MARITIME SOLUTIONS FOR A CHANGING WORLD

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TERRA ET AQUA

LAKE REVIVER

CONTRACTOR AND NGO JOIN FORCES TO RESTORE LAKE'S ECOLOGY

MUDDLED SEDIMENTS
Examining backscatter accuracy amongst mixed sediments

SCHELDT SAVER
Ecologist investigates estuarine problems to reverse the damage

HIGHLIGHT

LAKE REVIVER

CONTRACTOR AND NGO JOIN FORCES TO RESTORE LAKE ECOLOGY

Located in the heart of the Netherlands, the Markermeer is an artificial lake which emerged from the completion of two infrastructure projects.

The Afsluitdijk was constructed in 1932 to separate the North Sea from the Zuiderzee, a saltwater inlet. The then-protected saltwater inlet transitioned into an artificial, freshwater lake called Lake IJssel, or the IJsselmeer.

Then in 1975, another dam – the Houtribdijk – was built between the cities of Enkhuizen and Lelystad. The newly-separated water body was given the name Markermeer, and became its own freshwater lake with unique ecological values. More than 40 years later, several ecological problems have been seen in the Markermeer including a decrease in biodiversity, changes in nutrients' volume and constitution and suspended sediment in the water ultimately leading to a decrease in light penetration. These circumstances decimated the fish population, which impacted the diversity and populations of bird species in the area.

An initiative by Natuurmonumenten – the Dutch Society for the Preservation of Nature – was created to improve the quality of the Markermeer, and make the lake healthy and productive again. In April 2016, Boskalis began constructing the Marker Wadden. One of the largest nature restoration projects in Western Europe, the archipelago of islands and sand banks form a paradise for birds and fish, and natural recreation area for visitors. Read more on page 30.

CONTENTS

HOW CAN DREDGED SEDIMENTS BE USED BENEFICIALLY?

Frank Verhoeven
President, IADC

One of four subjects which were a central focus at the Dredging for Sustainable Infrastructure Conference was the beneficial use of sediments for win-win situations. Comprised of representatives from dredging contractors, consultants, suppliers, research institutes and universities, the audience was given a widespread challenge to solve: what can be done with "waste sediment" at a one of Europe's largest ports? In 20 small groups, attendees put their heads together.

Attendees brainstormed unhindered ideas which ranged from conventional to extraordinary. Each group presented their shortlist of ideas which had the conventional proposals which ran the gamut from cleaning the sediment for use in beach replenishment, and the creation of wetlands as well as islands for offshore energy or airports.

Then came the out-of-the-box ideas which expanded the conversation's boundaries.

Many thought it was worth turning the waste sediment into aggregate, bricks or stones for use in the construction industry. Some suggested strategies to lower the amount of sand that needs to be disposed of by channeling the river with the sediment to increase the flow, and let the sediment flow out on its own. Through creating shallow habitats, friction would be increased with the incoming flood tide, having a beneficial effect upon erosion and sedimentation patterns.

Among the more unique suggestions was to make a digital platform which helps those with unwanted sediment to connect with those looking for sediment, including selling the sediment to entities or places in need sand like Singapore. The group's imaginative ideas included involving local artists to make sculptures with some of the sediment, holding a world championship for sand castle building and using the material to build an artificial mountain for skiing.

A key takeaway was to promote a change in perception surrounding 'waste' sediment. Instead of paying to send it to the sea and dispose of it, entities should engage with stakeholders. Solutions with the most benefits in cost savings should be applied and invested in society. This discussion aimed to bring the philosophy of beneficial use of sediments outside the dredging industry, as the importance of improving recognition through consultants and clients cannot be overstated.

The focus given to sediment in the following pages demonstrate sediment is on dredging contractors' agendas: building environment-enriching landscapes with material dredged to make way for a major infrastructure project, understanding the challenges of monitoring of sediment with optical backscatter techniques in mixed sediment environments and creating bird habitats on islands which improve a lake's ecological situation. An interview with Dr Patrick Meire also addresses how sediment may be key to returning productivity to overly-manipulated rivers.

A key takeaway was to promote a change in perception surrounding 'waste' sediment.

PROJECT

FEHMARNBELT: A NEW GREEN LINK BETWEEN GERMANY AND DENMARK

An aerial view of the Fehmarnbelt's site on the island of Fehmarn in Germany, situated adjacent to the Puttgarden ferry harbour.

Photo Jan Kofod Winther Femern AS

To be built in northern Europe and connect Scandinavia with Germany, the Fehmarnbelt will be the world's longest immersed tunnel. The infrastructure will close a major gap in the European transport network, reduce the risk of shipping collisions, energy consumption and create a new region in Europe, while also fostering the development of new nature and recreational landscapes by Working with Nature concepts.

The Fehmarnbelt Fixed Link is a joint Danish and German transport infrastructure project across the Fehmarnbelt.

Presentation of the project

The Fehmarnbelt Fixed Link – the proposed eastern route between Germany and Denmark – has been planned for a long time in an effort to create a rapid connection between the two countries with a faster and shorter link (see Figure 1). It will also close a major gap in the Scandinavian-Mediterranean corridor which is part of the European transport network. Once opened, the journey for freight trains between Hamburg and Scandinavia will reduce by 160 kilometres.

The Fehmarnbelt Fixed Link is a joint Danish and German transport infrastructure project across the Fehmarnbelt. Denmark is responsible for the planning, construction and operation of the Fehmarn Fixed Link. To carry out this task, the government of Denmark has established the company Femern A/S which is 100% owned by the Danish State and represented by the Danish Ministry of Transport. The initial feasibility studies of the project were already conducted in the mid-1990s and eventually followed by the Danish-German treaty signed in 2008. The project was given the go-ahead in Denmark in 2015 and approved by Germany in 2019. The

FIGURE 1

The upcoming Fehmarnbelt Fixed Link will be the eastern alternative to the western route from Hamburg over Funen and Zealand. The new green link will save time as well as energy.

project includes an immersed tunnel that will run for 18 kilometres under the Fehmarnbelt and connect Puttgarden (Fehmarn island, Germany) to Rødby (Lolland island, Denmark). The maximum water depth will be about 30 metres and the tunnel has an estimated total construction cost of EUR 7 billion.

The conceptual design of the link and its land reclamation was developed with the support of both environmental consultants DHI and COWI, the technical consultants Ramboll-Arup-TEC and the landscape architects Schønherr.

The Fixed Link is a combined road and railway connection carrying two lanes of road traffic and a single, high speed rail track in each direction. When complete, it will be the third largest marine infrastructure project in southern Scandinavia. It will supplement the first one, the Great Belt Link between the Danish islands of Funen and Zealand which opened in 1998, and the second, the Øresund Link which opened in 2000 and connects Denmark's capital, Copenhagen, with Sweden's third largest city, Malmö. Ten million people will then be brought closer together, enlarging each country's growth region into one major regional centre. This will bring numerous opportunities for development, exchange of culture and business, trade and education, and so forth.

The journey to the immersed tunnel

The immersed tunnel will be constructed by placing tunnel elements in a trench dredged in the seabed (see Figure 2). The proposed methodology for trench dredging comprises mechanical dredging using Backhoe Dredgers (BHD) up to 25 metres and Grab Dredgers (GD) in deeper waters. A Trailing Suction Hopper Dredger (TSHD) will be used to rip the clay before dredging with GD. The excavated material will be loaded onto barges and transported for beneficial use to the inshore reclamation areas where it will be unloaded by small BHDs. Some 19 million m^3 of sediment will be handled.

A bedding layer of gravel will form the foundation of the elements. Each element will initially be kept in place by depositing locking fill followed by general fill. Finally, there will be a stone layer on top to protect against damage from grounded ships or dragging anchors. The protection layer and the top of the structure will stay below the existing seabed level, apart from near the shore. However, at the very nearshore area, the seabed will be raised at the coastal locations to incorporate the protection layer over a distance of approximately 500-700 metres from the proposed coastline. Here, the protection layer will be an extended armour rock layer.

Reclamation areas are planned to run along both the German and Danish coastlines to use the dredged material from the excavation of the tunnel trench. The size of the reclamation area on the German coastline has been minimised. Two larger reclaimed areas are planned on the Danish coastline. Before the reclamation takes place, containment dykes are to be constructed some 500 metres out from the coastline.

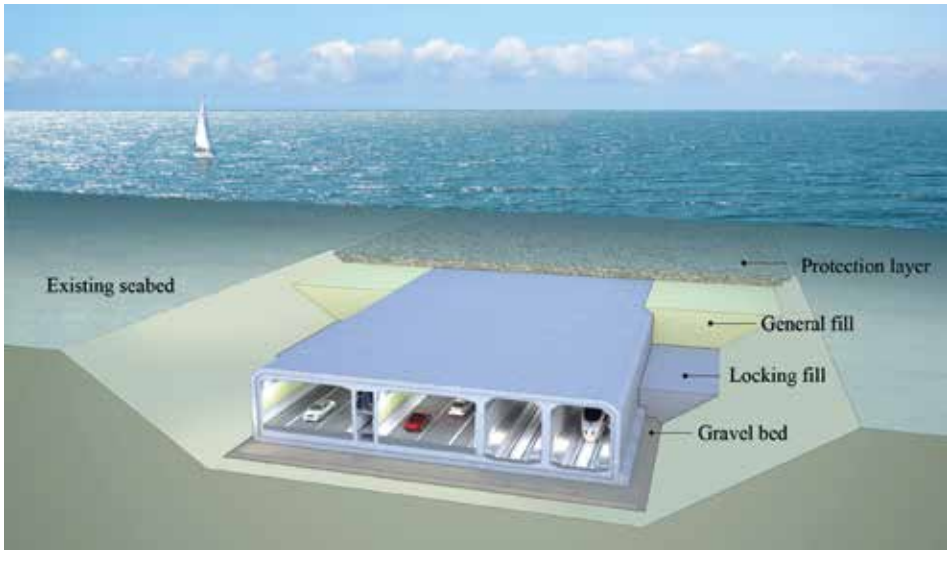
The cut & cover sections of the immersed tunnel passes through the shoreline reclamation areas on both the Danish and German sides.

Key requirements

One key requirement of this project is that it has to be designed and constructed in harmony with the landscape and its nature areas, thereby offering the opportunity to:

- Re-establish/re-generate some of the environmental values lost during the construction of major dykes and reclamation works in the early 1900s;
- Use the opportunity to create new landscapes;
- Incorporate the link into the landscape without visual harm; and
- Make sustainable options a requirement.

Another requirement was that the Fixed Link pose minimal navigation risks to the important



When complete, it will be the third largest marine infrastructure project in southern Scandinavia.

FIGURE 2

A cross section of the dredged trench with tunnel element and backfilling.

international navigation route connecting the North Sea and Baltic Sea. Finally, that the Fixed Link should have a minimal impact on the environment, particularly the water and salinity exchange through the project area.

Understanding the environment

To ensure the fulfilment of the above mentioned requirements, it is necessary to understand the existing environment, not only to minimise the potential impacts of the project but also to identify win-win opportunities to meet the project requirements.

A detailed two-year survey programme was undertaken using a combination of fixed measurement stations, vessel and air surveys, as well as modelling works to study the important hydraulic and ecosystem components. These included water quality, benthic flora and fauna, fish, marine mammals and seabirds. With this information, it would be possible in the first instance to identify sensitive areas. The understanding of the environment also included analysis of the potential impacts on the sensitive areas.

The effects on higher trophic levels such as birds and marine mammals were assessed based on the outcome of these simulations. Ecological modelling was used to quantify the impacts arising from spilled sediment on water quality and benthic flora. The ecological model describes the relationship between dispersed sediment spill concentrations, light availability and primary producers, between nutrients, as well as the interrelationship and interspecific competition between three distinct groups of producers: pelagic phytoplankton, benthic macroalgae and rooted vegetation.

The simulation of a realistic construction scenario for the entire construction period and of the permanent operation period of the link demonstrated that the Fixed Link could be built with only minor temporary and permanent impacts. A thorough understanding of the ecological aspects and coastal processes was important in order to identify options to regenerate the environment as well as to define sustainable coastal protection options. Understanding of the environment was a key element for the subsequent stages of the project and for selection of the preferred solution: the immersed tunnel that would provide the option of the beneficial use of dredged material to regenerate the landscape. Some characteristic elements of the Fehmarnbelt area are described below.

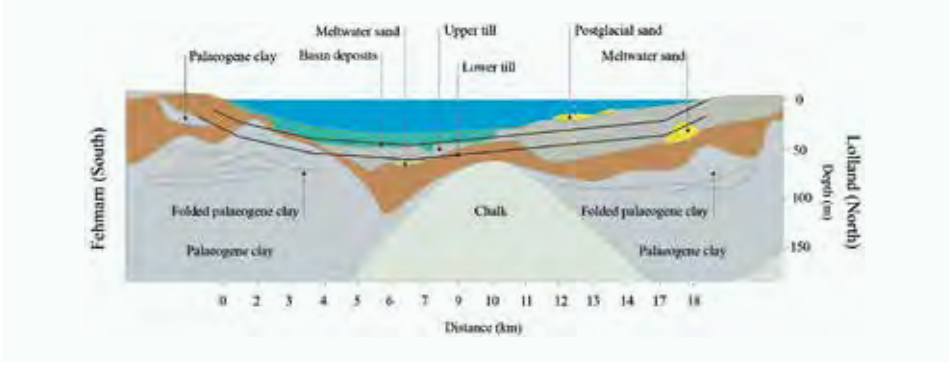


FIGURE 3

The geology of the Fehmarnbelt.

Geology

The landscape of the area was shaped by ice masses mainly during the last Ice Age. Since the final retreat of glaciers from the southwestern Baltic area, the Fehmarnbelt has been characterised by highly variable sedimentary processes and environments when the outflow from the Baltic Sea to Kattegat through the Great Belt and Øresund changed position several times. The present day topography and bathymetry was formed by the last Ice Age, which ended about 10,000 Before Present [B.P.], with varying water levels in the period.

The upper subsoils in the Fehmarnbelt consist mainly of glacial meltwater sand covered by clays and topped by post glacial marine sand, gyttja and peat. Beneath these layers are mostly glacial tills – also called boulder clay or moraine clay – of different types with local pockets of meltwater sand and silt (see Figure 3). Deeper layers consist of chalk and paleogene clay that are older than the Quaternary period.

Hydrography

The Fehmarnbelt is part of the transition area between the central Baltic Sea and the North Sea. The flow and stratification in the Fehmarnbelt is highly related to water exchange between the North Sea and the central Baltic Sea. The upper water strata in the Fehmarnbelt consists of brackish water from the central Baltic Sea which, close to the surface, flows through the Belt Sea and continues up into Kattegat. A layer of water with higher salinity from the North Sea forms a lower layer.

Environment and Nature

The Fehmarnbelt is a very dynamic area in terms of water exchange and sediment transport, which forms different types of seabed substrate and forms, as well as coastal features such as cliffs and beaches.

In the shallow areas, the benthic flora is dominated by different flora communities determined by the water depth (light penetration) and substrates (mud, sand, hard bottom). Red algae communities (Fursellaria, Phycodrys, Delesseria species) are replaced in less shallow water by brown algae (Fucus Sp). In water depths over 20 metres, algae communities are rare. In wave-protected lagoons and bays, red algae are replaced by eelgrass. Blue mussels dominate along the Danish coast and are succeeded by amphipods (Bathyoireia and mussel communities (Corbula, Artcica species) in deeper water.

In terms of fish, the Fehmarnbelt is an important route for migrating cod, herring and silver eel as well as a spawning area for a number of fish species including cod and flatfish in general. In the Fehmarnbelt area, three species of marine mammals occur regularly: the harbour porpoise, the harbour seal and the grey seal. The harbour porpoise uses the Fehmarnbelt as a transport corridor whereas the seals do not, although seal haul-out sites are located over

Birds are a special issue as the Fehmarnbelt is an important migration route for both north-south and east-west migration.

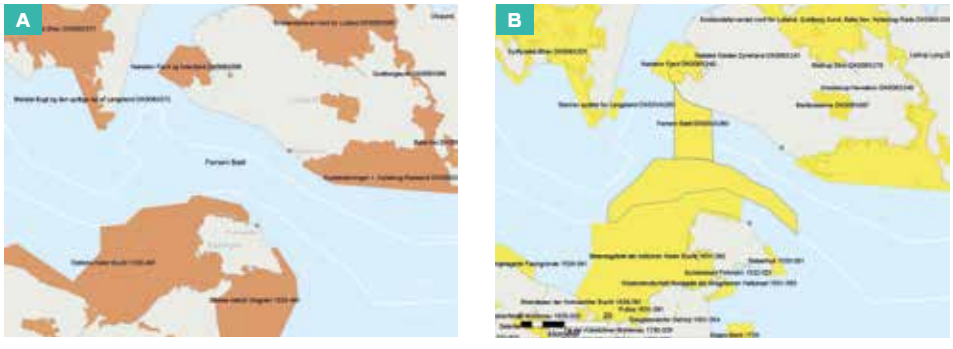


FIGURE 4

Nature 2000 areas in Germany and Denmark for birds shown in orange (A) and habitats shown in yellow (B).

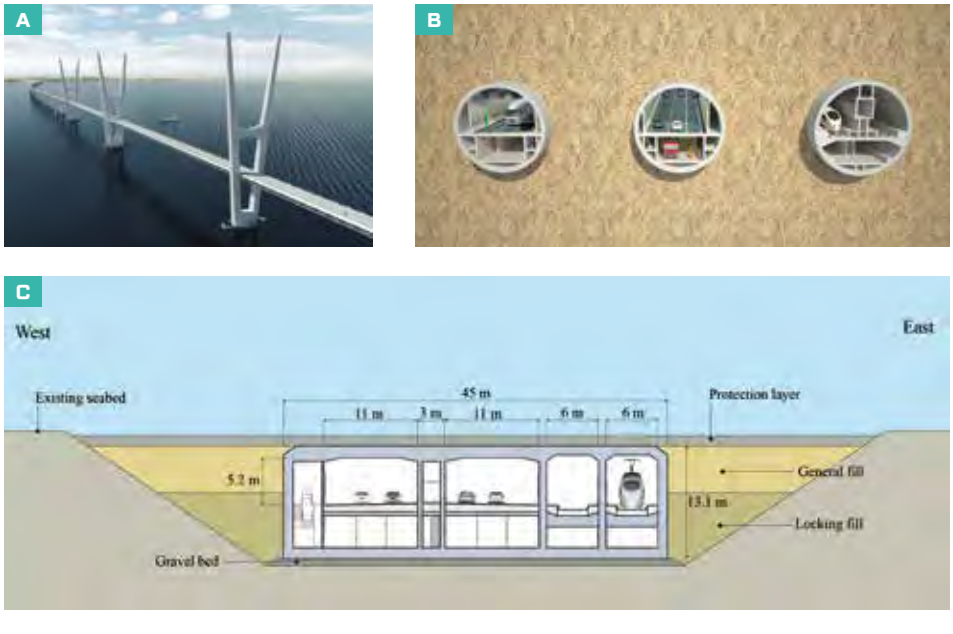


FIGURE 5

The cable-stayed bridge with two main spans of 724 metres and a navigation clearance above the sea of at least 66 metres (A). A cross section of the bored tunnel consists of three tubes. The railway tube has an internal diameter of 15.2 metres while the two road tubes' diameter are 14.2 metres (B). The immersed tunnel consists of 79 standard elements (approximately 9x42x217 metres) and up to ten special elements (approximately 13x45x39 metres) (C).

20 kilometres away, both west and east of the alignment.

Birds are a special issue as the Fehmarnbelt is an important migration route for both north-south and east-west migration. Many species of water birds use the areas during either winter or summer. For that reason, a number of protected habitats and bird areas have been designated. These are called Natura 2000 areas according to EU legislation (see Figure 4).

Human activity

Archaeological investigations conducted by the client reveal that the proposed alignment has been a human migration corridor over the last 6,000 years. DNA tests of archaeological finds of goat remains show that ancient human migration from central Europe to Scandinavia used the Fehmarnbelt as the main transport corridor. Today, the Fehmarnbelt is one of the heaviest trafficked waters in the world because it is the main entrance to the Baltic Sea. Ferries between Puttgarden and Rødbyhavn contributed with 35,000 crossings in 2013.

Project design to benefit navigation and nature

The conceptual design was developed by a multidisciplinary team consisting of engineers, architects, biologists, environmental engineers and so forth. The design was based on the project objectives defined in early stages of the project and the understanding of the existing environment. These, together with extensive stakeholder engagement, worked towards a design that meets the stakeholder objectives and identifies win-win opportunities. Three options initially proposed for the link (see Figure 5) include:

- a cable-stayed bridge,
- a bored tunnel and
- an immersed tunnel.

The immersed tunnel was identified as the preferred option in the light of engineering, environmental, navigational and economic considerations. A tunnel provides safe navigation conditions since it avoids potential damage and associated oil spill resulting from ship collisions with piers and other obstacles.

With respect to the landscape, the impacts of a tunnel and bridge solution differ. As opposed to the tunnel, which is submerged, a cable-stayed bridge has a clear visual impact on the entire area. On the environmental scale,

FIGURE 6

Design proposal for a land reclamation area on Lolland in Denmark.

the bridge would entail permanent barrier effects, for example on the hydrographical conditions of the Baltic Sea and bird migration in the area. The impact assessment on the surrounding Natura 2000 areas proved that the tunnel produces significantly fewer environmental conflicts than the bridge.

One reason for deselecting the bored tunnel solution was the uncertain time horizon for the possible re-usage of the bored material for land reclamation purposes, due to its slow dewatering process. Other reasons were that the bored tunnel had a larger (environmental) footprint on Fehmarn and significantly higher greenhouse gas emissions.

The immersed tunnel provided a 'win-win' solution because the 19 million m^3 of dredged sea-bed material from the tunnel trench would provide an opportunity for beneficial use. This was seen as a great and feasible opportunity to create new landscapes and re-establish some of the historical features that were lost due to coastal protection and flood mitigation works carried out in the past.

New reclamation areas add nature and recreational values

The new landscape will be shaped as a streamlined area along the existing coast to an extent similar to that of the existing Rødbyhavn harbour. This will ensure that there will be no additional blocking of the flow through the strait.

The new landscape (see Figure 6) will extend approximately 3 kilometres west of the harbour and 3.5 kilometres east of the harbour. The extent of the area is decided mainly by the volume of the surplus sediment that can be absorbed by the landscape. The western part of the reclamation area is designed with the purpose of serving recreational values whereas the eastern part – although it accommodates the tunnel portal – is designed for serving nature values.

These new features will introduce positive aspects by supplying new natural, environmental and recreational values and will partially rehabilitate an area that has suffered severely from past engineering flood protection projects. The use of this surplus sediment will allow the re-creation of features such as those discussed below.

The landscape

The new landscapes will connect the tunnel portals to the adjacent coastal areas. This will be achieved in a gradual and harmonious way, thus minimising the visual aspects via a green transition zone. On the German side the natural elevation forms a kind of hill, which on one hand will hide the portal structure from the hinterland, and on the other hand secure the tunnel portal against raising sea level and minimising the scour protection mound. In contrast to a more traditional design, the elevated landscape would probably have been removed and replaced by a rubble revetment mound. Finally, the passengers are allowed to overlook their journey across the sea.

Protected areas

The existing dyke on Lolland – which runs along the coast line – is not influenced by the new reclamation areas in front and will consequently still protect the low-lying hinterland. The reclaimed areas will be designed with different perimeter types

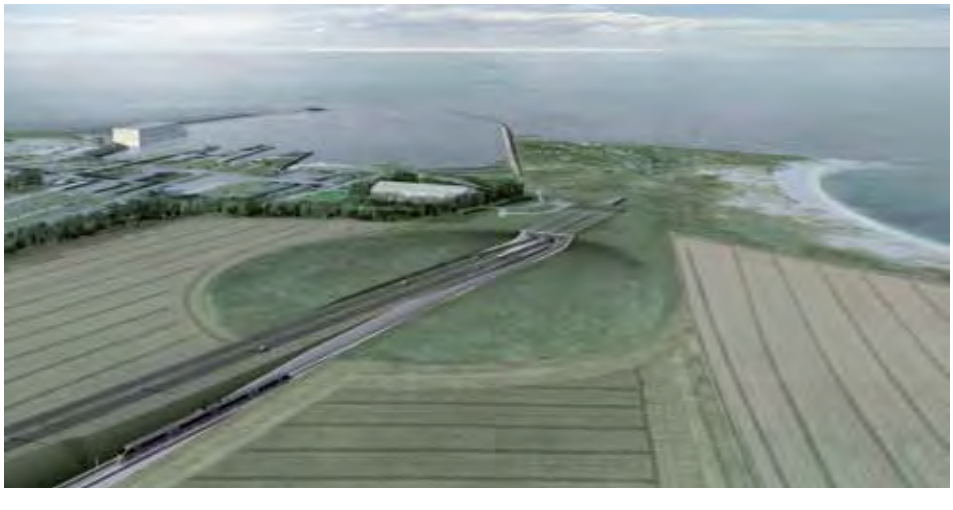


FIGURE 7

At the tunnel portal in Fehmarn, the elevated landscape was retained. No larger revetment was necessary like on the Danish side.

FIGURE 8

The portal area at Lolland is protected by a revetment.

FIGURE 9

Visualisation of the wetland in the eastern part of the land reclamation area in Denmark on Lolland. The bird island is the small island in the background of the lagoon.

dependent upon the different technical and environmental functions.

The stretch around the portal at Lolland will be scour protected. The structures are designed to minimise the visual aspects of the tunnel portal but also to protect against possible rising sea levels due to climate change.

Re-establish previous landscape

Some of the area's environmental values were lost in connection with the construction of a major dyke along the coast following a major flood event in 1872. The dyke cut off the previous shallow archipelago, Rødby Fjord and other shallow areas which were later reclaimed by the installation of a pumping station.

Artificial lagoon

Wetlands, salt meadows and grassland lost due to the construction of the new dyke will, to a certain extent, be re-established at the new land reclamation area east of Rødbyhavn (see Figure 9). Overall, it will be a 3.7-kilometre long and 0.5-kilometre wide green band featuring an artificial lagoon with two fixed openings east of the tunnel portal. The lagoon includes wetlands, a major recreational island and a small sea bird island. The vegetation in the nature and wetland areas will be allowed to develop naturally which will enhance the biodiversity of this environment.

Cliffs

The ferry harbour, Rødbyhavn, was constructed over a century ago and extends 500 metres out from the coastline. This extension has resulted in a beach with sand dunes that has built up west of Rødbyhavn but on the eastern side of the harbour, the blocking of the littoral transport has resulted in sand erosion along approximately 3.5 kilometres of the coastline

Most of the eastern area will be filled up to a level of seven metres. Natural erosion is allowed here whereby a 'natural' cliff will form and the eroded sand will be transported eastward by the predominant littoral transport (see Figure 10). This supply of sand will help to stabilise the beaches to the east, following a smooth transition area.

Artificial beaches

On the western side of the harbour, the area with its beaches will be used for recreational and leisure activities which feature a major leisure area. The recreational and leisure value will increase with the construction of the beaches and grasslands. Three artificial beaches are planned, with one at the extreme west end of Lolland and one lagoon beach in the middle plus a paddling beach close to the harbour on the Danish side. On the German side, a grassland is planned as well as a beach east of Puttgarden harbour (see Figure 11). The beaches are designed in their equilibrium orientation by fixed structures.

Reefs

Stones and boulders on the seabed form hard substrate to which sea algae will attach and start to increase the biodiversity which gradually leads to reef formations. Many of these stones and boulders have been removed for the purpose of constructing harbours, piers, revetments and so forth over the last 100 years or more. Stones and boulders large enough to create artificial reef structures will be used for the protection layer on top of the tunnel close to the coast in shallow water where there will be no barrier effect on the water exchange. If feasible, surplus 'reef-stone' from the dredging work will be placed at the Natura 2000 area, Sagas-Bank, in order to mitigate earlier stone removal over a 25 hectare area (see Figure 12).

Stakeholder engagement to identify possible win-win opportunities

Extensive stakeholder engagement was obtained for this project already from the start. The public, professionals and NGO organisations as well as authorities were invited to comment on the project. An exhaustive range of consultations (some public) was conducted along the way. This

FIGURE 10

East of Rødbyhavn's harbour, natural erosion is allowed, forming a 'natural' cliff as the eroded sand is transported eastward by the predominant littoral transport.

Understanding and mimicking nature plays a key role in the project's vision.

included the scoping process and environmental impact assessments. There were also public plan application document exhibitions.

Cross-border project consultations were conducted in both Germany and Denmark as well as one involving all the countries around the Baltic Sea (ESPOO hearing).

The outcome of this stakeholder input has had a major influence on the whole project including the marine area and the new reclamation landscapes, the marine ecosystem's functionality, the bird migration routes, and, of course, the Fehmarnbelt as a transport corridor for other marine life between the North Sea and the Baltic Sea. They are all part of both the Danish and German plan approvals which have been granted.

Conclusions

The Fehmarnbelt Fixed Link is an outstanding example of the application of the Working with Nature principles for large marine infrastructure projects. The construction of the project is planned to start in 2020. The main features of the project can be summarised as:

- The proposed marine and landscaping are a win-win situation discussed and proposed during the stakeholders engagement;
- 19 million m^3 of dedged material will be used to create new landscapes;
- These will add new nature, environmental and recreational services much to the public needs and requirements;
- Understanding and mimicking nature plays a key role in the project's vision; and
- The immersed tunnel avoids long-term over-water disturbance of the aquatic environment.

FIGURE 11

Aerial perspectives of the new western beach section with dunes at Lolland, east of Puttgarden harbour.

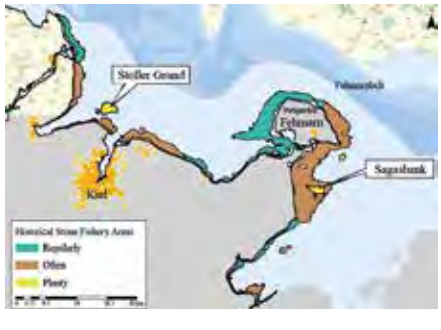


FIGURE 12

Sagasbank, Germany has suffered from intensive stone fishery and 25 hectares will be re-established.

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Summary

The proposed landscaping for the Fehmarnbelt Fixed Link – an immersed tunnel which will provide a transit connection between Germany and Denmark – is considered a 'win-win' situation by using the surplus of 19 million m^3 of dredged material generated by the project. This dredged material will be utilised to create new landscaping features that will add a positive impact to the project in the form of providing 'natural' landscape elements. Ranging from lagoons to beaches and reefs, these features will bring new natural, environmental and recreational values to the area, and rehabilitate areas which have long been blighted by engineering projects in the past.

At the 34th PIANC World Congress 2018, Femern A/S was granted the accolade of 'Supporter of Working with Nature' because of its incorporation of environmental considerations into the Fehmarnbelt Fixed Link's conceptual design.

Anders Bjørnshave

Anders Bjørnshave, M.Sc., has decades of experience in project management for large-scale construction projects around the world. As Head of the Environmental Department at Femern A/S, he conducted the vast environmental impact assessment of the Fehmarnbelt Fixed Link. He served as Chief Technical Adviser for a large environmental donor programme in Egypt and has in-depth experience of foreign investors' environmental performance and compliance in developing countries. In addition, he has years of hands-on experience in the remediation of soil and groundwater contamination from oil stations, oil depots, airfields and military bases in Europe.

Ian Sehested Hansen

Ian Sehested Hansen has over 30 years' experience in mathematical modelling in environmental hydraulics and water quality assessments as well as operational forecasting of marine hydrodynamics and water quality conditions. He has experience in estuarine/marine conditions in the tropics – especially the waters of Dubai, Hong Kong and Lake Maracaibo in Venezuela – as well as estuarine dynamics and water quality from several Danish and international projects. He serves as project manager for several large consulting and research projects including the EIA service to Femern A/S for the Fehmarnbelt Fixed Link since 2009.

Victor Magar

With more than 20 years of environmental engineering experience, Victor Magar, PhD, PE, has expertise in sediment management, hazardous waste remediation, contaminant fate and transport, contaminant transformation processes, and technology evaluation, testing, and selection. He serves as a lead civil/environmental engineer for sediment and marsh restoration projects, responsible for managing client services in contaminant assessment, monitoring, and remedy selection and implementation. He chaired PIANC Working Group 176 to develop PIANC's *A Guide for Applying Working with Nature to Navigation Infrastructure Projects* released in 2018.

Juan C. Savioli

As head of the Coastal and Marine Department of DHI Water & Environment Malaysia, Juan Savioli has over 20 years' experience in the application of numerical models in coastal and marine projects, and gained a deep understanding of the evaluation, modelling and analysis of flows, waves, and sediment transport processes. His expertise lies in coastal developments where reclamation, dredging and sedimentation processes are evaluated for their design and optimisation, and believes concepts such as Working with Nature can be applied to benefit coastal developments. He was part of PIANC's Working Group 176 which produced *A Guide for Applying Working with Nature to Navigation Infrastructure Projects.*

CHAIR OF THE BIOLOGY DEPARTMENT AT UNIVERSITY OF ANTWERP PATRICK MEIRE

‘HOW CAN WE CHANGE OUR BEHAVIOUR AND ACTIVITY TO WORK WITH THE ECOSYSTEM **RATHER THAN TO DESTROY IT?’**

Guided by an expertise in biology, Patrick Meire remains dedicated to understanding the delicate and intertwined estuarine ecosystem of the Scheldt which has been increasingly threatened by human activities and sea level rise. Turning research into action, he helped design a flood control area in the polders of Kruibeke, Belgium alongside garnering communal and governmental support over a 25 year span to make it a reality. A joint research project of Greenland’s melting glaciers is further evidence of his environmental passion and dedication to future generations.

What is your academic background and how has it impacted your work today?

I studied biology and spent most of my research career on studies of estuarine and wetland systems. I started the research for my PhD with a study on the impact of the construction of the storm surge barrier in the eastern Scheldt on the benthic invertebrates and bird populations. At that time, in the early 80s, the main focus of the study was assessing the impact of human activities on the environment as it was obvious that the storm surge barrier would have quite some negative impacts on the ecosystem of the eastern Scheldt. Gradually as time went on, my work changed from studying the impacts of human activities on the environment to see how human activities could *improve* the environment. That was the change towards the concept of restoration and how we can do things in a better way for the environment, or even enhance the environment.

In this way, I've developed very much from the early days where I was studying how oystercatchers were feeding on mussels, so doing very detailed feeding ecology studies focusing on just a few species. My interest gradually grew towards looking at the whole system and that's now also the strength of the work that we are doing. It's not just focusing on one detailed aspect of an ecosystem but trying to have a more holistic view of the different aspects and how the system as a whole is really working. Over the course of my career, it's quite a big development that I was lucky to be able to make and it was also very exciting. This also makes it very difficult, people say I'm a physical oceanographer or a wetland ecologist or a benthologist or something like that. For me, I feel more like an ecologist linking different things together and looking from the system's perspective to understand: how is the system working?, how are the interactions between human activities and the system?, and how can we change our behaviour and activity to work with the ecosystem rather than to destroy it?

The link between science and application and management is a very important point because we do science to improve the world.

It is a very clear choice that my research group ECOBE is called Ecosystem *Management* Research Group because the link between the fundamental science and the management, the more applied science is extremely important to me. On the one hand it is essential that we do fundamental research and look into new directions, so researching topics which do not immediately have a link to the application. But on the other hand, at a certain moment, we must look for the link between the science and the application. The link between science and application and management is a very important point because we do science to improve the world. We must try to use the best of the science to manage the environment. That is, at least for me, a very important thing.

What was your role in bringing Ecosystems Services to the fore?

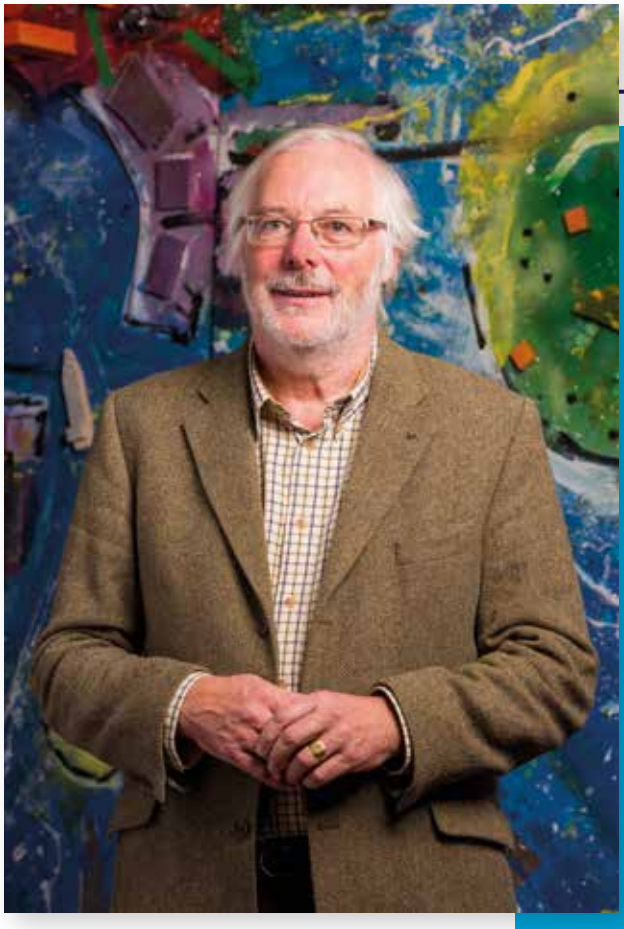
We wrote the first report on the ecosystem services (ES) of the Scheldt estuary in 2000 when the concept of ES was still poorly known. Ecosystem services are the direct and indirect contributions of ecosystems to human well-being. It was only three years earlier, in 1997, that the very influential paper *The value of the world's ecosystem services and natural capital* by Robert Costanza and co-workers was published in *Nature* and it was not yet very well-known at that time. The Millennium Ecosystem Assessment – a next very important step forward in the concept of ES – was only published in 2005. Since our report in 2000, I'm sure that the concept has greatly helped in convincing people of the importance of trying to change our way of managing estuaries, wetlands and coasts by taking more into account the values of ecosystems, and understand how ecosystems are important to us as human beings. The report *Ecosystems Services: Towards Integrated Marine Infrastructure Project Assessment* – made in collaboration with IADC and released in 2016 – has certainly contributed to spreading the knowledge and the ideas of the concept of ES within the dredging community.

In essence, the concept of Ecosystems Services is nothing new, it is mainly a way of presenting fundamental knowledge. If you have an ecosystem service like waste water treatment – the removal of nutrients from your system – that's pure ecology and has been studied for a long time. The crucial point of ES is translating all of the scientific knowledge into something which is understandable for a broader audience and which also links to human uses. In that way, indeed we have been embracing the concept since the beginning of the year 2000 when we wrote the first report on ES in the Scheldt estuary, as a concept which brings the fundamental knowledge of the functioning of the systems to a broader audience and to a lot of different stakeholders. The latter was very important in finally managing our ecosystems like estuaries because there are ports, fisherman, people for recreation, and a link with agriculture. All of these people are stakeholders and you have to bring them to the level of understanding of the system. ES was a crucial tool for doing that.

Can ES provide incentive to those with only economically-driven motivations?

For sure. There are two very important things. First, there is mitigation which means reducing emissions of greenhouse gases. That's mainly a technical issue where we have to change to renewable energy although also ecosystems can play a very important role as a sink for carbon. Next, there is adaptation. Temperature will rise, precipitation patterns will change and the sea level will rise. How much will depend on how far we go with mitigation but these changes will happen and impact our society. Adaptation are those measures we must take to reduce the negative impacts of climate change. This is very important and in my opinion, ES should play a crucial role in adaption strategies because it gives the possibility to come to multiple objectives.

An essential objective of Environmental Management will be to implement adaptation strategies in which natural habitats play a crucial role. As this will create multiple benefits by delivering ecosystem services that represent a large economic benefit this becomes interesting to those with only economically-driven motivations. We can restore wetlands such as peat lands



Meet Patrick Meire

While obtaining his PhD in biology from University of Ghent, Patrick Meire was dedicated to researching the impacts of human activities on ecosystems. His interests evolved, expanding from merely understanding these impacts on ecosystems to include an active role in reversing them. Alongside his roles as chair and professor in University of Antwerp's biology department, he frequently contributes knowledge through scientific publications, coordinates the OMES project that monitors the environmental impact of the Sigmaplan within the Scheldt estuary in Flanders. The latter is a decades-long initiative to ensure the area's safety against flooding as well as enhance recreational, natural and navigational resources.

and coastal marshes. All of these are very important for storing carbon so by recreating these habitats, you can create a carbon sink. When plants take up carbon for growing, part of that organic matter is stored in the soil and kept there for a very long time, acting as a sink for the carbon in the atmosphere. Forests do the same thing but wetlands are especially effective as carbon sinks because there is a wet condition in the soil that keeps the organic matter from mineralising and therefore remains in the soil for a very long time.

While there is the issue of storing carbon on one hand, on the other hand, tidal marshes or mangroves play a crucial role in attenuating waves from storms or hurricanes. By creating these habitats, society can be adapted towards climate change by reducing impact of storms and storing carbon. The concept of ES can bring a lot of ideas for the adaptation of society and the environment towards climate change. Having multiple objectives and understanding what these habitats can deliver to human beings is the most crucial thing, and will help to motivate people to invest in these measures.

Do you believe the dredging industry can make a difference in improving the environment's quality?

In the past, the dredging industry destroyed a lot of the environment by dredging, altering coasts and building huge constructions along the coasts. At that time, the considerations for the impacts on the environment were not important but people within the dredging industry started to understand the consequences of what they were doing and saw it could be very significant. As an industry, it is important to take into account these negative consequences of what is being done. The concept of Ecosystems Services gives the possibility to not only look to the negative consequences of certain works but to look to the possibilities, adapting and changing the planning to not only have the classical economic benefits but in fact to make the projects in such a way that there is a much broader societal benefit. That's, I think, very important and I am quite confident as time goes on, the importance of creating an overall societal value – and not just access to a port or having a container terminal – will become very important and also a crucial factor for the dredging industry. I would even go as far to say that this vision will be essential for successful continuation of the industry.

It is a matter of objectives. If we talk about twenty years ago, access to the port was *the* objective. Just dredge the fairway so that ships with such a draught can reach the harbour and dump the sediment in the most economical way more or less independent of the impacts on the system. In this way, dredging and the placing of dredged sediments can become a crucial management option for sustainable use and management of estuaries but this requires a holistic view, and the concept of ES must play a crucial role in this.

The book *Dredging for Sustainable Infrastructure* addresses the topic of beneficial use of dredged sediment. Can this resource improve environmental quality?

For instance, all the estuaries along coasts are confronted with erosion. Some of the experiments that are going on now are to see how these sediments that are dredged

in one place can be used to enhance the morphological development of another place. The sediment can be used to prevent erosion and keep the system in place. In the Scheldt estuary, there are several examples of what is called 'morphological dredging' where sediments are placed where there is erosion. And you can see how the sediments are being transported by the currents to the tidal flats. There is also the example of the Sand Engine in the Netherlands which is a similar idea although not related to access to a port but to safety and maintenance of the coastline. The Sand Engine is also a nice concept which combines these different aspects and also makes use of the forces of nature.

When multiple objectives are created for a project, it is no longer only about having a fairway to the port. It is having a fairway to the port *and* maintaining the morphology in the system that also helps to maintain the hydrodynamic characteristics which are also important for the morphological aspects. Then a whole series of objectives have become important and can have a much bigger societal value than just access to the port.

In that way, I think a lot of changes *can* take place and *will* take place but of course not everything can be done at once. It will take some time to reach those working in government, the people asking for the projects and the dredging industry looking towards these projects to be implemented everywhere. There are already some very nice examples and I think there will be a kind of snowball effect once people see that some of these projects were very successful. Then it will be very easy to multiply them and apply them in other sites as well.

Do you think the dredging industry can have a larger role in reversing environmental damage?

Yes for sure. There are different things. First of all our knowledge on how the system is functioning and the interaction between morphology, hydrodynamics, and ecology is increasing very fast. This is a crucial point that the dredging industry can take up, using this knowledge to change or adapt their programmes or projects in such a way to improve some of the functioning. Dredging in a classical way, by taking some sediment here and placing it somewhere else without taking into account the functioning of the system, will

Using an Ecosystems Approach

At the turn of the millennium, the concept of Ecosystems Services (ES) had been widely accepted among scientists for decades but was still entering the public conversation, going mainstream with the Millenium Ecosystem Assessment in 2005. In 2000, Patrick Meire published a report about the concept's application in the Scheldt estuary, and by 2016, co-wrote IADC's report *Ecosystems Services: Towards Integrated Marine Infrastructure Project Assessment* which oriented the ES concept towards the dredging industry.

In November 2018, at the CEDA-IADC Dredging for Sustainable Infrastructure Conference held in Amsterdam, he presented 'Using an Ecosystems Approach', one of four key enablers discussed in the book *Dredging for Sustainable Infrastructure*, CEDA and IADC's recently launched guidebook which elevates sustainable dredging to the next level. Following his presentation, the entire audience participated in a group, interactive activity which invited attendees to apply their newly acquired knowledge to mock project scenarios, making informed decisions with an ecosystems approach.

I think if we are able to keep within these 1.5 degrees, then at least only part of the problems created in the past will be able to be solved.

no longer be accepted by the broader public and environmental NGOs. In addition, the cost of that is very high. Changing projects in a way which is more sustainable and enhance societal benefit and the environment will be, in my opinion, the future. The dredging industry can contribute to that by having new projects which improve or restore some of the damage to our systems that have been made before.

Do you think the damage done to rivers can be reversed or is it too late to make a difference?

It depends very much and this is very much related to climate change. If we do not keep global warming below 1.5 degrees Celsius, then the problems that will face our estuaries and deltas will become so big that we will not be able to resolve the problems we created in the past. The problems of the past will become bigger and bigger and bigger. I think if we are able to keep within these 1.5 degrees, then at least only part of the problems created in the past will be able to be solved. That will take a huge paradigm shift in the broader community, not only in the dredging industry but beyond it, to understand that we have to work *with* nature rather than *against* nature. Just think, in many of the deltas, the supply of sediments is limiting the accretion of the delta to grow with the sea level. These are all major problems that can be solved partly. And we will have to *really* understand the problems and tackle them, and then we will be able to partly solve it.

The Port of Rotterdam announced its Incentive Scheme Climate-friendly Shipping' to promote projects to attain zero-carbon fuels for ships passing through its port. What are your thoughts about the impacts of initiatives like this?

All of these projects such as incentives to emit less are very important. The Port of Antwerp is now working on a programme that when the ships are boarded, they use onshore power so that they do not have to generate it by themselves which means less emissions from their engines. There are many, many things that can be done and the more that organisations like the ports give incentives to do that, the more we can realise. In fact, its these big players who can make a *real* changes because if they require things from their customers or they put up some regulations, then it will have a much broader impact than just at the Port of Antwerp or Rotterdam. It will have an impact worldwide. They can play a crucial role in pushing sustainability a step ahead.

What your thoughts are about the plastic problem plaguing the world's waterways? Can initiatives such as Boyan Slat's The Ocean Cleanup help in tackling this problem?

The fact that Boyan Slat was able to put the macro-plastics issue on the agenda is the great thing that he did and is very important. At such a young age, to collect that amount of money to start something is really incredible. Until now, the most important point is that he put the issue of plastics – which is a crucial issue – clearly on the political agenda and that's a very big thing he did. If his strategy will work is a question to be answered, as we know the plastic is much deeper in the water and will thus escape from his construction. In my lab, we have a PhD student which is supported by several organisations studying the flux of macro-plastics in the Scheldt estuary and this work should be the basis for remediation of the problem. The crucial point is: how much plastic is being transported throughout the estuaries? That's just basic knowledge we need to have. Then, from where is the plastic coming? What is the major source of plastic towards the estuary? How is it transported in the estuary? We clearly see that in the upper layers of the water, a tiny fraction of what is passing through the estuary is found. It is at much deeper layers that the plastic is transported. There are big differences between the left and the right banks according to currents and so forth. We are trying to understand *where* the plastic is transported and then this knowledge can be used to design some measures that capture the plastics in a more efficient way.

Of course, this is just the end of the pipe solution. The *only* solution is that we prevent the plastic from *entering* the system. That is the end point. We all know that by now there is a lot of plastic coming into the system and cleaning it up before it is getting to the ocean will remain an important task for the next five to ten years or longer until we prevent any significant transport of plastic towards the rivers and the sea. So that is what we are doing. We are not working on micro-plastics or big plastics becoming micro-plastics as they are broken down in the water of course, but by removing the macro-plastics, the formation of micro-plastics can be prevented.

In addition to the plastic pervading the Scheldt estuary, is turbidity also a problem?

There are many problems. We are studying some ecological aspects and some issues on water quality in detail, and indeed also turbidity. Turbidity is a very crucial parameter in all estuaries because when there is a very high turbidity, then there is low primary production. Primary production – the production of organic matter by algae –needs light. If the turbidity is very high, then you have very little light in the water column. And therefore very little primary production.

In the Ems estuary, the turbidity increased dramatically over time, most likely due to deepening of the fairway. So in all of the estuaries, a lot of attention is given to the development of turbidity or suspended solids in the water column as it can be impacted by human activities and has a detrimental impact on the environment, at least in some circumstances. That's the reason we are following it carefully in the Scheldt. In the past years, there is indeed a slight increase in turbidity and the main question we are looking at is 'what could be the cause of this increase in turbidity?'. It is a very complex matter and right now, I cannot give any clue to the cause, but that is what we are looking at.

It can be due to anthropogenic reasons and it can also be due to natural phenomena which may be interacting or interfering with human activities. Though I cannot say yet, it is certainly something we need to follow up in detail and to look clearly to see how it is further developing.

Is the turbidity concentrated in certain areas or a ubiquitous problem?

Turbidity is indeed an ubiquitous problem. Many estuaries, such as Gironde, Humber, Ems and many others are very turbid and worldwide increased erosion causes increased turbidity in many rivers and coastal areas with often detrimental impacts on ecosystems, just think about coral reefs! But still there is a lack of knowledge. The turbidity is everywhere in the estuary and the problem with turbidity is that it is *extremely* variable. It varies during one tide. It varies over the seasons. It varies over the years because of differences in fresh water discharge due to a wetter season or a dryer season and so on. So it is very variable and is

occurring across the whole of the estuary. Now we see some patterns in the upper part of the estuary. There is an increase – although much less in the lower part than the upper part – but the explanation of the pattern is still pending and we are working hard to find out why.

We hope to have a clear hypothesis within one year but we must be honest and realise that turbidity and suspended sediments is such a complex matter. Many people are working to understand turbidity everywhere in the world. Within one year, we will certainly have some hypothesis and some more clear thinking about how turbidity is working in the Scheldt estuary, but because these are really complex systems, we will need many more years for everyone to really understand what is happening. The more we *know*, the more we know what we *don't* understand.

Can you explain why is there a sluice named after you in Kruibeke, Belgium?

The polders of Kruibeke cover an area between 600 and 700 hectares, making it the biggest flood control area in the Sigmaplan, the plan to protect the Scheldt valley against storm floods from the North Sea. The Sigmaplan is the continuation of the Dutch Deltaplan along the Westerschelde towards the Flemish part of the estuary. In the original Sigmaplan designed in 1976, this area was already indicated to be a very important flood control area, but the local mayor opposed it for many, many years. Starting somewhere in the 90s when I started to work on the Sigmaplan, we developed some of the ideas and concepts to develop this flood control area not *only* as a flood control area but partly as an area which is subjected to the tides and has an added ecological value. We worked very closely together with the public works department in designing the new concept. The polders of Kruibeke are now a combination of flood control and ecological development which is very beneficial for the estuary itself and has a very big added value for the community all around the area.

There are two big sluices on the site, one inlet sluice where the tide is coming in and one outlet where the water is going back to the estuary. I was honoured by the fact that the inlet lock is called the 'Meiresluis'. The outlet lock is the 'Meyvissluis', named for Meyvis, the engineer of the public works department with whom I had been cooperating very closely to realise the project. Together, we were able to change the original idea and concept, and also to get a lot of the people behind us and the new concept. The local people now very much enjoy the area for recreation, in fact there are a lot more people enjoying the areanow than before. In addition, it provides many ecological values and ecosystem services, and on top of that its crucially important for safety.

It was an honour for all the work we have been doing there and realising this project finally notwithstanding that the local mayor had been opposing it for twenty to twenty five years. There was opposition from the local government and we were able to gradually counteract that. The Flemish government finally decided to go ahead with the plans we had been making. The whole project was inaugurated in June 2017.

How did your research on the glaciers in Greenland come about and can you offer some insight of your observations there?

That's a different story. My son went to Greenland more than six years ago for his PhD. He stayed there for a long time and did his work on the impact of the melting glaciers on the biogeochemistry of the fjords. Some of the measurements that he was doing in Greenland are similar to the measurements that we are doing in the Scheldt estuary, so we worked together on that. Some of the samples he took there are being analysed in my lab and we already published a few papers together. For the last two years, in 2017 and 2018, we went on a cruise in Greenland for sampling together which was very nice to be able to join and work with my son in a very exciting environment. So that's in fact my experience there. My oldest son is working at Flanders Hydraulics also on the Scheldt estuary and it is really a great thing for me to be able to work together with my children on such exciting topics and to see the next generation taking up the job!

But let's go back to Greenland. The main issue is to try to understand how the melting of the glaciers is impacting the fjords because the fjords' systems are in fact marine systems. Due to the increased melting of the ice cap and the glaciers, the amount of fresh water coming into the fjords is *increasing dramatically* and the *way* the fresh water is coming into the fjords is *changing*. Whether you have a calving glacier or a land-terminating glacier has a big impact on *how* the water is coming into the estuary and into the fjords.

We are looking at how this is affecting the productivity and the whole biogeochemistry of the fjords. This is very much related to the melting because in former times most of the glaciers were typically calving glaciers – when big glaciers lose the ice directly into the fjord – and certainly by melting the glaciers retreat. At a certain moment, the glaciers come on land and then in fact the ice is not falling in the fjord anymore but you have a small river which is moving towards the fjord. When you are there in the region, you can clearly see the rocks where the glaciers have been just a few years ago. From the local people, you hear 'at this place there was a calving glacier ten years ago' and now hundreds of metres or even kilometres away, you see the edge of the glacier on land. So that is really confronting. There, you feel the climate change happening and the ice melting. If you are sailing there and you see this huge amount of fresh water discharge towards the sea and you see how incredibly huge the ice cap is, then you start to realise sea level rise is an issue and we will have to be extremely careful for that.

That's also the reason this threshold of '1.5 degrees' is so important. If we get a sea level rise of four, five or six metres, then I'm afraid it is the end for the Netherlands, Flanders and for many other areas as well. Having and coping with a sea level rise of several metres will be completely impossible. Just imagine Amsterdam, Rotterdam, Antwerp and Bruges: all of these cities will become flooded within one hundred or one hundred and fifty years. To just imagine that all of these huge monuments are flooded by the sea because there is a five to six metre sea level rise, that idea is unacceptable. That is the reason we must really act.

Have your measurements from Greenland contributed to your realisation or would you say that 'seeing is believing'?

Its double. By studying it, you start to understand the mechanisms, but its sometimes difficult to understand the magnitude from behind your desk or computer. If you were in front of such a glacier or fly over the ice cap, you see the size of it. By seeing the magnitude, then this gives you a better understanding of the potential consequences. And it is a difference if you see that compared to just seeing it as

graphs on your computer screen. Yes you see the regression, the glaciers have retreated ten kilometres in the last ten years, but if then you see what an immense amount of ice and water this means, it gives you another dimension. So it is the combination which makes me understand what it is and what is the importance. Just being there and seeing the glacier without understanding the background is still not enough. Having the combination of both is really impressive and important for me.

An aerial view of the Meiresluis – the sluice named after Patrick Meire in Kruibeke, Belgium – at its inauguration on 24 June 2017.

Is there a way to convey your first-hand experience to those that don't believe in climate change?

That is a very good question. I wish I had a very good answer to that. Professor Jean-Pascal van Ypersele who is the most well-known climate scientist from Belgium, and was also vice chair on the intergovernmental panel on climate change, has given hundreds of lectures about climate change and went into hundreds of debates, He mentioned 'I don't want to debate with non-believers anymore because you will not get any advance with that'. They very often say ' I don't believe it' or state things without any background. Just discussing with these people will not help.

What is very important is to give the right information as a scientist. Luckily, a growing part of the population is indeed listening to this message and starting to understand that we need to do something. It is the biggest issue that humanity has ever been confronted with because all the previous environmental issues were all local. There would be pollution in one river and smoke in several cities but it was still localised. Climate change is really global. Everybody, everywhere – in every square metre of the globe – is impacted by climate change and that makes it such an immense challenge for humanity to tackle that. More and more people are starting to understand it. It's with those that we will have to continue forward and to see it as a challenge. Climate change is a huge problem and either we can say 'it's too big a problem and we cannot solve it' but this means the next generation will suffer. Or we can say 'we have a problem but let's tackle it' and let's look to the ways to get out of this problem. For me, the second way is the *only* way we can go forward and that can only create a better society.

Resumé

1999-Present
Full Professor in the Department of Biology at University of Antwerp

2013-2018
Chair of the Department of Biology at University of Antwerp

1999-Present
Head of the Ecosystem Management Research Group (ECOBE)

2008-2014
Chairman of IMK/IMDO (Institute for Environment and Sustainable Development)

2004-2008
Academic Secretary of IMK/IMDO

1995-1999
Guest Professor of IMK/IMDO

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2012-Present
Visiting Professor at Warsaw University of Life Sciences

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1990-1999
Senior Scientist at IN/INBO (Research Institute for Nature and Forest)

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1989-1990
Senior Researcher at Netherlands Institute of Ecology (NIOO-KNAW)

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1986-1993
PhD Candidate at University of Ghent

1980-1990
Research Assistant at the Laboratory of Animal Ecology, Zoogeography and Nature Conservation at University of Ghent

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Wetlabs NTU instrument mounted on rod for deployment on floating buoy.

Photo DHI

CHALLENGES OF OPTICAL BACKSCATTER MONITORING IN MIXED SEDIMENT ENVIRONMENTS

Optical backscatter instruments (OBS) are very popular instruments for measuring suspended sediments in the field. In the following, an analysis of the sensitivity of optical backscatter (OBS) measurements to sediment grain size and the applicability of OBS measurements in mixed sediment environments is given.

In this article, an analysis is given based on laboratory tests, numerical analysis and field measurements. As described in Downing (2006), OBS instruments are simple and effective devices for measuring turbidity. The signal however needs a transfer function to convert turbidity to total suspended matter concentration (TSMC). The transfer function is dependent on several variables, notably the grain size distribution. Downing (2006) states that there is an almost linear relationship between turbidity (e.g. given in NTU) and TSMC for specific sediment properties. However, as demonstrated in Bundgaard et al. (2011), suspended sediment properties may shift in time either due to flocculation or through erosion and deposition, which may result in erroneous results as calibrations are usually made for stationary conditions (Downing, 2006).

The present analysis demonstrates that for stationary sediment properties, there is a linear relationship between turbidity and TSMC, but also that the relation is not linear if the sediment properties shift in time. The conversion factors are shown to tend to an exponential function of median grain size and thus the calibration function between turbidity and TSMC for a mixed sediment environment also becomes exponential. This is demonstrated through thorough analysis of excessive field measurements of suspended sediment dynamics in a mixed sediment non-tidal lagoon on the Baltic coast in southern Denmark.

With the presented findings, it is also shown that for mixed sediment environments, it is not enough to take water samples for conversion during calm weather because the calibration factor will shift with turbulence intensity, causing larger grain sizes to be suspended and affecting the stability and size distribution of flocs. It is therefore necessary to take water samples under a broad range of occurring conditions. The analysis shows that the conversion curve for mixed sediment environments is exponential with growing conversion factors for increasing grain sizes consistent with smaller light scattering. An indicative method for assessing grain sizes based on the calibration factors is given and finally, the findings are validated using an example from the field.

Introduction

Sediment measurements in shallow coastal waters and lagoons are often associated with challenges relating to determining the actual sediment concentration levels. Sediment concentrations can be determined by a

range of methods and all applied instruments have both strengths and weaknesses. Some of these are described in literature like Downing (2006) and Sutherland et al. (2000). Generally, all light scattering devices require calibration and they are furthermore sensitive to biofouling. Apart from sediment concentration (TSMC), almost all instruments are also sensitive to shifting grain size distributions, sediment grain shapes, sediment reflectivity, suspended organic material and the colour of the water. Of these, grain size distribution is the most important factor. The effect has previously been documented by various authors (Battisto et al., 1999; Black and Rosenberg, 1994; Conner and De Visser, 1992; Ludwig and Hanes, 1990; Sutherland et al., 2000). In the mentioned studies, only Battisto et al. (1999) used natural mixed sediments while the remaining studies did not include the effect of shifting sediment composition in the water column.

If sampled and treated properly, water samples and subsequent filtrations is the most reliable measure to give the correct sediment concentration. The downside is that physical presence is needed to take the samples which can be costly and challenging in rough weather. Therefore, and to achieve a higher data coverage, it is attractive to setup systems which are self-recording and eventually online, and which can operate in shallow lagoons without the need for physical presence during the campaign. This, however, leads to a new set of challenges as the applied instruments must be able to measure changing sediment concentrations with varying grain size distributions. One of the most applied instruments is the OBS (Downing, 2006; Sutherland et al., 2000). The challenge for this instrument becomes how to make an optimum transfer function between the OBS reading in NTU and the TSMC in mg l^{-1}. The correlation is expected to be linear for fixed sediment properties but if the sediment properties change over time, little is reported on the transfer function to be applied. The present article studies the correlation between grain size distribution and calibration coefficients for OBS measuring devices under static sediment conditions only varying concentration levels and under dynamic conditions, and shows both variations of concentration levels and grain size distributions.

In many studies, the turbidity is obtained from optical instruments, and during recent decades, most notably by optical backscatter (OBS). However, OBS devices do not measure the sediment concentration directly but rather a calibrated unit like NTU or FTU. The calibrated unit must be transferred to true sediment concentrations (TSMC) using manually collected water samples. Turbidity signals obtained from the OBS device are subsequently correlated to the TSMC results from the water samples and from this correlation, a transfer function is obtained (Downing, 2006). The transfer function is not generally valid as it is dependent on several variables including but not limited to: sediment grain size distribution, sediment colour and occurrences of biological substances. The transfer function therefore changes both in time and space, and therefore needs to be updated regularly.

The data used for the study have been gathered partially from an online monitoring system placed in the non-tidal Rødsand lagoon at the coast of Lolland in southern Denmark and partially from experimental geotechnical sampling and investigations in the adjacent Fehmarnbelt related to the planning of the Fehmarnbelt Fixed Link between Denmark and Germany.

The static conditions were studied in the laboratory and transfer functions were developed for different sediment types. This lead to an improved understanding of the expected variation that could be found in situ. The assumption was then validated based on field measurement campaigns from the Rødsand lagoon.

Materials and methods

The laboratory works

A single OBS sensor was tested with several sediment samples in the laboratory. The aim was to establish the response of the sensor to different sediment types with constant grain size distributions.

The test setup consisted of a 10 litre black container filled with 8 litres of saltwater with 8 PSU (practical salinity unit) and a magnetic stirrer. The OBS sensor was mounted centrally in the container. The water was allowed to rest for about one hour before the test began to limit the effects of air bubbles.

TABLE 1

Overview of sediment median diameters (d_{50}) tested.

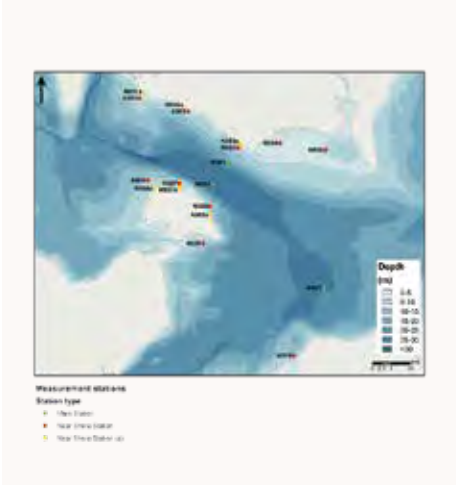
Test ID	d_{50} (mm)
A008	0.002
A014	0.005
A015	0.01
NS06	0.01
NS08	0.02
NS02	0.04
A003	0.05
A002	0.09
A010	0.09
A001	0.1

The magnetic stirrer was started and readings from the OBS in clear water was recorded. As the test progressed, small amounts of sediment was subsequently added and the OBS response was continuously logged. Water samples were taken during the test to establish a transfer function. The grain size distributions of the applied sediment had been established through laser diffraction analysis prior to the test. The OBS response was tested for increasing concentrations of a total of nine different median grain sizes (see Table 1).

After each test, the correlation between turbidity and TSMC was established for the specific sediment. In this way, a curve for conversion factors as function of median grain size was established by plotting NTU against TSMC and establishing a linear correlation.

Field work

A series of measurement campaigns were conducted in Rødsand lagoon in southern Denmark and sediment dynamics were studied using several instruments including Wetlabs NTU, Sequoia LISST-100x and RDI ADCPs. Initially, it was attempted to create transfer functions for the OBS sensors by extracting water samples on planned service visits. Eventually, it was found that service visits were always planned in reasonably calm weather situations and therefore only



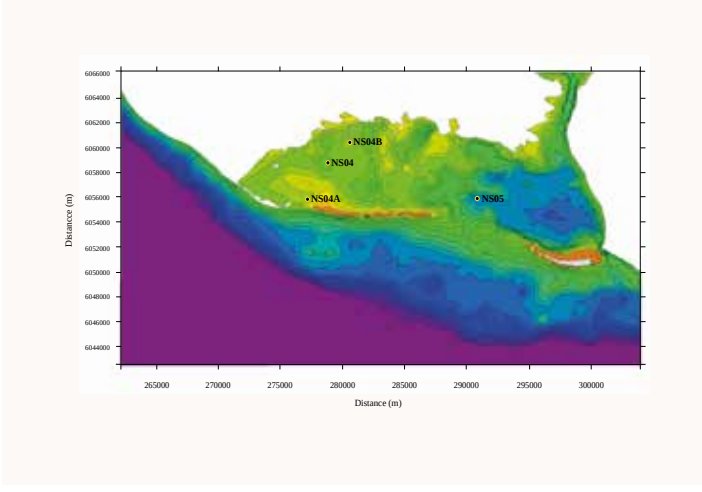


FIGURE 1

The sediment investigations in Rødsand were carried out as part of a larger program in connection with the planning of the Fehmarnbelt fixed link. Studies in Rødsand lagoon were more intensive due to the protection status of the area.

low concentrations were represented in the water samples. To overcome this constraint, it was decided to mount automatic water samplers on each monitoring station. Each water sampler contained 24 one-litre samples. These water samplers were connected to an online system in a way, so the water samples could be extracted based on a message from a remote location. This made it possible to extract water samples based on the NTU signal which could be followed on the online system. In this way, it was possible to extract a total of 144 water samples covering both calm weather and six rough weather events.

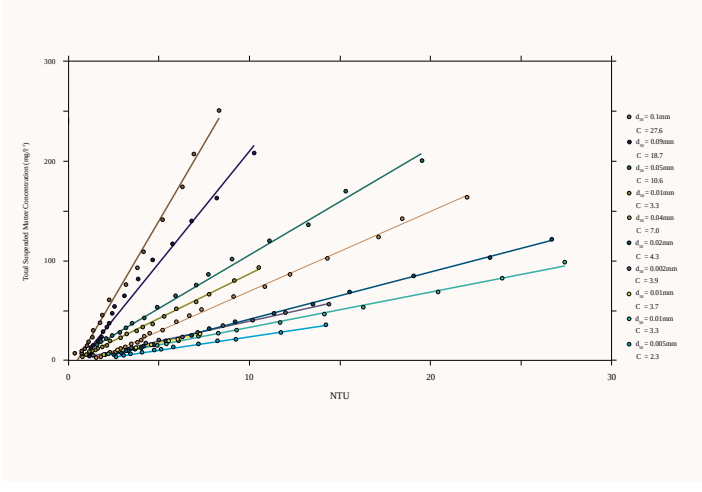


FIGURE 2

Results of applying different grain size distributions to the same OBS device. The slope of the transfer function increase with increasing median grain size. This is important when applying transfer functions in area with varying grain sizes.

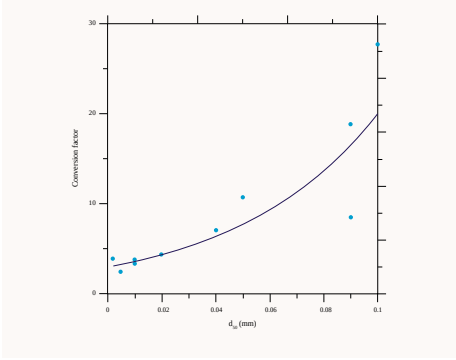


FIGURE 3

The graph shows the interdependency between the correlation factor and the mean grain size. When a range of correlation factors have been obtained with different mean grain sizes it becomes clear that the dependency of grains size is of importance when investigating the output from the sensors.

The water samples thus included a large range of sediment concentrations. All water samples were analysed for TSMC and used for conversion of the OBS measurements. An overview of the measuring stations is given in Figure 1. All the results were plotted as shown in Figure 2 and used to establish correlations between NTU and TSMC during both calm and rough weather situations.

Results

Laboratory results

In Figure 2, a range of analyses are shown. Each colour and line show the result for one specific sediment sample, characterised by its mean grain size which is indicated. The results show that for all specific samples tested, a linear correlation can be used to determine a calibration factor, and that the correlation factor generally increases with increasing median grain size values. Applying d_{50} as a proxy for the grain size distribution of the ten tested sediment types, a function for the correlation factor can be worked out which is shown in Figure 3.

Automatic water sampling

The results of the field tests with the automatic water sampler are evaluated for

The correlation factor generally increases with increasing median grain size values.

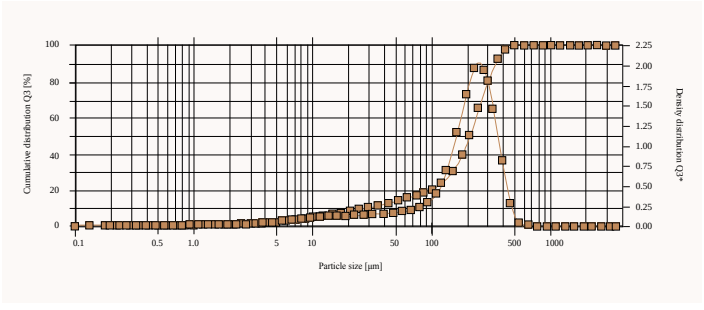


FIGURE 4

At site NS04a, the grain size distribution of the seabed is a mixture between cohesive and coarser material.

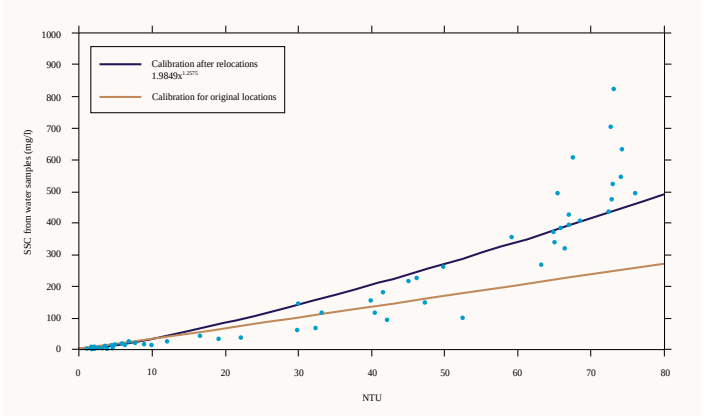


FIGURE 5

Calibration correlation. As expected from the laboratory tests shown in Figure 3, the conversion correlation is exponential which corresponds well with the mixed sediment environment.

position NS04a (see Figure 1). The seabed at NS04a bed is a mixed bed with mainly fine sand but also with coarser materials as well as silt and clay. Figure 4 shows dispersed grain size distribution of a grab sample extracted at the site. This qualifies as a mixed sediment environment as it contains significant parts of both cohesive and non-cohesive material. In the following, the calibration and the measurements made at this station will be used.

Water samples at NS04a in Rødsand lagoon were taken using an automatic water sampler. The samplings were triggered automatically in order to cover a variety of both calm periods and periods with more rough wind and wave conditions. The measured TSMC were plotted against the NTU values from the OBS and the results for station NS04a are given in Figure 5.

To show the variability of the grain size distribution during stormy weather, the grain size distribution was measured at NS04a using a laser scattering LISST-100x instrument (see Figure 6). The grain size measurements show that the grain sizes observed in the suspended sediment vary significantly over time which further supports the need for applying a calibration factor that takes varying grain sizes into account when measuring in a mixed sediment environment.

Discussion

Laboratory tests

If the measured sediment has a fixed and relatively uniform structure with respect to grain size distribution, the conversion from OBS-NTU values to sediment concentrations (TSMC) becomes a linear function. This is supported by Downing (2006). All sediment types show identical near linear behaviour although calibration factors vary, generally showing increasing calibration factors with increasing mean grain sizes of the measured sediment (shown in Figure 2).

The observed increase of the calibration factor with increasing median grain size means that light backscatter is decreasing with increasing grain size. This is consistent with the scattering being a function of the surface area of the sediment (Battisto et al., 1999; Downing, 2006; Ludwig and Hanes, 1990).

Figure 3 and Figure 5 show that the conversion factor can be expressed as an exponential function of the median grain size. This means that if one knows the median grain size or even the characteristics of changing particle sizes of mixed sediments, it is possible to use an exponential transfer function and get a higher accuracy with respect to OBS-based measurements of true suspended sediment concentrations (TSMC).

If the conversion factor for a given location is known and the concentrations are not excessive, the conversion factor might be used to give an indication of the grain size distribution and thereby the amount of fines. The argument for this is that the fines account for most of the light dampening so if very fine material is present at a given site, the conversion factor will be low whereas high

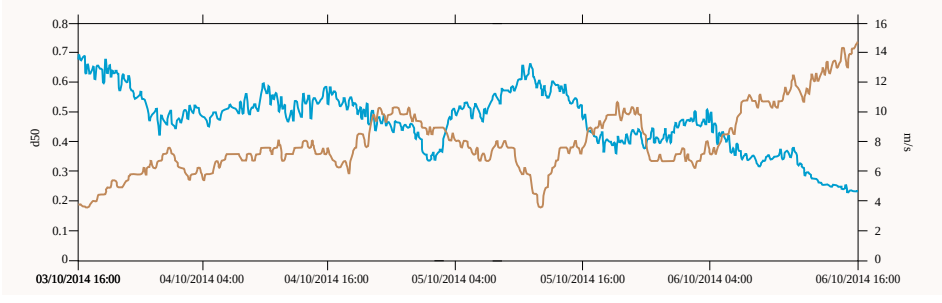


FIGURE 6

Grain size variation and wind speed variation at position NS04a. At this site, the median grain size is inversely correlated to the wind speed. The wave energy destroys the fragile flocs resulting in a decreasing size during rough periods. The flocs reform quickly as the wind speed decreased.

TABLE 2

Interpretation of grain size distributions from calibration factors.

Calibration factor	Material
<5	High amounts of fines
5–10	Medium to low amounts of fines
>10	Well graded sand with low amounts of fines

calibration factors indicate presence of coarse materials. In Table 2, an interpretation of the relation between grain sizes and conversion factors is suggested.

Judging from Table 2 and the calibration curve in Figure 5, the suspended sediment should consist of quite a bit of fines, indicated by the lower parts of the calibration curve, as well as of coarser materials, indicated by the steeper right part of the calibration curve. This is consistent with the found bed composition illustrated in Figure 4 and the observations of sediment being eroded and deposited sequentially during rough weather periods. The variation in conversion factors and the shape of the calibration curve covering the full spectrum of hydrodynamics is of high importance in a mixed sediment environment where the grain size distribution of the suspended sediment varies. In such environments, a varying conversion factor must be considered because amounts of coarser grain sizes will increase substantially with higher currents and wave intensity. Simultaneously, the floc size of cohesive sediments can temporarily decrease due to increasing turbulence levels (Bundgaard et al., 2011). In such an environment, the optimum conversion function will be exponential. Practically, this means that water samples will have to be taken under all occurring conditions to get an optimum calibration. Otherwise, the correlation may be erroneous.

The error will vary from place to place as a function of local sediment characteristics and wave conditions, and the possible error in Rødsand lagoon can be quantified based on data shown in Figure 5. The error will result from the difference between applying a standard linear calibration factor based on standard calm weather water samples (the orange line in Figure 5) and applying the exponential calibration equation based on water samples covering all conditions (the black line in Figure 5). The calculated error in percentage at increasing suspended sediment concentrations is shown in Figure 7.

The error varies with sediment concentrations consistent with the expected change in grain size distribution during storms. The error is significant for larger concentrations and should be considered before choosing the approach for calibrations of the OBS measuring device in mixed sediment environments.

Conclusions

Studies were carried out, including comprehensive sampling and analyses of water samples, to convert NTU signal from OBS sensors to total suspended matter concentration using water samples. The analysis showed that the conversion factor is strongly dependent on grain sizes in suspension. This is consistent with the findings in literature (e.g. Battisto et al., 1999; Black and Rosenberg, 1994; Conner and De Visser, 1992; Downing, 2006; Ludwig and Hanes, 1990)N.C., during October 1997. The distinct scales of resuspension for sand and mud at this location allow concentrations of both size classes to be determined simultaneously from a single OBS time series. For this study, OBSs were calibrated separately using sand and mud collected off Duck, N.C.. OBS voltage gain associated with mud was found to be an order of magnitude larger than that for sand. Based on this calibration, it was shown that the mass concentrations of particles smaller than 63 microns pumped off Duck during October 1997 were consistent with the lowest 1st to 5th percentile of voltage recorded by the OBSs. Calibrated OBS response above this background turbidity was consistent with pumped sand concentration as long as corrections were made for (i. Tests with various natural sediments with varying grain size distributions show that the individual conversion factors for each sediment type are linear functions of concentrations, where the conversion factors themselves are exponential functions of d_{50} for the individual sediments. The precise relation between d_{50} and the conversion factors is most likely a function of specific local sediment characteristics and local wave and current conditions. The conversion factor should therefore be regarded site specific and cannot be generalised. Analysis show in conclusion that for mixed sediment environments, it is not sufficient to extract water samples for conversion during calm weather. The conversion approach has to take into account that during rough weather, substantial amounts of coarser sediment can be mobilised and floc sizes temporarily change. Therefore, the conversion factor will shift with more intense hydrodynamics. To determine a reliable local conversion for an OBS in a mixed sediment environment, samples are needed under a wide and representative range of conditions. The achieved data allow for an indicative method for assessing median grain sizes based on the conversion factors. Disregarding the effects of changing and variable grain sizes of sediments in suspension on the conversion of OBS values, the error is proven significant especially at higher sediment concentrations.

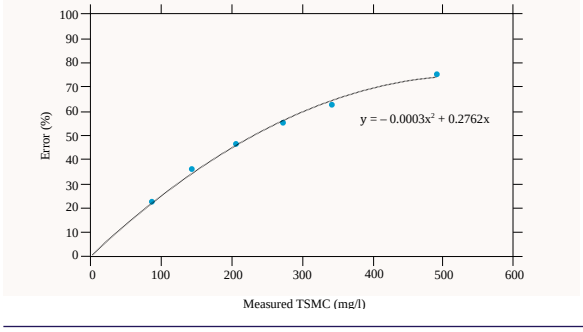


FIGURE 7

Error in % between using a standard calibration equation a more realistic exponential equation.

Summary

Optical backscatter instruments (OBS) are very popular instruments for measuring turbidity and suspended sediments in the field. An analysis of the sensitivity of optical backscatter (OBS) measurements to sediment grain size and the applicability of OBS measurements in mixed sediment environments is given based on laboratory tests, numerical analysis and field measurements.

As described in Downing (2006), OBS instruments are simple and effective devices for measuring turbidity. The signal however needs a transfer function to convert turbidity to total suspended matter concentration (TSMC). The transfer function is dependent on several variables notably the grain size distribution. Downing (2006) states that there is an almost linear relationship between turbidity (e.g. given in NTU) and TSMC for specific sediment properties.

With the presented findings, it is also shown that for mixed sediment environments, it is not enough to take water samples for conversion during calm weather because the calibration factor will shift with turbulence intensity, causing larger grain sizes being suspended and affecting the stability and size distribution of flocs. An indicative method for assessing grain sizes based on the calibration factors is given and finally, the findings are validated using an example from the field. This is demonstrated through thorough analysis of excessive field measurements of suspended sediment dynamics in a mixed sediment non-tidal lagoon at the Baltic coast in southern Denmark.

An indicative method for assessing grain sizes based on the calibration factors is given and finally, the findings are validated using an example from the field.

Klavs Bundgaard

Klavs Bundgaard holds an Msc in civil engineering from Technical University of Denmark specialised in Coastal and Ocean Engineering. He has a strong background working with fine grained sediments and measuring techniques, first as senior hydraulic engineer with DHI and later as team leader, senior consultant, and senior project manager for SWECO and NIRAS. Klavs was the project manager for the spill investigations for the EIA for Europe's largest marine infrastructure project, Fehmarnbelt for DHI and has been involved in numerous marine studies on cohesive sediments in Denmark and around the world, affirming his expertise in modelling and measuring cohesive sediments. Klavs is also a member of CEDA's environmental committee.

Ulrik Lumborg

Ulrik Lumborg started working for DHI in 2005 after finishing a PhD from University of Copenhagen on modelling of cohesive sediment dynamics. In the first years, Ulrik focused on numerical modelling issues. After some years he became involved with survey work and has since studied a number of sites based on a combination of monitored data and numerical modelling. His main works during recent years have been with the environmental impact assessment of the Fehmarnbelt Fixed Link as well as spill monitoring on dredging projects throughout Europe.

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Lotte Nyborg

As a geographer and remote sensing specialist, Lotte Nyborg has broad experience with sediment-related issues and marine mapping in Denmark and around the world. Lotte played an important role in developing the complex QA and filtering procedures used for the OBS measurements in the Fehmarn Belt Study. With more than 15 years in DHI GRAS, she has experience in remote sensing analysis in both terrestrial and marine environments including coastal studies, mapping of suspended sediment as well as marine habitat mapping based on satellite imagery.

Bjarne Holm Jakobsen

Prior to joining Femern A/S in 2011 as an environmental coordinator, Bjarne Holm Jakobsen received his MSc and PhD in Geography and further Master's courses in International and European Environmental Law at the University of Copenhagen. As associate professor, head of department and research station manager, he has been involved in many research and development projects within environmental sciences, focusing on the marine area and land-ocean interactions. He is currently responsible for the transnational coordination of environmental management for planning and construction of the Fehmarn Belt Fixed Link and is part of research activities and methodological studies discussed in the present article.

CAN A LAKE'S ECOLOGY BE RESTORED WITH UNWANTED SEDIMENT?

By constructing the Marker Wadden, a nature reservation is created allowing for natural processes as much as possible.

In April 2016, Boskalis started constructing one of the largest nature restoration projects in Western Europe. First and foremost a bird paradise, the Marker Wadden consists of a 1,000-hectare landscape above and below the waterline, multiple rows of dunes, and a 1500-metre trench to collect fine silt from Lake Markermeer.

The Marker Wadden project has been a long-cherished dream of the project's client, Natuurmonumenten, or the Dutch Society for the Preservation of Nature. By constructing the Marker Wadden, a nature reservation is created allowing for natural processes as much as possible. The contractor and the client were both well aware that control of nature and natural processes is often limited. The challenges that this limited control posed were not only solved technically but were also solved due to the good collaboration between both parties. This article describes some of these unique challenges – both technically as well as in terms of collaboration – and how they were solved.

FIGURE 1
The Marker Wadden is situated in Lake Markermeer.

The ecological context and purpose of Marker Wadden

Lake Markermeer is a 680 km² artificial lake in the centre of the Netherlands which was formerly part of the larger Zuiderzee. After the area was closed off with two dams, Lake Markermeer became a fresh water lake with unique ecological values (Natura2000 area). Over the past decades, several ecological problems have arisen related to, amongst others, highly turbid water leading to a decrease in light penetration, a decrease in biodiversity and a change in nutrients' volume and constitution (Vijverberg 2011 and De Lucas Pardo (2014)). These circumstances caused the fish population to be decimated leading in turn to a further decline in the population and variety of birds in the area. What remained was an enormous lake of untamed turbid water in the centre of the 'blue heart' of the Netherlands.

Several solutions for these problems were investigated in the research project 'Natuurlijker Markermeer IJmeer' which was initiated by Rijkswaterstaat in 2010 and finished in 2015. One of the recommendations to improve the ecological quality of Lake Markermeer was to increase the habitat diversity. Given the large size of the lake, the diversity was rather limited due to the depth of the lake. Besides, the lake has steep and hard shores, reducing the habitat diversity from water to land. Rijkswaterstaat – the Dutch Directorate General for Public Works and Water Management – together with other governmental agencies developed a vision which gives Lake Markermeer a sustainable future by proposing the development of a wetlands area in the lake. Natuurmonumenten

Not only sand, but also fine sediment and soft mud are used as a core building material.

then took the initiative for the construction of the Marker Wadden and thanks to financial contributions from the Dutch National Postcode Lottery, the Dutch Ministries of Economic Affairs and Infrastructure and the Environment, the provincial authorities of Flevoland and North Holland, several companies and Natuurmonumenten itself, the plan was turned into reality. With the Marker Wadden, an archipelago of islands and sand banks has been created that will ultimately improve the quality of Lake Markermeer by making it healthy and productive again so it will become a paradise for birds and fish as well as a place where people can enjoy nature.

The technical context of Marker

Globally, sand as a resource for land reclamations is increasingly hard or costly to come by. Alternative land fill materials and methods are being explored worldwide. The Marker Wadden is constructed using all locally available material (see Figure 2). Not only sand, but also fine sediment and soft mud are used as a core building material. The fine sediment is a thin layer (locally less than one metre) of silty sand resting on the bottom of the lake. This fine sediment layer comes into suspension during storms and presently causes the ecologically detrimental turbidity. Underneath the fine sediment lies the soft mud which is a thicker layer (locally approximately eight metres thick) of Holocene (inorganic) clay and peat. The use of these materials for large-scale land reclamations is innovative and not yet common practice, and predicting the behaviour of such reclamations is challenging. Under this thick layer of fine sediment and soft mud lies the Pleistocene sand. In traditional marine contracting, only this sand layer would be of interest. The layer on top would traditionally be considered 'unsuitable' and therefore has to be disposed of in the most cost-effective way. For the Marker Wadden, this 'unsuitable material' is a key building material. Because of this, the Marker Wadden is a perfect example of beneficial use of sediment (CEDA 2018).

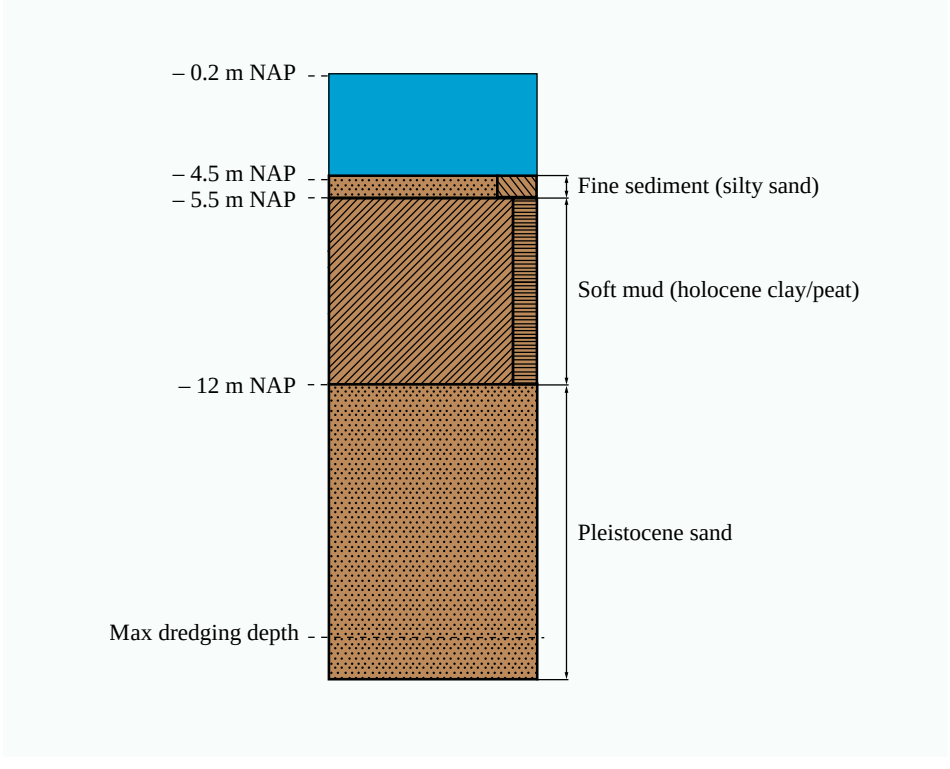

FIGURE 2

Schematic original bottom profile.

Design and construction

The design was approached from an ecological and landscape architectural perspective. The guiding principle was to create a healthy habitat for flora and fauna that maximises the ecological value of the Lake Markermeer region. It was only later that the Boskalis team put on its more traditional engineering hat to put the plans into practice. The interaction between the various parties with the aim of orchestrating the different wishes and practicalities resulted in an exceptional design. The landscape design of the Marker Wadden was made by Vista Landscape Architects, as part of the Boskalis consortium during the tender. All discipline

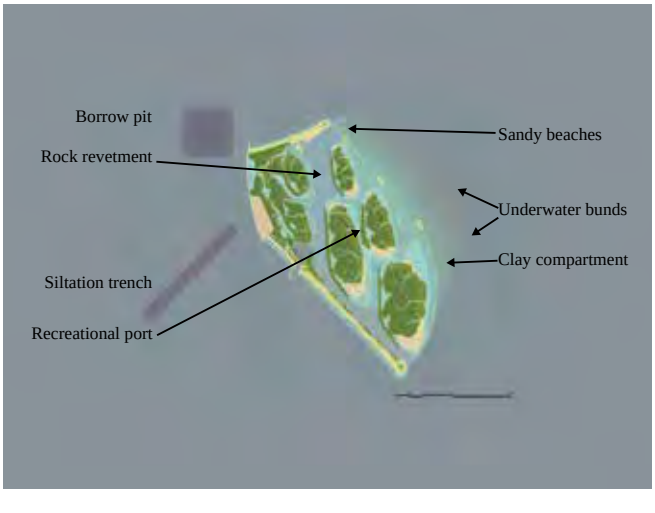

FIGURE 3

Design of the Marker Wadden project.

FIGURE 4

Construction of sandy beach and dunes (A) as well as the rock revetment at the west side of the island (B).

inputs were integrated into this design during an iterative design process allowing for a high-quality, economical design and operational work method. Figure 3 shows a top view of the design with its characteristic features.

Almost all material used for constructing the Marker Wadden – sand, soft mud and fine sediment – was collected in the borrowing pits and the siltation trench. The reclamation area is divided in several compartments divided by bunds. Sand was used to create the sandy beaches along the north and southwest shores (see Figure 4A), the underwater bunds at the east side, and the compartment bunds inside the area. Beaches, bunds and a rock revetment (see Figure 4B) were needed to protect the area from wave attack. At the edges of the beaches, a buffer volume was placed to compensate for sand transport and erosion. The main compartments, such as the swamp area indicated in green in Figure 3, were filled with soft mud and fine sediment.

The area is constructed in several steps and layers, as indicated in Figure 5. First, small sandy bunds of 1 to 1.5 metres high were constructed

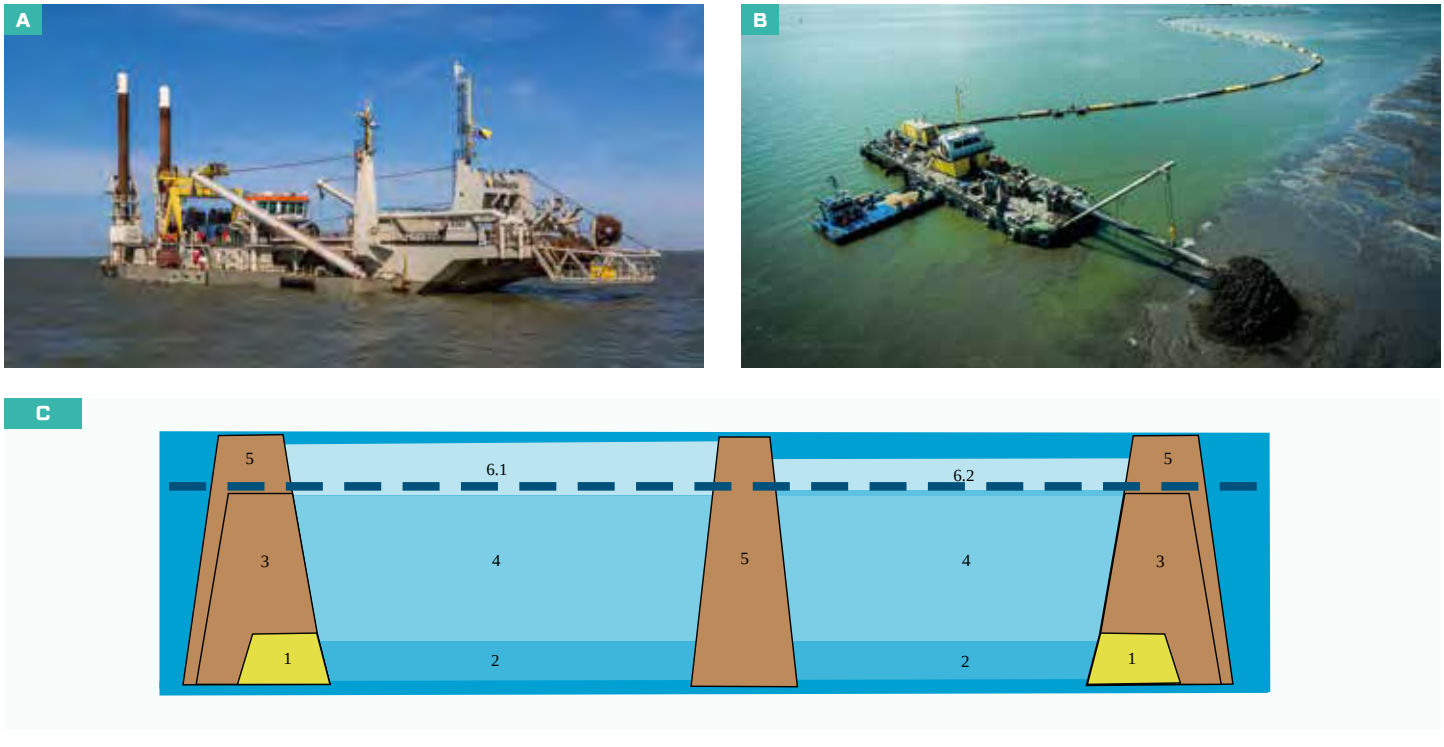

FIGURE 5

Cutter Suction Dredger Edax (A), spreader pontoon Steenbok (B), and indicative construction steps (C).

FIGURE 6

Areal overview of the Marker Wadden (situation summer 2018).

(1). The area in between was filled with a mud-water mixture (2). Next, the sandy bunds were raised up to the water level, around 0 metres (3), and in succession, the area in between was filled again with a mud-water mixture (4). The sandy bunds were then raised above the water level and sub-compartments were created by intermediate bunds (5). The sub-compartments enabled different water levels and filling rates in the different compartments. Finally, the mud mixture was pumped into the area above the lake level (6). After that, the consolidation process continued. A spreader pontoon was used to fill the compartments, allowing for the controlled installation of thin layers of soft mud. Figure 5 shows the pontoon in operation during the construction of one of the sandy bunds of Marker Wadden.

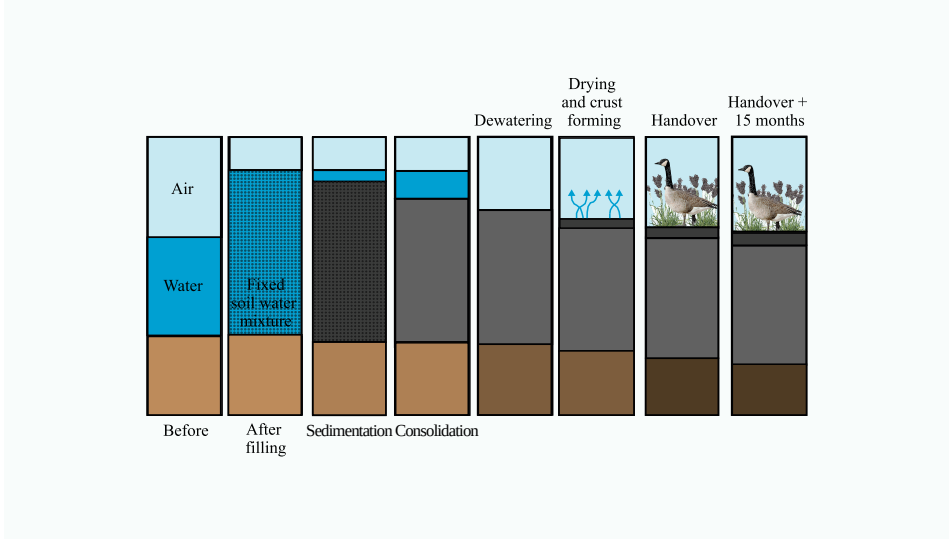

FIGURE 7

Process from reclamation to final handover condition.

Processes from reclamation to handover

Because the islands are made with hydraulically dredged material, the soft mud and fine sediment from the borrow pit is mixed with water and bulks (expands). After the bulked material is placed in the compartments, the material undergoes a de-bulking process called consolidation. This process from filling of the compartments to final strength development is indicated schematically in Figure 7. First, the compartments were filled with the dredged mixture. After reclamation, the mud and sediment starts to settle and consolidate, forming a 'clear' water layer on top. After some time, when consolidation of the bed has progressed, the water layer on top was removed and drying of the bed started, forming a dry crust on top of the soft bed. The weight of the crust on top of the soft material increased the rate of consolidation. During the design phase, the consolidation process was modelled and estimations were made for the moment in time the final bed elevations will be achieved, and if strength requirements will be met. The elevation requirements are rather strict in order to achieve an optimal ecological value for the area.

The process can only be numerically modelled to a certain extent. As we are building with nature and allowing for natural processes to assist in the construction as much as possible, extra aspects play a role in the development of elevation and strength. One aspect is vegetation (see Figure 8A). Roots of the reed plants – which are sowed after lowering of the water in the compartment – can extract water from the fill, resulting in increased consolidation rates. Vegetation also has a sediment-retaining capacity, keeping loose sediment in place. Another aspect is the morphology that is caused by water-level differences over space and time. This causes flows to occur from one compartment to another and between the compartments and Lake Markermeer. These flows can have a scouring effect (see Figure 8B) but can also result in creek formation towards outflow locations.

Real time research and adaptive management during construction

The project has a stringent set of elevation requirements. Having to meet these requirements in the face of consolidation, crust formation of the soft clay material and

FIGURE 8

The project saw the development of sown reed through natural processes.

FIGURE 9

Natural processes led to creek development caused by bund excavation. A hover craft was used to sow the reed.

all other naturally occurring effects, is rather unique and experimental. For this reason, real time research was performed and adaptive management was applied during execution of the project.

During the design phase and also execution of the project, testing on various scales was performed: column testing in a laboratory, container scale testing and testing in the actual reclamation. Many of these tests were executed by Boskalis together with universities to verify consolidation parameters, crust formation and monitoring techniques. The effect of vegetation is also part of research projects at universities (Smart Ecosystem project).

Adaptive management was applied during the construction phase. Before construction, the margin of error in modelling the behavior of the compartment fills was significantly larger than the margin in contractual elevation requirements. The understanding of the behaviour of the fill material was constantly updated based on monitoring and analysis. This way, the reclamation process was controlled. The monitoring data was used to validate or correct our predictions and to support project execution. There was anticipation on operational or requirement-related problems if the soil material behaved differently than expected. When necessary, the work method was adjusted.

To support the adaptive management, different types of measurements were carried out:

- When the compartments were still underwater, bed levels of the fill material were measured with both a single beam echo sounder and a multi beam. The survey was carried out on a fixed grid system to guarantee coverage of the area and to compare different surveys in time.

- Vertical density profiles from the fresh bed to the original bed were taken at various locations inside the compartments, using a Hydramotion MudBug (Hydramotion company). Before the Marker Wadden's construction started, different systems to measure the density were tested. The MudBug performed best for the Marker Wadden fill material (Kleine Schaars, 2016). Density profiles were measured directly following completion of a fill layer and then at regular time intervals (see Figure 10). These measurements gave an idea about the evolution of the density profiles and the settlement/ consolidation over time

- Aerial topography measurements of the bed levels inside the compartments were carried out after the compartments were filled and the water levels were lowered. Quarterly measurements were carried out using a Topcon Sirius Pro drone, an unmanned aerial vehicle (UAV) installed with a high-resolution camera,

The monitoring data was used to validate or correct our predictions and to support project execution.

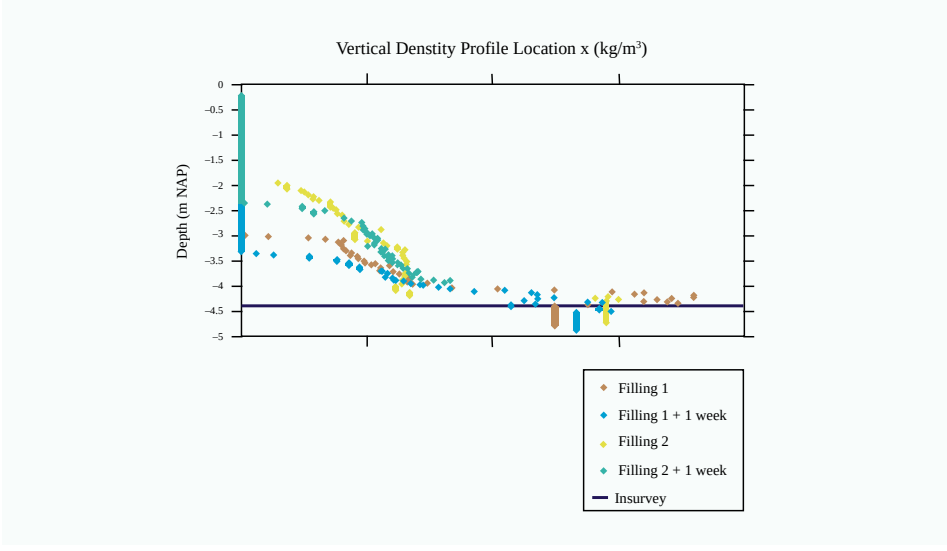

FIGURE 10

Density profile evolution over time after two consecutive fillings.

used for stereo photogrammetry. By comparing the topography data from every quarter, the contractor was able to evaluate the behaviour of the soil in the compartments. Together with the density information from the MudBug, additional filling layers were designed to finally end at the correct bed level. Figure 11 shows a typical result of the 2D drone survey.

FIGURE 11

Example of 2D topography data, measured with a drone.

- The behaviour of the sandy shores was monitored frequently just after initial construction. Bathymetry measurements underwater were carried out with a survey boat equipped with a multibeam echosounder (SeaBat 7101). Topographic profile measurements of the beach and the shallow beachfront were carried out with handheld GPS equipment (Trimble R10 – GNSS System). Beach profiles were analysed on cross-shore as well as longshore sediment transport processes. These analyses provided the contractor information about the initial behaviour which was useful to determine the final profiling of the beaches and dunes. More information to be found in Steetzel (2017).

- Settlements of the sandy bunds, beaches and hard revetments just after construction were measured with 'classical' settling plates. Observations were compared with the original settling calculations during the design phase. Where needed, final construction heights were adapted based on the monitoring of the behaviour. This enabled the contractor to finalise the bunds and revetment at a proper level such that future settlement is covered by the surplus height of the structures.

- In August 2017, a first part of the Marker Wadden – the part which was above water at that moment – was sowed with reed seeds to start vegetation development. Sowing was carried out in a specially designed way, with a hoover craft. (see Figure 9) In a smaller part of the area, vegetation development was started with reed rhizomes, for example along the shores of the port. After sowing, the reed started to germ and grow. During this period, frequent monitoring was carried out to follow the development process. Parameters like plant density (plants/m$^{2)}$, height and stem thickness were systematically determined to determine success rates of vegetation development.

The contractor's understanding of the various objects was greatly increased based on the real-time analysis of field measurements, observations, numerical design modelling and the operational lessons learned. Because of the integrated adaptive management process, we were able to continuously optimise the work method to reduce the risk of not fulfilling the project requirements. The following construction method components could be adjusted with respect to the compartment filling: management of the compartments (size, number of filling layers and water levels), mixture density and production rates of the dredger, time interval between the filling layers, and filling volume distribution over individual compartments.

Collaboration and contract

Contractor Boskalis and client Natuurmonumenten/Rijkswaterstaat have a strong mutual drive towards meeting the project's ecological goals. Apart from the apparent intrinsic motivation, this drive is strengthened by the way the contract and collaboration were set up. The client is not intrinsically interested in technical specifications such as elevation, bearing capacity, density and so forth. The explicit interest is in ecological value. This is strongly reflected by the project requirements. One good example is the formulation of the 'goose

FIGURE 12

Goose footprints can be seen on top of the compartment fill.

accessibility' requirement: the client formulated this as a functional requirement in the tender specification. The contractor translated this requirement to a set of technical values – in terms of undrained shear strength – to check feasibility of this requirement. However. if during project execution it is clear that geese can walk on the compartments, this undrained shear strength does not have to be established.

This requirement is a testament to the client's attitude, which was to ensure that there was room for a skilled contractor to operate in a way that best serves the client's intrinsic goals.

Although the tender was set up towards designing and pricing of 300 hectares of wetland area, initially only the western-most island was be constructed (180 hectares). In case extra funding would become available and the execution of the first island was successful, the second island could be contracted as well. This is a strong example of setting the formal stage such that contractor would be as motivated towards meeting the project goals as the client. The additional islands were contracted in 2016 and 2017.

One of the starting points was to allow for natural processes as much as possible. By accepting these processes, natural forces have had a big influence on what the Marker Wadden looks like (see Figure 13). When unexpected results were witnessed during construction of the island, the client was not focused on jumping to corrections. On the contrary, a local pocket of shells or an occasional high-spot which was not intended beforehand or explicitly in line with the design became welcome as they diversify the habitat. Being allowed to, in collaboration, optimise the final design and construction of the islands allows then for more economical construction and for more ecological value.

FIGURE 13

Supported by vegetation development, natural processes have created a diverse landscape near the hydraulic fill locations.

Lessons learned and first successes

Perhaps the most important lesson learned is the way in which client and contractor collaborated. Starting at the conception of the Marker Wadden, throughout the tender phase and execution, the client set the stage by creating the (formal) boundary conditions that ensures that successful execution is mutually beneficial. An example of this was the client requirement to ensure that the public can experience the islands from the earliest moments. This was needed for public support and finance.

In addition, client and contractor shared the same project office from the start of execution which allowed for open and transparent communication, frequent informal contact, a proactive attitude and easy adaptation towards mutually beneficial results (one final project goal). As a result, above the initial one, in total five islands were contracted and constructed by contractor, in time and within budget, resulting in an even greater ecological improvement for the Markermeer region.

The first ecological research findings are very promising. Not only is a variety of bird species visiting the islands, but also insects have settled on the islands. In the surrounding

FIGURE 14

Birds found their way to the Marker Wadden early on during construction.

waters, a dramatic increase of plankton is being observed providing an important food source for fish and birds in Lake Markermeer.

The good positioning of the Marker Wadden from an ecological point of view became apparent during early construction. Many bird species were attracted the moment land over water was created (see Figure 14). In fact, some of the areas were temporarily closed

FIGURE 15

Turning a nuisance into ecological value.

The good positioning of the Marker Wadden from an ecological point of view became apparent during early construction.

for personnel and equipment during breeding season.

The main technical breakthrough is the use of soft mud and fine sediment as a core building material. The main challenge is to place the fill material such that the height requirements are met after consolidation. Before execution started, the uncertainties of the self-weight consolidation of hydraulically placed clay was larger than the margins within the contractual requirement. By applying adaptive management, this uncertainty was dealt with. Also, allowing for natural processes resulted in a more economical construction of the Marker Wadden. In doing so, larger habitats could be constructed for the fixed budget.

Because soft mud and fine sediment are used as a core building material, a precedent is created that may change at the perception towards the world's most available resources. Soft mud and fine sediment are generally considered to be unsuitable for construction and a costly nuisance to dispose of. The Marker Wadden project proves that this material, if used correctly, may be a valuable resource (see Figure 15). In fact, it was the source of the ecologically detrimental turbidity and used to improve the ecology. Soft mud and fine sediment exhibit highly varying characteristics at each project but the same construction (floating equipment) and design principles as applied for the Marker Wadden project can be applied to other projects around the world. This makes the Marker Wadden project a valuable pioneering example for how to reclaim large volumes of soft mud and fine sediment.

Summary

In April 2016, Boskalis began construction on one of the largest nature restoration projects in Western Europe which is first and foremost a bird paradise. The Marker Wadden consists of a 1,000-hectare landscape above and below the waterline, multiple rows of dunes, and a 1500-metre trench to collect fine silt from Lake Markermeer. The project has been a long-cherished dream of the project's client, Natuurmonumenten, or the Dutch Society for the Preservation of Nature, and forms a nature reservation which allows for natural processes as much as possible. The contractor and the client were both well aware that control of nature and natural processes are often limited, and the challenges that this limited control posed were not only solved technically but were also solved due to the good collaboration between both parties. This article describes some of these unique challenges – both technically as well as in terms of collaboration – and how they were solved. The main technical breakthrough is the use of soft mud and fine sediment as a core building material.

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Roeland Lievens

After obtaining his Hydraulic Engineering degree from Delft University of Technology, Roeland Lievens worked at Royal Boskalis Westminster as a Marine Morphological and Environmental discipline engineer. Roeland was involved with the Marker Wadden as a Project Engineer since the start of construction. Specifically, Roeland was responsible for setting up and executing the monitoring and analysis of the hydraulic fill behaviour, increasing the understanding of building with soft mud and fine silt.

The project has been a long-cherished dream of the project's client, Natuurmonumenten, or the Dutch Society for the Preservation of Nature.

Jeroen van der Klooster

Working for 15 years at Boskalis, Jeroen van der Klooster is currently Project Manager for the Marker Wadden project. He received his BSc in Environmental Engineering in 2003 from the HTS in Utrecht, the Netherlands.

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André Rijsdorp

André Rijsdorp is director of Plan&Proces, a strategic consultancy in spatial development and ecological restoration. From the first day, André was involved in the set-up of Marker Wadden and the funding and collaboration needed for the realisation of the project. He plays a key role as 'entrepreneur' in the development and lay out of the islands. André has a BSc degree in Landscape Planning.

CULTIVATE SKILLS TO GROW SUCCESS

WEDA Dredging Summit & Expo '19
4-7 June 2019
Hilton Chicago
Chicago, Illinois, USA
https://dredging-expo.com

Organised by the Western Dredging Association (WEDA), the Dredging Summit & Expo '19 is a technical conference which will descend on downtown Chicago. With a theme of Waves of Change: Oceans of Opportunity, topics will emphasise the importance of understanding and development of solutions for problems related to the protection and enhancement of the marine environment as well as improving communications, technology transfer, and cooperation among associations and societies. The annual three day forum will offer high quality presentations and an exhibition with over 90 exhibitors. A lively social programme with ice breakers, ice cream socials and gala dinners is planned.

Representing all facets of the dredging industry, attendees will convene and share knowledge on dredging, navigation, marine engineering and construction. The audience will be comprised of contractors working in dredging, navigation, coastal and inland flood protection, deep-sea mining, offshore wind energy, and oil and gas production fields as well as marine engineers, manufacturers, dredging technology providers, harbour & port representatives, consultants, port engineers, hydrographic surveyors and geologists, environmental managers, infrastructure managers, public authorities, suppliers, universities, research institutes, civil engineers, and geotechnical engineers.

An on-site visit to the dredging yard of a IADC member is an integral element in the learning process.

Seminar On Dredging and Reclamation

24-28 June 2019
IHE Delft Institute for Water Education
Delft, the Netherlands
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 their International Seminar on Dredging and Reclamation for the 57th time. This time the seminar will be held 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 Seminar on Dredging and Reclamation is a five-day course which covers a wide range of subjects, from explanations about dredging equipment and methods, rain bowing 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
- environmental aspects of dredging

Site Visit

Activities outside the classroom are equally as important. An on-site visit to the dredging yard of a 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.

Your Lecturers In Short

Seminar Coordinator

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

Seminar 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 is a senior production engineer at Van Oord, mainly 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.

As part of Van Oord's Geology Group Supervisor within the Engineering & Estimating Department, Marcel van den Heuvel develops internal knowledge on Offshore Mining and assessing Offshore Mining projects on feasibility.

As Manager Technology & Innovation at DEME, Paul Vercruijsse's prime responsibility is the strategic management of technology development and innovation processes. His major challenge is the bridging of gaps between science, engineering & operations.

Luk Verstraelen is Senior Engineering Manager in the Research, Method, Production and Engineering (RMPE) Department of DEME. In view of the more and more complex and multidisciplinary marine infrastructure projects nowadays, he manages different project engineering teams, both in tender preparation works as in project execution related issues.

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 of Achievement in recognition of the completion of the coursework.

Register for the seminar at

http://bit.ly/2FczJwi

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