digital service provider of geoscientific information. Rapid advances in gaming technology has enabled a renaissance in digital ground modelling and particularly in 3D visualisations. A Digital Ground Model (DGM) is a three-dimensional, mathematical representation of the landform and all its geological features, stored in a computer database. A DGM is extremely useful in the design and construction process, as it enables easy and accurate determination of the coordinates and elevation of any point and together with referenced boreholes and samples allows an assessment of the likely soil or rock types



**FIGURE 4**

Vertical geological section of the metro tunnel at Sydney harbour. Aquares resistivity survey data has been inserted into the project IDGM allowing vertical sections to be exported to GIS/CAD, Google Earth, Augmented Reality and holographics.



that may be encountered between sample locations.

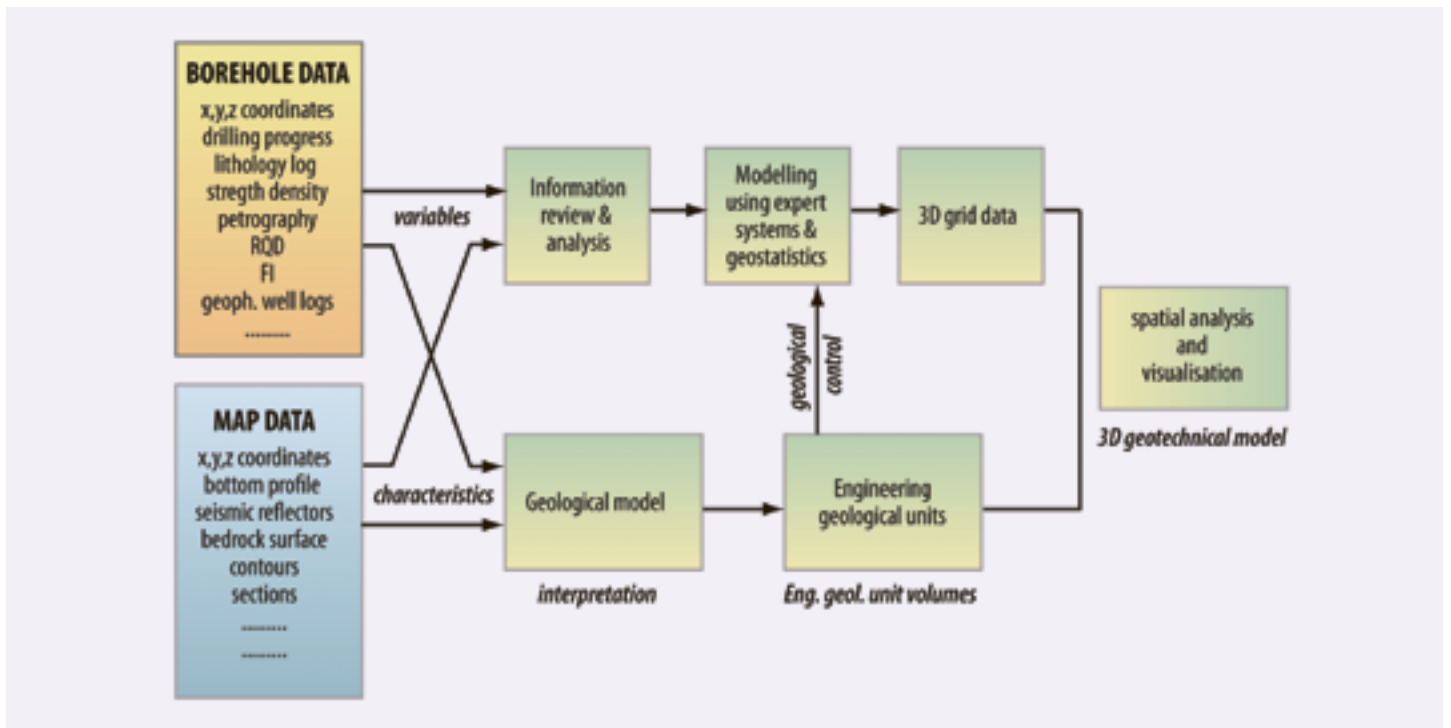
The DGM is formed by integrating a hydrographic survey of the surface with geophysical methods and sampling points under the seabed (using borehole log data and sample testing), and using appropriate algorithms to process these points to represent the surface being modelled.

Geophysical methods are broadly broken into quantitative and qualitative methods. Quantitative geophysics are reflection based seismic methods. They are used to define depth to layer, but cannot be used to resolve quality variation between or within layers. Qualitative geophysics, usually seismic refraction or resistivity methods, are used to define structural variation in the geology at a site. Refraction methods do not readily resolve the level and depth of structures or complex geology due to technical limitations. Another approach relies on resistivity methods that are designed to quickly acquire large volumes of high-resolution data about the structural geology over a large area.

These advanced geophysical methods are digital and allow for determination of thickness and depth of geological layers as well as layer and intra-layer information from the one sensor. Sensor intervals are better than one per second make it possible to collect large volumes of high-resolution data in a short period of time. The objective is to understand subsurface complexities in detail at a site, which makes it possible to then target boreholes to illuminate any observed geological anomalies.

**Advanced geophysical methods**

Over the past decade advanced resistivity technology has been improved upon which enables the capture of high-resolution quantitative and qualitative information about the strata under a site. Quantitative data includes depth and thicknesses of sub-bottom structures. Qualitative data includes type of sediment; sand, silt or clay and rock characteristics such as fresh or weathered. High resolution combined quantitative and qualitative data is extremely useful as an aide for successful project planning. With this information



**FIGURE 5** Borehole and geophysical data combined (Verhoef, 1997).

Application	Scope of work	Penetration (m)	Sample testing
Lowering seabed	Number of boreholes strongly depends on risk involved with ground variations. Bates (1981) suggested $3 + A^{0.5}D^{0.33}/50$ , where A is area in m <sup>2</sup> and D is average thickness of material to be removed in metres. Samples & SPTs every 2 m with at least one in each layer. Some (P)CPTs if undrained shear strength (clay) and/or relative density (silt and sand) is relevant.	Slightly deeper than level of required lowering of seabed.	Classification tests to find the basic soil and rock parameters.  Additional laboratory tests depending on the need for additional parameters.
Slope stability	1 borehole (samples & SPTs every 2 m, with at least one in each layer) or (P)CPT per 100 m. (P)CPT especially relevant in case of silt or sand and relatively steep slope.	0.5 x the slope height below required level of lowering of seabed.	
Fill material	Number of boreholes strongly depends on expected ground variations, with a minimum of three required.	To depth of potential fill material.	
Settlement and stability of subsoil of reclamation area	Number of boreholes or (P)CPTs strongly depends on risk involved with ground variations, e.g. one borehole (samples & SPTs every 2 m, with at least one in each layer) or (P)CPT per 1000 m <sup>2</sup> to a minimum of three per 10000 m <sup>2</sup> .	1x to 3x reclamation height depending on risk involved with influence of deeper layers.	

**FIGURE 6**

Typical scope of geotechnical investigation for dredging.

project planners and engineers have a complete picture of the existing subsurface environment. This allows designs to take into account subsurface structures such as weathered and unweathered rock outcrops or buried river valleys to considerably reduced dredging and construction costs.

Advanced geophysical methods are defined as geophysical methods with capabilities to acquire both quantitative and qualitative information of the subsurface, presented in a georeferenced 3D model to integrate all sorts of other information including bathymetry, boreholes, Standard Penetration Test, side scan sonar, seismic, infrastructure and 3D surfaces (e.g. top of rock). The accuracy and resolution of advanced methods however, varies widely with outcomes dependent on the resolution and data sampling density. Site investigation boreholes are critical for the acquisition of engineering data about a specific soil and rock types, but fall short when used to infer geological structures.

Utilising only boreholes as a primary data source to derive the entire project site's

structural setting is problematic for two reasons. Firstly, as point source data, the geologist has very little geological context to assist in the understanding and classification of, particularly deeper, layers as they relate to a project site. Secondly, and most importantly, it is not statistically possible to demonstrate that a sampling pattern has adequately sampled all the materials that may be present on a project site.

The latter is a problem inherent in the marine infrastructure industry whereby borehole locations are not targeted but may be randomly chosen or even restricted due to budget constraints. There is little in the way of guidance or recommendations as to borehole sampling patterns and spacing.

The publication 'Geotechnical and Geophysical Investigations for Offshore and Nearshore Developments' (Kinlan, 2005) recommends the scope of geotechnical investigation for dredging as shown in Figure 6.

The publication contains the caveat: More boreholes or (P)CPTs may be required

**Site investigation boreholes are critical for the acquisition of engineering data about a specific soil and rock types, but fall short when used to infer geological structures.**



**Modern DGM practice is increasingly seen as essential for marine infrastructure planning and asset management.**

near anomalies or near discontinuities in the soil layering, especially if a type of rock or soil is present that cannot be excavated, raised or transported with the proposed dredging equipment, or if another high risk is involved.

In *Obrascon*, with reference to boreholes, Justice Akenhead made the following remark: 'Most civil engineering tenderers are aware that boreholes and trial pits only sample what is within the 100 mm or 150 mm tube or 2 or 3 m<sup>2</sup> trial pit. Particularly in made or contaminated ground, it is difficult to extrapolate what may lie between the boreholes and pits. It is easier to extrapolate in relation to the natural ground profiles of the underlying soil or rocks.'

As Justice Coulson stated in the *OSR* case: 'Every experienced contractor knows that ground investigations can only be 100% accurate in the precise locations in which they are carried out. It is for an experienced contractor to fill in the gaps and take an informed decision as to what the likely conditions would be overall.'

It is precisely the 'gaps' and extrapolation between borehole locations and the degree of variation between these data points that need to be assessed and to which the experienced contractor test will apply.

**Conclusion**

The use of DGM is proving invaluable in the assessment of a project site. Modern DGM practice is increasingly seen as essential for marine infrastructure planning and asset management. Advanced remote sensing, sophisticated digital data acquisition and management tools that are now available, compared to just a decade ago, help to reduce the risk of unforeseen adverse physical conditions that cause delay and significantly increase the cost of marine infrastructure projects. Advanced digital geophysics provides a reliable source of 3D data that can be integrated into an integrated ground model to provide engineers with a digital tool to manage and control risks relating to unforeseen and adverse physical conditions.

This has become ever more relevant given the development in case law and the *Obrascon* and *OSR* court cases have developed the

## Summary

In the past decade, there have been noteworthy advances in case law with respect to adverse physical conditions as well as the development and the use of digital ground models that have become more widespread. Advanced digital geophysics provides a reliable source of 3D data that can be integrated into an integrated ground model to provide engineers with a digital tool to manage and control risks relating to unforeseen and adverse physical conditions. This has become ever more relevant given the development in case law and the *Obrascon* and *OSR* court cases, which have developed the concept of the experienced contractor test to a new level. The contractor has the burden of satisfying the experienced contractor test on the balance of probabilities and cannot solely rely on the Employer's Site Data alone as a sort of guarantee, and this is implicit from the decisions of *Obrascon* and *OSR*.

concept of the experienced contractor test to a new level. These cases have shown that an experienced contractor at tender stage cannot simply limit itself solely to an analysis of the geotechnical information contained in the pre-contract site investigation report and the underlying sampling.

The statement in the OSR case that, 'it is for an experienced contractor to fill in the gaps and take an informed decision as to what the likely conditions would be overall', sets the basis for the test as to what should be reasonably expected from an experienced contractor. The contractor has the burden of satisfying the experienced contractor test on the balance of probabilities and cannot solely rely on the employer's site data alone as a sort of guarantee, and this is implicit from the decisions of Obrascon and OSR.

Increasingly, potential tenderers will be expected to interrogate the available source data. If there is any perceived lack of geotechnical data between boreholes, they could use (as part of their site 'inspection') geophysical resistivity methods that are designed to acquire large volumes of

high-resolution data about the structural geology over the project area. This can be completed in a matter of days. It has to be said however, that the employer is best placed to do this at pre-tender phase and provide the geophysical information it obtains to all tenderers rather than multiple tenderers carrying out such an exercise. It should be noted that the requirement to have 'inspected' the site is a lesser standard than a requirement to 'examine', 'verify' or 'investigate' the site so contractors should be cautious if such wording is used in any contract.

Lastly, in the event of anticipated complex geotechnical conditions on a marine infrastructure project, employers may consider the recommendation in FIDIC's Blue Book (2016) note for guidance on addressing the foreseeability of those conditions by using a Geotechnical Baseline Report (GBR) as a reference. A GBR would set out what the expected ground conditions on a project will be and in effect create a specification for the anticipated conditions. In the event of the project running into difficulties due to unforeseen adverse physical conditions, the

GBR can be used to decide if the conditions were really unforeseeable and or fall within the conditions expected at the site.



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# 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.**

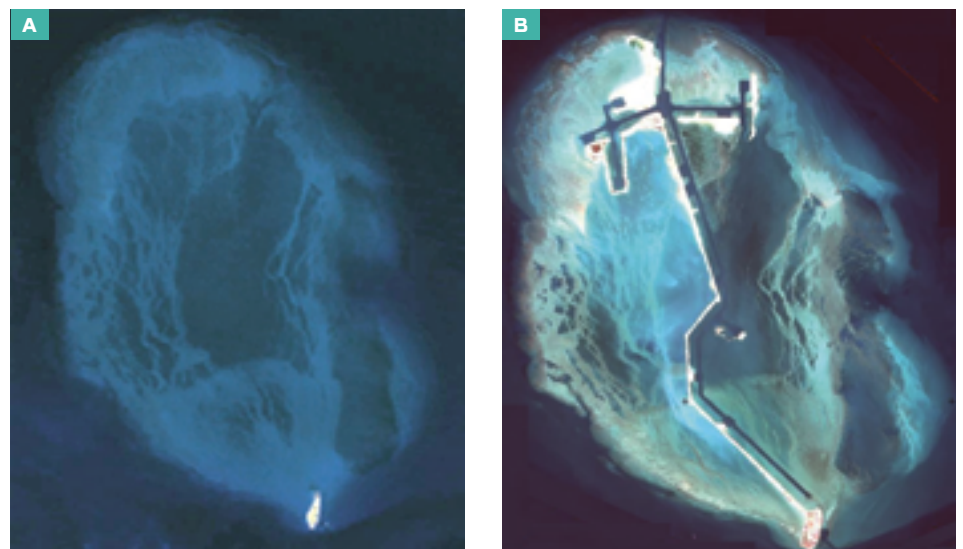
Over the past decades, there has been a growing interest in exploring innovative ways to minimise the environmental footprint of coastal developments and in nature-based approaches for shoreline protection. At Mubarraz Island near Abu Dhabi (UAE), an international oil company beneficially reused ~12 million m<sup>3</sup> 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<sup>2</sup>) 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<sup>-1</sup>. Average wind conditions are governed by land and sea breezes with

typical speeds of 7 m s<sup>-1</sup> (northern wind) during the day and 6 m s<sup>-1</sup> (southern wind) at night. Much stronger winds (up to 12 m s<sup>-1</sup>) 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<sup>-1</sup>.



**FIGURE 1**

Mubarraz (Landsat satellite image) in 1972 (A) and (EDOMAP 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<sup>3</sup> of carbonate sediment, consisting mostly of sand (70%), with 22% gravel and 8% fines (Aces, 2016).

Approximately 10 Mm<sup>3</sup> 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<sup>3</sup> 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

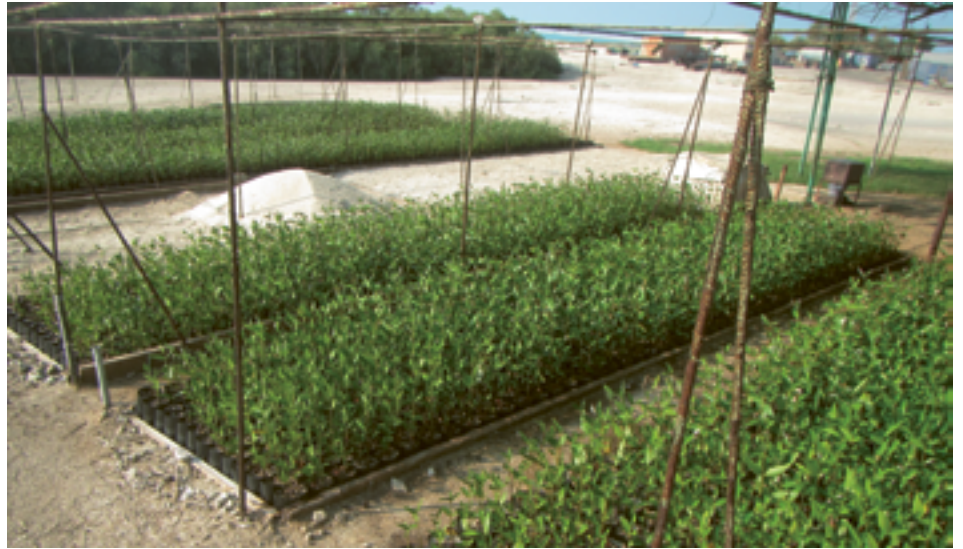
The first mangrove planting campaigns at Mubarraz were carried out during the start-up phase of causeway construction and oil operations during 1983–87. These plantings were conducted with seedlings of the mangrove species *Avicennia marina* obtained from a mangrove tree nursery in mainland Abu Dhabi, 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<sup>-1</sup>), stunted tree height (mean: 3 m), narrow stem diameter (mean: 5 cm), moderate basal area (5–37 m<sup>2</sup> ha<sup>-1</sup>), mean pneumatophore density of 589 m<sup>-2</sup>, and healthy recruitment (>14,000 natural seedlings ha<sup>-1</sup>) (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<sup>-2</sup>) and gastropod snails (up to 429 m<sup>-2</sup>). 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.





**Mubarraz currently supports 50 species of birds, which can be attributed almost entirely to the creation of new land and successful establishment of mangrove vegetation.**

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.

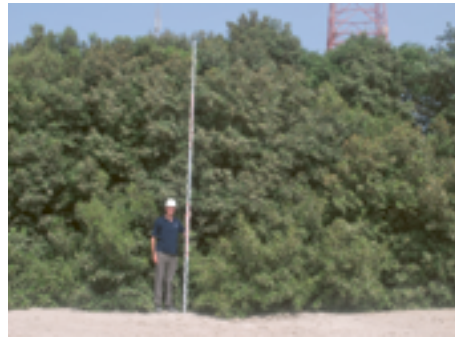
### Beneficial reuse of dredged material for mangrove habitat

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.

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](http://www.pianc.org/working-with-nature)), 'Building with Nature' in the Netherlands ([www.ecoshape.org](http://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.

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,



**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<sup>3</sup> 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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Paul graduated in 1993 with a PhD in Marine Ecology from Radboud University Nijmegen, The Netherlands. He has worked for over 25 years as an applied scientist and in a consulting role with industry and other clients focusing on the prevention of human impacts and restoration of critical marine and coastal ecosystems worldwide, in particular in relation to dredging operations. After working for Wetlands International, DGIS, Deltares and Jacobs, Paul now operates as an independent consultant (DAMCO Consulting) and is affiliated as adjunct research fellow at the University of Western Australia.



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# LIFE MARINA PLAN PLUS PROJECT: SUSTAINABLE MARINE AND COASTAL SEABED MANAGEMENT



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In June 2019, the research team of the LIFE MARINAPLAN PLUS project began operating the first-of-a-kind demonstration plant installation at the harbour entrance of Marina di Cervia (Italy). Fulfilling the project's objective to apply at industrial scale a reliable technology for the sustainable management of sediment in marine infrastructures, this technology prevents harbour silting through the use of submerged devices called 'ejectors' installed on the seabed.

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**The main objective of the ejectors plant installed in Marina di Cervia is to guarantee navigability at the harbour inlet while in operation.**

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The research project entitled 'LIFE MARINAPLAN PLUS: Reliable and innovative technology for the realisation of a sustainable marine and coastal seabed management plan', began in October 2016 and was completed in December 2020. Funded by the European Commission within the framework of the LIFE programme and co-funded by the Executive Agency for Small and Medium-sized Enterprises (EASME), the project was coordinated by the Italian company Trevi. A world leader in subsoil engineering, Trevi coordinated the research team that included the participation of three partners: the Municipality of Cervia (Italy), that played the role of technology end-user; the University of Bologna, responsible for the impact monitoring of the installation; and the International Council of Marine Industry Associations (ICOMIA) that acted as main dissemination and communication contributor.

The project team received EUR 1.45 million to design, realise, operate and monitor the first-of-a-kind demonstration plant installation (from here on referred to as 'the ejectors plant') at industrial scale of an innovative solution for the sustainable management of sediment in marine infrastructures. The ejectors plant operated from June 2019 to September 2020 and was able to guarantee navigability of Marina di Cervia's harbour

entrance for the whole period. This article presents the preliminary assessment of the ejectors plant results after 15 months of continuous operation and monitoring.

The need to remove deposited material from water basins is a common feature shared by many ports, harbours and waterways, and has been since the earliest settlements along coasts and rivers. Normally, the most widely used solution to remove sediment deposits is dredging. Dredging is a well-known, reliable and diffused technology. Nevertheless, in specific conditions (i.e. smaller marinas and channels), dredging in shallow water requires scaled technologies that are less productive and more expensive than standard configuration.

While dredging is able to restore the desired water depth, it is not without impact on sedimentation causes and therefore cannot guarantee avoiding sedimentation over time. Furthermore, dredging operations can often interfere with navigation and other nautical activities, and imply potential environmental impacts for the marine ecosystem: modifying marine habitat related organisms and disturbing contaminants already present in the seabed. Therefore, maintenance dredging operations often become too expensive and/or are not allowed by normative framework due to the related environmental impact.

#### **Description of the ejectors plant**

Cervia is a municipality of ~30,000 inhabitants, located along the Adriatic Sea in the Emilia-Romagna region. Marina di Cervia is located on the north-east side of the old harbour (Figure 1B), reserved for recreational craft, consisting of a dock with eight piers. The marina has a capacity of 300 boats with a maximum length of 22 m. The harbour is affected by a cyclic problem of inlet sedimentation. The technological solutions adopted until now, including seasonal dredging and/or sand underwater resuspension by boat propellers, as well as docks lengthening (completed in 2009), have not solved the sedimentation problem. In fact, from 2009–2015 ~EUR 1.3 million was spent on dredging and sediment handling with propellers (i.e. a mean yearly cost of EUR 185,000 (Pellegrini et al., 2020)).

The main objective of the ejectors plant installed in Marina di Cervia is to guarantee navigability at the harbour inlet while in operation. The plant consists of ten ejectors located at the harbour entrance as shown in Figure 2. The ejector (see Figure 3) is an open jet pump (i.e. without closed suction chamber and mixing throat) with a converging section instead of a diffuser and a series of nozzles positioned around the ejector. Each ejector is placed on the seabed and transfers momentum from a high-speed primary water jet flow to a secondary flow that is a mixture of water and the surrounding





FIGURE 1

Cervia's location in the northern Italian region of Emilia-Romagna (A) and aerial photo of the harbour study area (B).

sediment. The sediment-water mixture is then conveyed through a pipeline and discharged in an area where the sediment can be picked up again from the main water current (as in Cervia's application) or where it is not an obstacle for navigation. Based on preliminary tests carried out in 2017 (Pellegrini et al., 2020), with a primary water feeding flowrate of  $\sim 27 \text{ m}^3/\text{h}$ , a working pressure of  $\sim 2.4 \text{ bar}$  and a discharge pipeline characterised by 60 metres in length, each ejector is able to convey a peak sand flowrate at the discharge pipeline of about  $2 \text{ m}^3/\text{h}$  (whole discharge flowrate is  $\sim 34 \text{ m}^3/\text{h}$ ) and a water pump power consumption of about 3.5 kW. The ejector works on a limited circular area created by the

pressurised water outgoing from the central and circular nozzles, whose diameter depends on the sediment characteristics such as, for example, the repose angle. By ejector integration in series and in parallel, it is possible to create or to maintain a seaway.

The technology is reliable as, generally speaking, jet pumps have been applied for coastal application since the 1970s. Regarding the ejectors technology, it was developed and tested in 2001 by the University of Bologna and the start-up Plant Engineering Srl. In 2005, the first experimental plant (Amati and Saccani, 2005) was realised and tested in the port of Riccione in

Italy. In 2012, a second experimental plant (Bianchini et al., 2014; Pellegrini and Saccani, 2017) was implemented in Marina di Portoverde in Italy. Both installations were realised at harbour entrances and designed to handle sand. A third experimental installation was established in 2018 in Cattolica in Italy, where for the first time the ejectors were applied in the management of silt and clay sediments and installed in a river channel (Pellegrini et al., 2020).

The Cervia ejectors plant also includes a fully automated and remotely accessible pumping station equipped with auto-purging filters. The Piping and Instrumentation Diagram (P&ID) of the pumping plant is schematically shown in Figure 4, where only one ejector line is drafted. There are two pumps, each one feeding five ejectors. Each pumping line has an auto-purging disk filter: the auto-purging cycle is activated once the pressure drop in the filter reaches a certain level. The total pumped water flowrate is controlled by an inverter, while the flowrate for each ejector feeding pipeline is balanced through electro valves. An air compressor can be used to inject compressed air in the line to easily

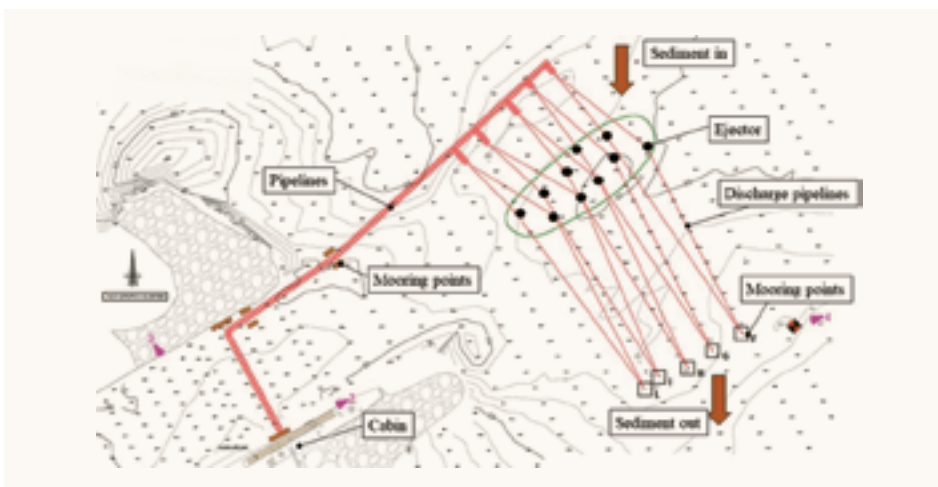
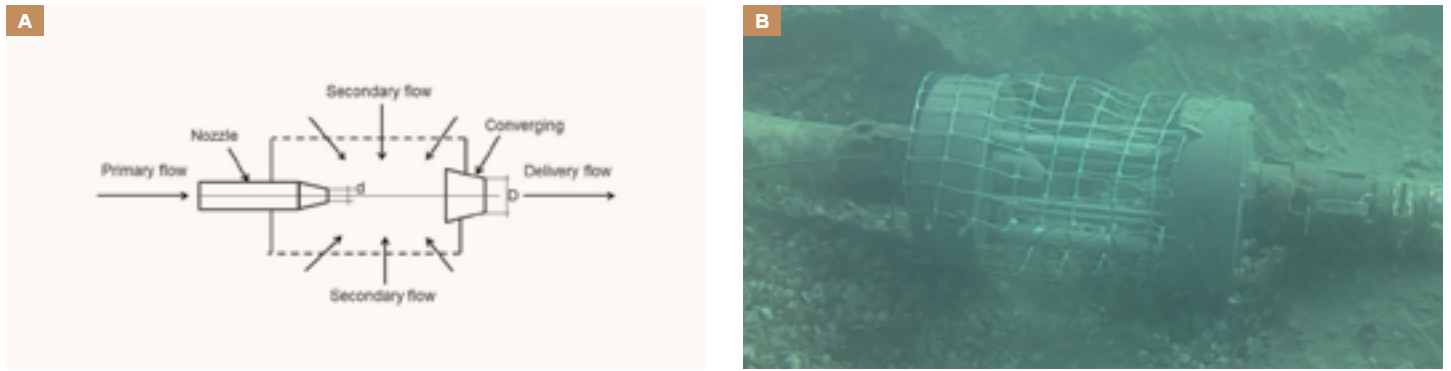


FIGURE 2

Location of ejectors in the Cervia plant.



**FIGURE 3**  
Diagram of the ejector (A) and underwater photo of the ejector in operation (B).

identify the position of the ejectors on the seabed. The total installed power is about 80 kW. A local meteorological station has been installed to relate plant operation with sea weather conditions.

The main novelty of the LIFE MARINAPLAN PLUS project is that the ejectors plant is designed and controlled to bypass the settling sediments, and not to remove them from the seabed. This feature is important in authorisation and permit procedures, since the mass balance in the area where the ejectors are installed can be considered as zero, and therefore the ejectors plant operation is not equated to maintenance dredging. Moreover, the continuous operation of the plant reduces the environmental impact to near zero, since the sediment management follows the rhythm of nature.

**The monitoring plan**

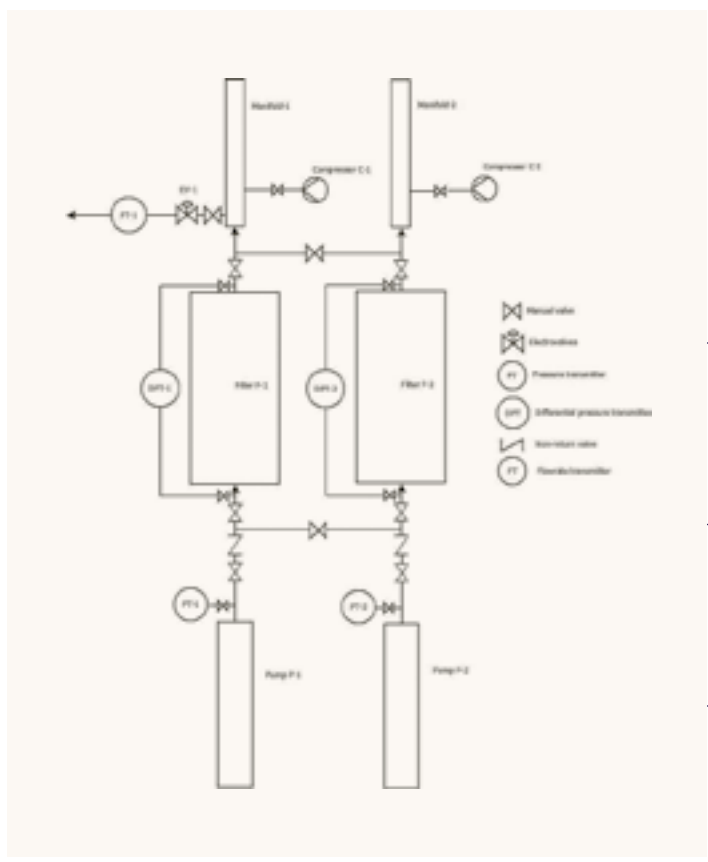
Bianchini et al. in 2018 already demonstrated through a literature review that a sand bypassing plant can be more economical than dredging, even if operation and maintenance costs are usually based on estimation more than on real data. One of the main objectives of the LIFE MARINAPLAN PLUS project was to measure the operation and maintenance costs over a consistent period. The efficacy of the ejectors plant was monitored through bathymetries in the ejectors area, while the efficiency was assessed through power consumption analysis.

Environmental monitoring activities are fundamental in the LIFE MARINAPLAN PLUS project, since reliable data are crucial to:

- evaluate the impact of the ejectors plant on the marine environment;
- compare the impact of the ejectors plant with that of dredging activities; and
- design sustainable sediment management.

The environmental impact of sand bypassing systems has never been analysed in

detail (Bianchini et al., 2019). Therefore, another interesting novelty of the LIFE MARINAPLAN PLUS project is the assessment of the ejectors plant impacts on marine benthic and fish communities, due to both sediment reworking and possible noise production. Moreover, the environmental impacts of the realisation and operation of the ejectors plant, projected over 20 years of



**FIGURE 4**  
Piping and Instrumentation Diagram (P&ID) of the pumping plant.

**PROJECT**

operation, have been evaluated through the Life Cycle Assessment (LCA) approach.

**Project results: navigability guaranteed**

The Cervia ejectors plant operated continuously from June 2019 to September 2020, thus achieving the objective of the LIFE MARINAPLAN PLUS project; namely the monitoring of performance and impacts produced for a minimum period of 15 months operation. Table 1 summarises the five operating phases in which plant operation can be divided. In the first and second phases, the ejectors plant operated with a reduced load (25% and 50% respectively) and manual control: such a control strategy was necessary to limit pressure and power consumption, since some devices showed lower performances than the one declared by the suppliers. The plant then entered the third and fourth phases of operation, in which the full load of the plant was reached. In this period, however, a growing issue related to mussels (*Mytilus galloprovincialis*) fouling in the pipes and filters was detected. The performance of the ejectors plant was highly affected by fouling, since a reduced water flowrate was available for the ejectors and a higher pressure was needed, thus

dramatically increasing power consumption. Hence in the fifth phase only two ejectors were in operation.

Bathymetries have been carried out through a digital hydrographic ultrasound system with narrow emission cone, preliminary calibration and differential GPS Trimble positioning system; the resulting error is estimated as not exceeding 3 cm. Figure 5 shows the bathymetry before the ejectors plant installation: in Figure 5A there is a detailed colormap of water depth at the harbour entrance, while in Figure 5B specific areas with water depth more than 3 m, between 2–2.5 m and lower than 2 m are reported.

Despite the numerous problems encountered, which have been solved or for which a technical solution has been identified, the effectiveness of the ejectors plant is demonstrated by the ability of the plant to maintain a navigable channel with a minimum water depth of 2.5 m, measured with respect to the mean sea level leaving the harbour; a condition previously never reached at the beginning of the summer season without dredging operation. Figure 6 refers to the end of April 2020, i.e. after 10 months of continuous operation. Up until that date, the

effect of fouling was not critical in terms of effectiveness, even if efficiency was reduced.

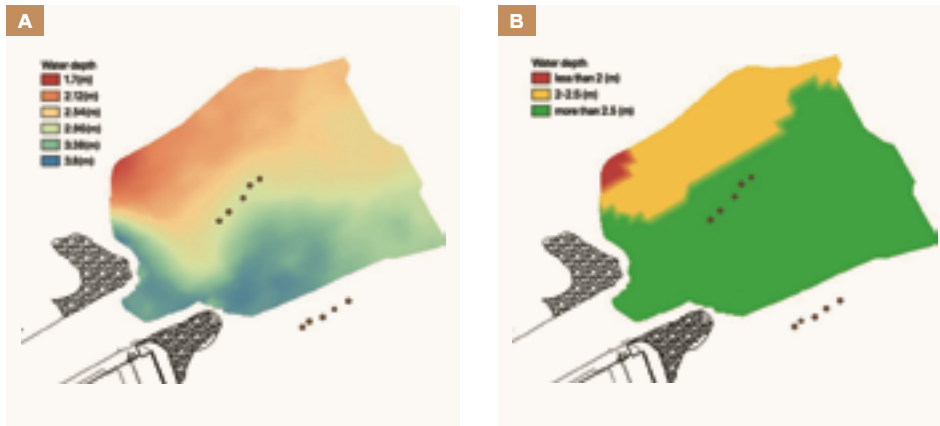
The final bathymetry of the monitoring period (see Figure 7) was completed on 11 September 2020 and shows a critical sedimentation between the harbour entrance and the area of installation of the ejectors, which is not consistent enough to impede navigation. Nevertheless, it should be noted that only two ejectors were in operation from the end of July 2020 due to fouling limitations.

With regard to efficiency, the ejectors plant's consumption was higher than expected: as previously stated, starting from January 2020 until July 2020 (with a peak in June 2020), the uncontrolled growth of mussels in the pipes and filters considerably increased the pressure losses in the system, forcing the pumps to work with higher pressure, but with the same flow rate, compared to the operating conditions recorded in 2019. Various technical solutions alternative to chlorination are under evaluation to prevent the proliferation of organisms in the pipes, such as low-frequency electromagnetism. For this reason, based on the data collected in the first period of operation of the plant and the measured water flowrate for the whole monitoring period, it is

**TABLE 1**  
Classification of operation phases of the ejectors plant in Cervia.

Demonstration plant operation regime	2019							2020									
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
Phase 1 Manual, partial load (25% of maximum)	■																
Phase 2 Manual, partial load (50% of maximum)						■											
Phase 3 Manual, full load									■								
Phase 4 Automatic - 10 ejectors													■				
Phase 5 Automatic - 2 ejectors																■	





**FIGURE 5**  
Colormap of water depth at the harbour entrance on 12 June 2019 (A) and of water depth for specific ranges (more than 3 m, between 2–2.5 m and lower than 2 m) on 12 June 2019 (B). The red circles indicate the GPS reference of the mooring points of inlet and outlet ejectors pipelines. The ejectors are installed between the inlet/outlet mooring points, as shown in Figure 2.



**FIGURE 6**  
Colormap of water depth for specific ranges (more than 3 m, between 2–2.5 m and lower than 2 m) on 30 April 2020. The red circles indicate the GPS reference of the mooring points of inlet and outlet ejectors pipelines. The ejectors are installed between the inlet/outlet mooring points, as shown in Figure 2.



**FIGURE 7**  
Colormap of water depth for specific ranges (more than 3.0 m, between 2.0–2.5 m and lower than 2.0 m) on 11 September 2020. The red circles indicates the GPS reference of the mooring points of inlet and outlet ejectors pipelines. The ejectors are installed between the inlet/outlet mooring points, as shown in Figure 2.

**The results suggest an improvement in the ecological status of the marine ecosystem in the area affected by the plant.**

possible to assess the average consumption of each ejector in normal conditions equal to 3 kW, i.e. an annual consumption for the ten ejectors of approximately 255,000 kWh/year.

**Environmental impact assessment**

While the effectiveness of the ejectors plant was already assessed in previous experimental installations, one of the main results of the LIFE MARINAPLAN PLUS project is related to the comprehensive monitoring of environmental impacts of plant operation, which includes:

- integrity of seabed sediments and communities;
- underwater noise;
- greenhouse gases (GHGs); and
- pollutant emissions through LCA.

Possible impacts of the ejectors plant on sediment characteristics, benthic and fish assemblages need to be assessed simultaneously at a variety of spatial scales, encompassing the full extent of the environmental variability of the area where the ejectors are positioned. Sampling sites are located in one putatively impacted location in front of the Marina di Cervia and in four control locations, placed 600 m and 1200 m north, and 600 m and 1200 m south of the impact location respectively (shown in Figure 8). Two sampling areas (~800 m<sup>2</sup> each), 20–30 m apart, were defined within each location. In particular, the impact location includes two distinct areas, the ejectors (I1) and the outlets (I2). Changes in time of the measured variables at each putatively impacted areas were compared to the whole range of control areas.

The use of the ejectors plant technology resulted in a reduction of the percentage of muddy fraction (Figure 9A) and of the organic matter content (Figure 9B) present in the sediment in the areas affected by the plant, compared to the initial values (samples taken in May 2018) conditioned by previous dredging, thus approaching the mean values observable throughout the study in the control areas. Species richness of marine macro-invertebrates (as shown in Figure 10), initially reduced in the impacted area near the harbour, probably as a result of previous repeated dredging, significantly increased 8 months after the ejectors plant began operation (i.e. February 2020), although still remained below the average for control sites. These results suggest an improvement in the



FIGURE 8

Map of sampling locations. Areas within location: N1 = North 600 m; N2 = North 1200 m; S1 = South 600 m; S2 = South 1200 m; and I = areas within location impact.

ecological status of the marine ecosystem in the area affected by the plant within less than one year from the start of plant operation.

The impact of the ejectors plant on underwater noise was assessed in September 2020. Since specific international standards do not currently exist for the measurement of underwater noise in a harbour environment, the document produced by the National Physical Laboratory (UK) has been taken into account (NPL, 2014). The acoustic measurements were carried out by a specialised operator and by using the SQ26-05 sensor, a pre-amplified hydrophone produced by Sensor Technology. The measurements were carried out on five sampling points (see Figure 11):

- nearest point from the hydraulic pumps (B1);
- 60 m from the hydraulic pumps (B2);
- ~200 m from the hydraulic pumps and 150 m from point B2 (B5);
- near the discharge point of the ejectors, approximately 50 meters away (M3); and
- ~185 m from point M3 (M4).

Furthermore, the measurements were carried out with the ejectors plant shut off and with the plant in operation in three different conditions: manual control at two different speeds of the centrifugal pumps, plus automatic control (variable speed of the centrifugal pumps).

The measurement sampling was conducted over 4 days (Friday to Monday) and performed during different time slots (day and afternoon). The measurement period, which included the weekend, was chosen to be able to observe the effect of tourism traffic, i.e. motor boats, with respect to the condition that occurs on working days (Friday and Mondays) in which traffic is more limited. While the assessment carried out in sampling points M3 and M4 relate to the impact on open marine environment, sampling points B1, B2 and B5 were measured to evaluate the impact of submersible centrifugal pumps for Marina di Cervia customers. All the acoustic data were analysed through MATLAB software. For each of the audio files, the average value of the Sound Pressure Level (SPL) in the frequency spectrum 12–20,000 Hz was calculated taking into account the gain level set for the recorder (M), for the pre-amplifier (G) and the sensitivity of the instrument (S), accordingly to equation 1:

$$SPL = 20 \log_{10} [\sqrt{P_x}] + M - G - S \quad [1]$$

where  $P_x$  corresponds to the ratio between the digital values of the audio file in 'wav' format (i.e. the uncompressed format that guarantees the preservation of a sound identical to the original without quality reduction in the analog-digital transformation that takes place inside the acoustic recorders) and the number of bits set for analog-digital conversion of the

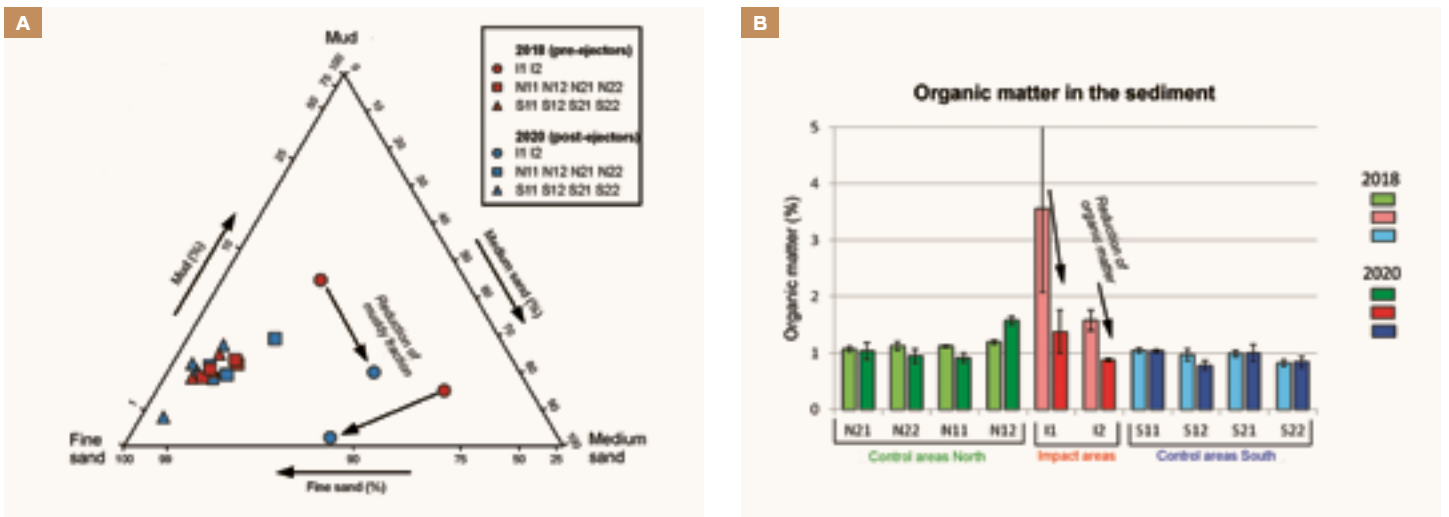


FIGURE 9

Proportions of the sediment granulometric fractions: medium sand >250 µm; fine sand 250–63 µm; and mud <63 µm (A) and percentage in weight of organic matter in the sediment (error bars based on standard error) (B).

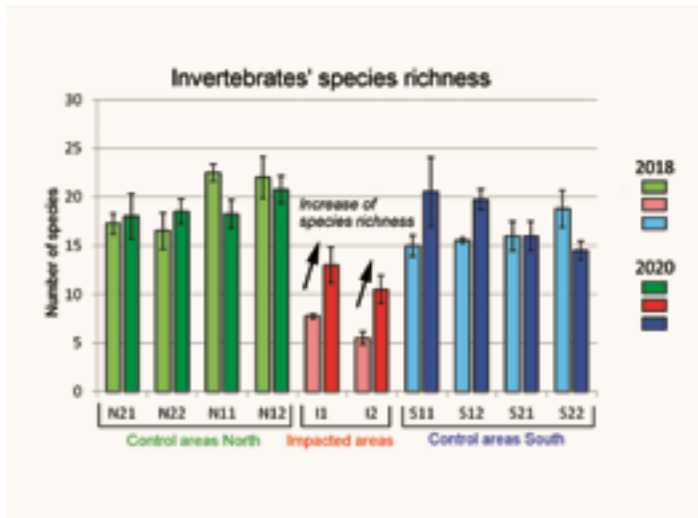


FIGURE 10

Mean number of macro-invertebrate species per sample in benthic communities [error bars based on standard error].



FIGURE 11

Locations of the five measurement points.

signal (16 bit). Particular attention was paid to the analysis of the average value of SPL in the operating frequencies of the hydraulic pumps (30–50 Hz). Where anomalies were found in the measured SPLs, the data were subjected to statistical tests, conducted with the aid of PAST advanced statistics software to investigate the presence of a statistically significant deviation from the average measured values.

The ejectors themselves had no impact on underwater noise level if compared with the 'natural' baseline, while only in the case of monitoring point B1 a difference was found between the noise levels in the recordings made with and without the hydraulic pumps in operation (see Figure 12). Nevertheless, the data were subjected to the Mann-Whitney statistical test for non-parametric distributions, to verify, in the presence of ordinal values from a continuous distribution, if two statistical samples come from the same population. The results obtained indicate that the difference between the measurements made with the inactive hydraulic pumps ('off' in Figure 12) compared with the measurements made with the hydraulic pumps 'on' and at different operating status (max, min and automatic control in day #1 and day #2) is not statistically significant ( $p = 0.12$ , which is greater than the significance value of 0.05) and therefore not attributable solely to the activity of hydraulic

pumps. The conclusion is that from the analysis of the acoustic data, it emerged that in the harbour environment the impact of ejectors and hydraulic pumps to underwater noise level is insignificant.

Finally, the impact of the Cervia ejectors plant construction and operation on GHGs and pollutant emissions was assessed through LCA. The choice of system boundaries considered only emissions related to raw materials processing and plant operation phases. The other phases of plant construction (components manufacturing, transport and assembly) as well as decommissioning phase was not included since their contribution was considered as negligible. This hypothesis is consistent with available literature data on LCA of pumping station (Jocanovic et al., 2019), which is comparable in terms of components and expected life with the ejectors plant. The Life Cycle Inventory (LCI) was performed on the basis of:

- bill of materials (BOM) analysis, to identify/classify the components used for the realisation of the ejectors plant;
- energy consumption in operation; and
- components substitution for damaging and/or wear over the years.

The estimated life of the ejectors plant is 20 years. To take into consideration the optimisation potential of energy consumption

that is estimated on the basis of the 15 months monitoring of plant operation in Cervia, the LCA analysis considers two different scenarios for energy consumption:

- the energy consumption measured during the LIFE MARINAPLAN PLUS project, which is about 530,000 kWh/year; and
- the energy consumption optimised, which is estimated at ~147,000 kWh/year.

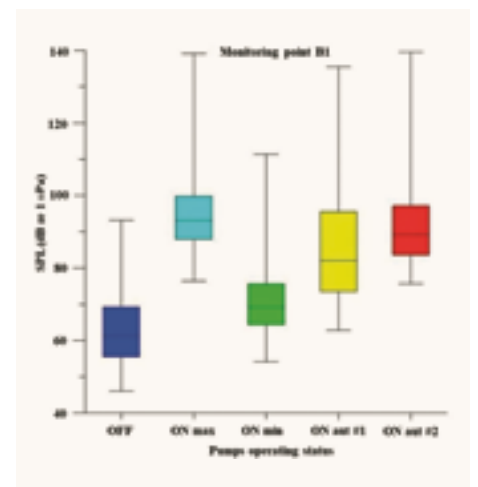


FIGURE 12

Box-plot of the average SPL values (on the ordinates) for the different operating states of the hydraulic pumps (on the abscissas).



TABLE 2

Impacts of the ejectors plant in the two different scenarios by considering the functional unit. NMVOC = non-methane volatile organic compounds.

		SCENARIO #1					
Boundary	Source	Environmental impact					
		CO <sub>2</sub> (kg)	CO (kg)	SO <sub>2</sub> (kg)	NO <sub>x</sub> (kg)	PM2.5 (kg)	NMVOC (kg)
Construction	Materials	57,816	33.5	6.7	4.4	1.2	6.5
	Energy	3,498,000	-	-	-	-	-
Operation	Materials	5,202	0.06	0.01	0.0	0.0	0.28
	<b>Total</b>	<b>3,561,018</b>	<b>33.6</b>	<b>6.7</b>	<b>4.4</b>	<b>1.2</b>	<b>6.8</b>

		SCENARIO #2					
Boundary	Source	Environmental impact					
		CO <sub>2</sub> (kg)	CO (kg)	SO <sub>2</sub> (kg)	NO <sub>x</sub> (kg)	PM2.5 (kg)	NMVOC (kg)
Construction	Materials	28,908	16.8	3.3	2.2	0.6	3.3
	Energy	970,200	-	-	-	-	-
Operation	Materials	2,601	0.03	0.01	0.00	0.00	0.14
	<b>Total</b>	<b>1,001,709</b>	<b>16.8</b>	<b>3.3</b>	<b>2.2</b>	<b>0.6</b>	<b>3.4</b>

The estimation of optimised energy consumption is based on the following considerations: the ejectors plant operated almost continuously, and by considering the hours of maintenance and the stop period registered during LIFE MARINAPLAN PLUS project implementation, it is possible to estimate that the ejectors plant worked approximately 8400 hour per year, which means a measured mean power consumption per ejector of 6.3 kW. Nevertheless, by considering the early operation period of the plant, which was not affected by fouling, it can be noticed that the mean power consumption per ejector could be ~3 kW, which is coherent with the yearly energy consumption estimated for the optimised scenario. Moreover, the results of monitoring actions highlighted how five ejectors instead of the ten installed should be enough to avoid sedimentation at the harbour inlet. Therefore, the final estimation

of energy consumption in an optimised configuration considers five ejectors with a mean power consumption of 3.5 kW. Operation strategy could be further optimised to reduce energy consumption by plant shut off in certain conditions, but such a strategy needs to be validated in the field.

Material consumption for components being damaged and/or worn has been included to also consider the impact of spare parts or component substitutions. The hypotheses are based on the manufacturers' datasheet and the monitoring of 15 months of operation of the ejectors plant in Cervia:

- Marine installation: substitution of 5 km of pipeline per year;
- Inverter: expected lifetime 10 years;
- Pump: expected lifetime 10 years; and
- Pipeline brackets (metallic): expected lifetime 10 years.

Table 1 summarises the impacts of the ejectors plant construction and operation referred to the functional unit and by considering the two different scenarios previously described. A further emission reduction could be reached if the ejectors plant would be powered by renewable energy.

The categories selected to describe the impacts caused by the emissions and the consumption of natural resources at midpoints are Global Warming Potential (GWP), fine particulate matter formation (PMFP), photochemical oxidant formation (EOPF and HOPF) and terrestrial acidification (TAP). All categories have been assessed accordingly to ReCiPe 2016 (Huibregts et al., 2016). Figure 13 shows the results of the LCA.

**Economic assessment**

The primary elements of the economic assessment are BOM analysis (purchasing costs of all the components used for the realisation of the ejectors plant), construction site work journal (manpower costs for installation and commissioning

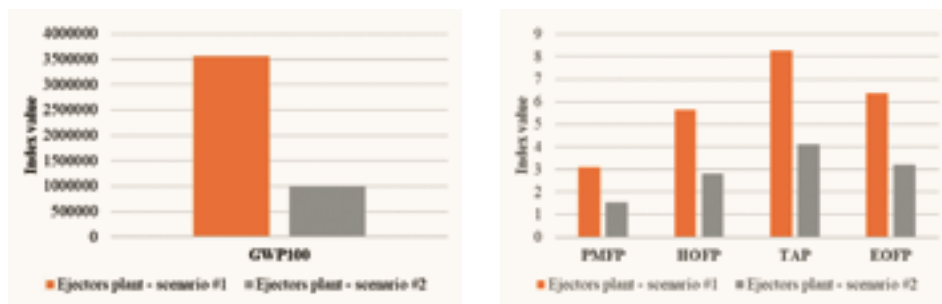


FIGURE 13

Comparison of midpoint characterisation between the two scenarios.

**The operation of the plant is expected to reduce sediment management costs for the Municipality of Cervia with a near-zero impact on marine environment.**

and number of hours), energy consumption in operation, costs for component substitutions for damage and/or wear over the years, and manpower for maintenance activities.

By considering the ejectors plant construction, some equipment has been added, in particular automatic anti-fouling system to prevent pipelines and filters clogging. Moreover, based on experience gained from the project, the divers and workers costs have been recalculated by considering the management optimisation that could be reached by having better coordination between Trevi's purchasing department, Trevi's human resources department and subcontractors in the organisation of the construction site. The realisation of a five-ejector plant (optimised configuration) would require 25 days of onshore activities, plus 10 days of marine activities. To evaluate the benefits for the ejectors plant customer, i.e. the Municipality of Cervia, the selling price is estimated by adding Trevi's costs plus unexpected events, overheads and profit. The final result is a total cost for the municipality of EUR 520,000.

The costs related to the ejectors plant operation can be summarised in the following categories: energy consumption and maintenance (components/spare

parts cost and manpower). The cost of energy is ~about 0.21 €/kWh. Based on the ejectors plant monitoring activities and by considering maintenance optimisation that could be reached through i) the installation of an automatic anti-fouling system and ii) more robust and cost effective solutions for the marine installation; it is assumed that a single diver for 12 days per year plus one worker for 52 hours per year are enough to guarantee the ordinary maintenance of a five-ejector plant. Extraordinary maintenance, including substitution of spare parts and main components affected by wear (such as pumps or inverters), is calculated as a percentage (20%) of the whole yearly operation and ordinary maintenance cost. The final result is an operation and maintenance (ordinary and extraordinary) cost of about EUR 50,000 per year for the Municipality of Cervia.

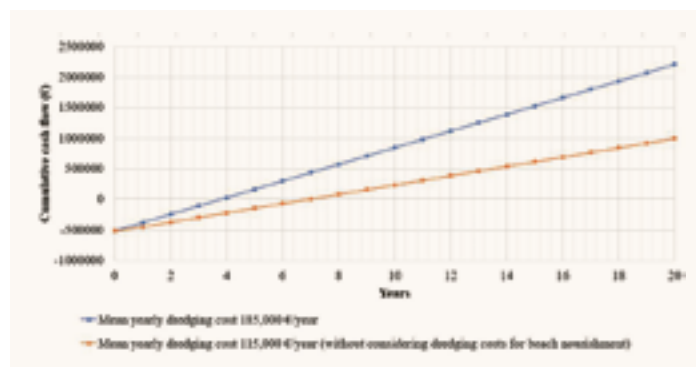
Figure 14 shows the simple payback time for the municipality by considering two comparisons with dredging costs: a yearly cost of EUR 185,000 (coherent with historical data) and a yearly cost of EUR 115,000 calculated excluding dredging costs for beach nourishment. The investment in the technology provides a very competitive result, with a simple payback time of 4 years in the best scenario. Nevertheless, if a lesser advantage is considered for the municipality, i.e. operation and maintenance cost increasing of the ejectors and/or partial use of dredging equipment for extraordinary maintenance, the investment still gives an attractive result with 7 years of simple payback time.

**Conclusions**

The LIFE MARINAPLAN PLUS project tested and validated an innovative technology for sediment management in water infrastructure. The first application at industrial scale of the ejectors plant has been realised at the harbour entrance of Marina di Cervia (Italy) with promising results in terms of effectiveness, since the navigability of the harbour entrance was guaranteed for the whole operation period of 15 months. Some technical improvements are needed to limit fouling issues, optimise power consumption and maintenance activities. Nevertheless, the solutions to address all the issues that arose during the project have already been identified.

Trevi is now committed to the retrofitting of the ejectors plant, which should be converted to a five-ejector plant. Based on monitoring activities carried out during the project, the operation of the plant is expected to reduce sediment management costs for the Municipality of Cervia with a near-zero impact on marine environment (i.e. seabed integrity and underwater noise level) and limited impact on GHGs and pollutant emissions.

Trevi is also looking for industrial partners, including dredging companies, to develop business-to-business opportunities related to integration of sustainable and green technologies for ports, harbours and waterways, as well as in combination with dredging. In the latter case, the match between an ejectors plant and dredging would result in a win-win opportunity since dredgers can support plant operation for extraordinary maintenance dredging.



**FIGURE 14** Simple payback time for the Municipality of Cervia.

## Summary

The project team received EUR 1.45 million to design, realise, operate and monitor the first-of-a-kind demonstration plant installation at industrial scale of an innovative solution for the sustainable management of sediment in marine infrastructures. This article summarises the results of monitoring actions carried out at the harbour entrance of Marina di Cervia (Italy), where the ejectors plant was installed and operated from June 2019 to September 2020 within the framework of the EU funded project LIFE MARINAPLAN PLUS. The ejectors plant was designed to continuously remove the sediment that naturally settles in a certain area through the operation of the ejectors, which are submersible jet pumps. The final aim of the project is to combine continuous water depth maintenance at the harbour entrance with environmental and economic sustainability through a reduction of the impacts on marine environment produced by sediment management. LIFE MARINAPLAN PLUS project was coordinated by Trevi SpA, which realised and operated the ejectors plant, while Municipality of Cervia, University of Bologna and ICOMIA participated as partners.



### Marco Pellegrini

Marco is assistant professor in Industrial Mechanical Plants at the University of Bologna. He joined the Department of Industrial Engineering in 2007 and has both research and teaching experience. Marco's research activities include sustainable sediment management, renewable energy generation, storage and distribution, and health and safety at work. He is author of more than 80 papers in peer-reviewed journals and relevant international conferences.



### Giovanni Preda

Since 2009, Giovanni has worked as R&D Project Manager for Trevi Spa – a worldwide leader in engineering, specialising in foundations, restoration of dams, ports and jetties, tunnels, confinement of contaminated sites and restoration of monuments. His main focus is on the development of innovative technologies for sediment management and treatment, environmental dredging, reclamation of contaminated areas, waste management and soil improvement.



### Barbara Mikac

Barbara is a marine ecologist and currently a research fellow at the Interdepartmental Research Centre for Environmental Sciences (CIRSA) of the University of Bologna. Her research is focused on diversity, structure, dynamics and ecology of benthic communities and natural and anthropogenic impacts on them, distribution and impacts of non-indigenous marine species and diversity and conservation of marine species and habitats. Specialised in ecology, systematic and taxonomy of polychaetous annelids, Barbara has described several species new to science.



### Massimo Ponti

Massimo is a marine ecologist and associate professor at the Department of Biological, Geological and Environmental Sciences (BiGeA) of the University of Bologna. He is president of the Italian Association of Scientific Divers, a dive master instructor and vice president of Reef Check Italy, a non-profit association. His research ranges from temperate to tropical benthic ecology, mainly focusing on species diversity, habitat-species interactions, effects of human disturbances and climate change at community and population levels, and biodiversity conservation.





### Cesare Saccani

Cesare is professor in Industrial Mechanical Plants at the University of Bologna, Department of Industrial Engineering. He has a decennial experience in multi-phase flow design, modelling and testing. Coordinator of the local unit in several international and national research projects, he is the author of over 110 papers on industrial mechanical plants topics and is the inventor of 10 patents.



### Arash Aghakhani

Arash is a PhD student at the University of Bologna. He joined the 'Future Earth, climate change and societal challenges' programme in 2019. His focus is mainly on the low-carbon systems for climate change mitigation and adaptation, coastal erosion, sediment transport and renewable energies. Arash gained his Masters in environmental engineering at the University of Bologna.



### Marco Abbiati

Marco is a professor at the Department of Cultural Heritage of the University of Bologna. Working in the fields of basic and applied marine ecology, environmental management and conservation, he has coordinated several research projects funded by the EU, ministries and private companies. Since 2020, Marco is Science Attaché at the Italian Embassy in Hanoi, Vietnam.



### Marina Antonia Colangelo

Marina is a marine ecologist and senior researcher at the Department of Biological, Geological and Environmental Sciences (BiGeA) of the University of Bologna. Her research focuses on the ecology of meio and macrobenthic communities and their role in the subtidal and intertidal ecosystem of sandy coasts.

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# IADC SAFETY AWARDS 2021

The IADC Safety Awards are intended to encourage the development of safety skills on the job and to reward people and companies demonstrating diligence in safety awareness in the performance of their profession.

**Nominations for both awards are now open!**

## Why is safety important?

The dredging industry poses many risks for its employees. Safety is always a top priority and the industry proactively maintains a high level of safety standards. It is not a one-time effort and constant vigilance requires innovation.

IADC is committed to promoting safety in the industry. A representative of contractors in the dredging industry, the global organisation

encourages its more than 100 main and associated members, as well as non-members, to establish common standards and a high level of conduct in their worldwide operations.

In 2013, IADC established a Safety Committee comprised of QHSE experts from its member companies to encourage the implementation of safety standards and enable the sharing of these practices amongst its members. The Safety Committee is committed to reducing the number of accidents and incidents in the industry and as a result developed a 'Charter of Best Practices' and annual safety award.

## Two safety awards

Conceived to encourage the development of safety skills on the job as well as heighten safety awareness, the IADC Safety Awards celebrate individuals and companies demonstrating special diligence in safety awareness while performing their profession, ultimately making working environments safer.

For several years, an award was granted to safety innovations made for the dredging industry. As of this year, two safety awards will be presented: one to a dredging company and a second to a supply chain organisation active in the dredging industry. This concerns subcontractors and suppliers of goods and

services. 'As IADC, we realise that suppliers of dredging contractors play an important role in increasing safety by offering innovative solutions with the help of the latest technical developments,' says René Kolman, Secretary General of IADC.

## Winners

The awards will recognise the exceptional safety performance of a particular project, product, vessel, team or employee. IADC's Safety Committee and Board of Directors will select the winners from the submitted nominations based on the criteria laid out in the guidelines for submission.

The winners of the IADC Safety Awards will be presented at the 2021 Annual General Meeting in September. In addition to receiving a bronze statue, the winners will present their safety innovation in an article in *Terra et Aqua* (published both in print and online) and be highlighted via media and social media platforms.

## Register your nomination

Nominations for both awards are now open and can be submitted via <http://bit.ly/SafetyAward2021>. The awards are open to both IADC members and all other dredging contractors. There is no limitation to the number of nominations that can be submitted. The deadline for submissions is 31 May 2021.



Winner of the IADC Safety Award 2019, the Floating Line Connection System developed by Boskalis.

# CULTIVATE NEW SKILLS AND SHARE KNOWLEDGE

## COVID-19

Due to the COVID-19 pandemic, events can be postponed or cancelled. IADC has been following the Dutch authorities' advisory measures with regard to limiting the spread of the virus and is keeping a close eye on the situation. We advise checking the IATA website regularly to see the COVID-19 travelling regulations for every country [<https://www.iatatravelcentre.com/international-travel-document-news.htm>].

## WEDA Virtual Dredging Summit

15–17 June 2021 Virtual  
<https://dredging-expo.com>

Organised by the Western Dredging Association (WEDA), the 2021 Virtual Dredging Summit is a technical conference to promote the exchange of knowledge in fields related to dredging, navigation, marine engineering and construction. The theme for this year's conference is 'Dredging: The Impacts of Climate Change'.

The three-day forum will consist of a series of technical and award presentations on 15, 16 and 17 June from 13:00–17:00 EST. The conference aims to provide a forum for improvement of communications, technology transfer and cooperation among associations and societies, while emphasising the importance of understanding and development of solutions for problems related to the protection and enhancement of the marine environment.

## IAPH World Ports Conference

21–25 June 2021  
Port of Antwerp  
Antwerp, Belgium  
[www.worldportsconference.com](http://www.worldportsconference.com)

The 2021 World Ports Conference will bring together leading ports, their customers and stakeholders as well as regulators in a world-class interactive event offering virtual and potential live, face-to-face interaction with the people who run and influence the world's ports.

This year's theme looks at the 'Changing of the Guard'. The five-day conference will explore the players who are shaping the new, complex environment in which ports operate. What they think and what their plans mean for ports. Topics explored will include data collaboration, risk and resilience, and business innovation.

**IADC and CEDA's  
one-day online  
course, Dredging  
for Sustainable  
Infrastructure, will  
take place on  
28 June 2021.**

## Coastal Dynamics Conference

28 June–2 July 2021  
Delft, The Netherlands  
(venue to be confirmed)  
[www.coastaldynamics2021.nl](http://www.coastaldynamics2021.nl)

Delft University of Technology and the Dutch community for coastal research will hold the 8<sup>th</sup> edition of the Coastal Dynamics Conference from 28 June until 2 July 2021, with a hybrid format of in person or online attendance. With the theme of 'Shaping the Future of our Coasts', the conference will look at how nature and humans are shaping our coasts, now and in the future.

IADC and CEDA's new course, based on the philosophy of the book *Dredging for Sustainable Infrastructure*, has been shortened into a one-day online course for Coastal Dynamics 2021 and will be held on Monday 28 June. During this course, participants will learn how sustainability principles can be implemented in practice in dredging projects. Emphasis will be placed on coastal processes, climate and coastal change, engineering and nature-based solutions.

The course is aimed at scientists and practitioners as well as professionals involved in dredging related activities for water infrastructure development. It is also for people with the ambition to achieve sustainable and resilient water infrastructure or dredging projects that contribute to the UN Sustainable Development Goals.





Photo © Marco Hofste

Held at the IHE Delft Institute for Water Education, IADC's Dredging and Reclamation Seminar gives participants the opportunity to complete a mock tender process in groups, competing against fellow participants for a prize.

## Dredging and Reclamation Seminar

21–25 June 2021

IHE Delft Institute for Water Education,  
Delft, The Netherlands  
[www.iadc-dredging.com](http://www.iadc-dredging.com)

For (future) decision makers and their advisors in governments, port and harbour authorities, off-shore companies and other organisations that have to execute dredging projects, IADC organises its international Dredging and Reclamation Seminar for the 60<sup>th</sup> time. This time the seminar will be held from 21–25 June 2021 at and in cooperation with the IHE Delft Institute for Water Education, in Delft, The Netherlands. Since 1993, this week-long seminar has been continually updated to reflect the dynamic nature of the industry and is successfully presented in cities all over the world.

IADC's Dredging and Reclamation Seminar is a five-day course that covers a wide range of subjects, from explanations about dredging equipment and methods, rainbowing sand and placing stone to cost estimates and contracts.

### Programme

The in-depth lectures are given by dredging experts from IADC member companies, whose practical knowledge and experience

add an extra value to the classroom lessons.

Amongst the subjects covered are:

- the development of new ports and maintenance of existing ports;
- project development: from preparation to realisation;
- descriptions of types of dredging equipment;
- costing of projects;
- types of dredging projects; and
- environmental aspects of dredging.

### Site visit

Activities outside the classroom are equally as important. An on-site visit to the dredging yard of an IADC member is therefore an integral element in the learning process. This gives the participants the opportunity to see dredging equipment in action and to gain a better feeling of the extent of a dredging activity.

### Networking

Face-to-face social contact is invaluable. A mid-week dinner where participants, lecturers and other dredging employees can interact, network and discuss the real, hands-on world of dredging provide another dimension to this stimulating week.

### Certificate

Each participant receives a set of comprehensive proceedings and a Certificate

## Your lecturers

### Course leader

Pieter den Ridder, deputy manager of the Production and Soil Department at Royal Boskalis Westminster, responsible for all production estimates for tender submissions in Middle and South America.

### Course lecturers

Maarten Dewint is a tender Engineer at Jan De Nul. His work encompasses being responsible for the price calculation of major dredging and maritime projects around the world.

Robert Dijkema, senior production engineer at Van Oord, responsible for production estimates for projects in South and Central America, Africa and the Middle East. He is also supervising the development of the in-house pump-performance and estimating software.

Paul Vercrujssse is Head of Research and Development at DEME where his prime responsibility is the strategic management of technology development and innovation processes. His major challenge is bridging the gaps between science, engineering and operations.

of Achievement in recognition of the completion of the coursework.

Register for the seminar at:  
<http://bit.ly/Delft2021>

For further questions contact:

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### Back Cover

Photo © Van Oord

### Design

Smidswater, The Hague, The Netherlands

### Typesetting

ECC B.V., Hardinxveld-Giessendam,  
The Netherlands

### Printing

Tuijtel B.V., Hardinxveld-Giessendam,  
The Netherlands

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ISSN 0376-6411

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*Terra et Aqua* is published four times a year by  
**International Association of Dredging Companies**  
Stationsplein 4  
2275 AZ Voorburg  
The Netherlands  
[www.iadc-dredging.com](http://www.iadc-dredging.com)





# ALWAYS READY TO MEET NEW CHALLENGES

IADC stands for 'International Association of Dredging Companies' and is the global umbrella organisation for contractors in the private dredging industry. IADC is dedicated to promoting the skills, integrity and reliability of its members as well as the dredging industry in general. IADC has over one hundred main and associated members. Together they represent the forefront of the dredging industry.

[www.iadc-dredging.com](http://www.iadc-dredging.com)

