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Special Issue on
CLIMATE CHANGE ADAPTATION AND COUNTERMEASURES IN COASTAL ENVIRONMENTS

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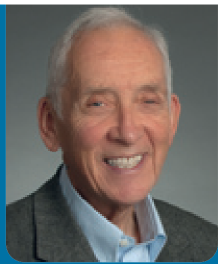
EXAMPLES OF RESEARCH AND DEVELOPMENT FOR CLIMATE CHANGE ADAPTATION AND MITIGATION IN COASTAL ENVIRONMENTS

EDITORIAL BY CORRADO ALTOMARE & ANGELOS FINDIKAKIS

The combination of sea-level rise and increasingly more intense storms associated with climate change has been raising the risk level of catastrophic damage to coastal communities around the world. In recent years, major tropical and extratropical cyclones have devastated coastal areas in Asia, North America and Europe. Considering that the number of people living in low elevation coastal zones is expected to rise from 625 million in 2000 to over a billion by 2060 , the development of coastal defenses and appropriate management policies to protect human life and prevent flooding and property damage becomes increasingly more important with time.

Corrado Altomare
Guest Editor



Angelos N. Findikakis
Hydrolink Editor

The degree of the climate-related hazards increase in coastal regions varies for different future climate scenarios. Considering the slow progress towards curtailing greenhouse gas emissions, it is wise to prepare for the worst-case scenario, in parallel with efforts to reach global cooperation towards the goal of moving away from the use of fossil fuels. This involves significant sea-level rise, larger storm surge and more forceful waves in many parts of the world. The Intergovernmental Panel on Climate Change in its Special Report on Ocean, Cryosphere in a Changing Climate estimated that under the high-emissions global warming scenario, RCP8.5, the global mean sea level can rise up to 1.1 m by the end of the century. In addition, changes in wave height, period and direction which will affect the impact of waves in many areas.

Recognizing the importance of understanding how these anticipated changes may affect coastal processes, many funding agencies have supported relevant research. For example, the European Union defined climate action as a cross-cutting priority in its Horizon 2020, the eighth European framework program for funding research, technological development, and innovation. Researchers and practitioners participating in this program, have been encouraged to contribute to the effort to “build resilience to phenomena such as flooding and other extreme weather events”, specifically by strengthening coastal defenses against storm surges and sea-level rise.

The last issue of Hydrolink published several articles on green coastal infrastructure, nature-based solutions for coastal protection developed to great extent in response to climate change. The current issue focuses on adaptation and mitigation measures for the coastal environment by presenting a series of articles on recent and ongoing laboratory research and field projects by leading institutions in coastal engineering.

The article by Mertens and Montbaliu offers an overview of the Climate REsilient coaST (CREST) research project aiming at improving the knowledge of the Belgian coastal system and the understanding of key processes including the interaction of hydrodynamics and sediment transport, wave overtopping and impact forces on sea defenses, as well as the natural resilience of the physical system to storms. The article discusses the evaluation of different technologies for monitoring morphological changes along the beach, the incorporation of key physical processes in numerical models that were used in parallel, and physical model studies of wave dike interaction at two hydraulic laboratories.

The article by Sterckx et al describes a program that tested and evaluated three ecosystem-based coastal stabilization solutions in terms of their erosion protection efficiency and their added long-term ecological value. The underlying concept of the tested solutions was the creation of new habitats in the form of biogenic coastal reefs, which would induce natural accretion of sand, attenuate storm waves and reinforce the foreshore against coastal erosion, thus, adding to coastal protection. Reefs formed by tube-building polychaetae worms, seaweed and seagrass, and mussels and oysters were evaluated as part of this project.

Another type of a nature-based solution is presented in the article by Fordeyn at al that presents a soft coastal protection design for the Prins Hendrik polder on the island of Texel in the Netherlands. The key element of the design to protect the polder was the landscaping of a dune seaward of the existing coast. The described project integrated coastal protection with nature development, public services and recreational appeal and enhanced recreational and ecosystem services.
The article by Goseberg et al argues that a deeper understanding of processes and effects is needed in order to provide timely and accurate knowledge-based policy recommendations. This is the conclusion of the authors based on their experience from two research projects along the coast of Lower Saxony in Germany. The first project includes the effort to parametrize the processes involved in wave attenuation and soil stabilization provided by coastal vegetation, and the search for seeding-mixtures and maintenance routines that would increase food supply for insects and enhance the aesthetic value of the area through greater flower color diversity, while maintaining the resistance to the mechanical stresses from wave run-up and breaking. The second project consists of field and laboratory investigations on the effects of oyster reefs on waves and currents.

The article by Gironella and Altomare focuses on the protection of urbanized coastal areas, which include two thirds of the world's largest cities. It describes the research project DURCWAVE, whose objective is to define new design criteria for wave action by modelling wave overtopping and post-overtopping processes of urban defenses. This project, which is funded by the European Union’s Horizon 2020 research and innovation program, consists of physical and numerical modelling studies at the Polytechnic University of Catalunya in Barcelona

The article by Mori and Shimura discusses the use of atmospheric global circulation models to predict changes in mean wave height, recognizing though that a quantitative assessment of expected changes in mean wave period, direction and extreme wave conditions is still the subject of future research. The article also discusses the challenges involved in estimating the impact of climate change on storm surge and presents an example of such an estimate obtained with the combination of a long general circulation model simulation and a simple storm surge model.

Addressing the challenge of providing coastal protection in the context of climate change requires continuous support and investment in research and the needed facilities. An example of such an investment is the construction of the new Coastal and Ocean Basin (COB) at the Flanders Maritime Laboratory in Ostend, Belgium, described in the article by Troch et al, and which is expected to be operational by the end of 2021. This facility will have one of the largest hydraulic laboratory basins in the world and will be able to reproduce a range of wave, current, and wind conditions.

These articles together with those published in the previous issue of Hydrolink provide a glimpse into ongoing research efforts to develop sustainable coastal protection strategies and mitigation measures in anticipation sea-level and more severe storm surge and wave action caused by climate change.

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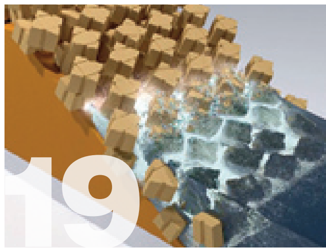

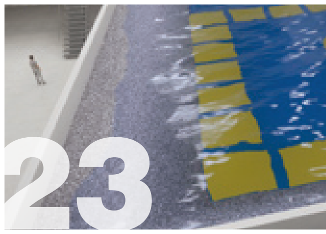

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CREST – CLIMATE RESILIENT COAST
RESEARCH HIGHLIGHTS WITH APPLICATIONS AT THE BELGIAN COAST

BY TINA MERTENS AND JAAK MONBALIU

On 24 September 2019, the IPCC presented the release of their new Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) in Monaco. Although purely by coincidence, the CREST team presented in their final conference on 26 September 2019 in Ostend, the highlights of 4 years of study on the physical system of the Belgian Coast http://crestproject.be/en/crest-final-conference

The Belgian coast is only 67 km long and is to a large extend a managed coast. It has mild sloping sandy beaches, varying from about 1/80 in the western part to nearly 1/20 in the eastern part. The coastal system is interrupted by the outlet of the Yzer estuary, a small river draining the low polder lands, by the access channel to the harbor of Blankenberge and by the break-waters of the harbors of Ostend and Zeebrugge. Also, many groins are present in the hope to keep sand in the section by reducing long shore-transport both by relatively strong tidal currents and by wave induced currents.

To protect the hinterland from flooding, either a dike or a dune system is present. Heavy storms in the past have eroded the dune foot and, in some sections, a hard dune foot protection has been constructed. Since the 1990's a protection policy of "soft if possible, hard if necessary" has been advocated and sand nourishment has been put forward as an effective measure against storm attacks. To ensure coastal safety, the Flemish government invests since 2011 in the implementation of the Master Plan for Coastal Safety.

Despite the fact that sand supply is an old and widely used protection technique, the design and the implementation of an efficient and sustainable nourishment is still a big challenge. Moreover, it is food for a public debate. Recent storms with high surge levels (in particular Xaver in December 2013 and Dieter in 2017) induced sharp and relatively high erosion cliffs and have led to critique in the media of having sand (and money) thrown into the sea.

To improve the knowledge of the Belgian coastal system, researchers from knowledge institutes and private companies with great interest and expertise in physical coastal processes joined forces in 2015 and set up the CREST project.

Figure 1. Sand cliff on a nourished beach after a storm

The main scientific objectives of this program included improving the understanding of coastal physical processes, of flood risk and impact, and of coastal resilience on the one hand, and on the other hand the more practical aspects of validating state of the art models with experimental data and defining climate scenarios for the Belgian coast. The most acute knowledge gaps identified in the physical system were: 1) the interaction of hydrodynamics and sediment transport at various spatial and temporal scales, 2) wave overtopping and wave impact forces on sea defenses including the risk for casualties in buildings on the sea dike for the specific case of a shallow sandy foreshore, and 3) the natural resilience of the physical system of the Belgian coast to storm impact.

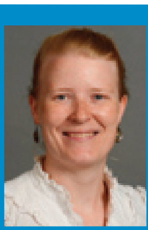
For the final conference, held on 26 September 2019, the CREST results were summarized in several take home messages and presented to the public along four themes: 1) climate change including morphological evolution on long time scale (decades) for the Belgian coast as a whole; 2) morphodynamics on time scale of days (storms) to years (lifetime of nourishments) for two pilot areas; 3) physical processes and innovation in modelling; and 4) wave-dike interaction. We illustrate a number of the take home messages below, for the full list and more detail the reader is referred to http://www.crest-project.be/sites/crestproject.be/files/public/CREST_TAKE%20HOME%20MESSAGES_EN.pdf linked from the homepage http://www.crest-project.be/en

THEME 1: Climate change including morphological evolution on long time scale (decades)

During a workshop in December 2018, organized by several stakeholders including CREST, it became quickly clear that *coping with long-term climate change involves many uncertainties* (http://crestproject.be/en/imis?module=ref&refid=311027).

A large contribution to the uncertainty regarding climate change is related to the uncertain worldwide climate policy development. Another large contribution to uncertainty is caused by the lack of knowledge on the possibility of rapid ice cliff failures in Antarctica. To support policy development, four climate scenarios for 2100 for the Belgian coast were defined in collaboration with research teams from all Belgian research institutes and universities. Three scenarios are based on IPCC (RCP2.6, RCP4.5, RCP8.5), and one scenario is based on the worst-case assumption of the most rapid failure of land ice, considered remotely possible. For sea level rise the four scenarios for 2100 predict respectively +50 cm, +60 cm, +85 cm and +295 cm rise compared to the 1990 sea level. Depending on the problem to be addressed, the time horizon put forward, the stakes at risk and the stake-holders involved, a balanced decision will have to be made and the appropriate tools will have to be used.

CREST showed that using the wind fields from climate model projections to estimate wave conditions and storm surges in the Southern North Sea, and assuming that the coastal



Tina Mertens is the vice-director of the Flanders Marine Institute. She has strong interest in the many different aspects of coastal protection.

Jaak Monbaliu is a professor in the Civil Engineering Department of the KU Leuven. His main research interests are in the broad field coastal and estuarine hydraulics.

Tina Mertens and Jake Monbaliu were the co-ordinators of the CREST project.

bathymetry will not change, extreme wave conditions and storm surges are not expected to change much by 2100. However, they will have a much larger impact because of sea level rise.

The Belgian coast is monitored on a regular basis over more than 30 years. This monitoring consists of two overlapping survey parts: the underwater bathymetric monitoring and the above water topographic monitoring. Together they cover a coastal strip of 1.5 km in width. This dataset was used to study the changes in the cross-shore profile from the sea to the coast. A sand balance was established for the active zone, from the top of the dunes or dikes to the depth of closure. Observed volumetric changes of the active zone were corrected for the sand works that were carried out, namely nourishments and dredging works near the harbors. For the Belgian coast as a whole, the result of this analysis shows a natural sediment supply from off-shore of the same order of magnitude as the artificial supply from nourishments (0,5 Mm^3/year or if it would be evenly spread over the entire length of the coast ~7.5 m^3/m/year). *This natural supply has contributed to the soft coastal defense.* However, this natural feeding is very variable along the coast. In the western and eastern part of the coast a net natural supply is observed, while in the central part of the coast a net loss has taken place. The middle coast has only been able to keep its ability to withstand storms thanks to nourishments. It is not fully clear why there is in total a net gain of sediments (more than supplied by nourishment) in the monitored coastal system. This needs further study to understand the impact on the more offshore coastal system which is characterized by sand banks and tidal gulleys on the sea floor. On decadal time scale the Belgian coastal dunes grow linear in time with a constant rate. Dune growth varies between 0 and 12.3 m^3/m/year with an average dune growth of 6.2 m^3/m/year, featuring large variations in longshore direction.

THEME 2: Morphodynamics on time scale of days (storms) to years (lifetime of nourishments)

During the CREST project several technologies were tested and evaluated to monitor beach morphology and it is clear that *the technology to follow evolutions in beach morphology is available.* Permanent static terrestrial laser scanning (PLS) allow for frequent scans (better than hourly) of the dry and intertidal beach with vertical accuracies better than 2 cm. A mobile LiDAR vehicle with RTK-GNSS in combination with an accurate inertial system (IMU) gives accuracies better than 1 cm at very high spatial resolution. Also, some unmanned aerial vehicle (UAV) photogrammetric surveys were obtained. In combination with traditional airborne LiDAR and ground surveys they can provide a wealth on topographic data to monitor and study beach morphology.
Dune growth is primarily caused by aeolian sediment input from the beach during west to southwest wind conditions (Figure 2). Transport rates depend on humidity and sheltering effects, but potential transports are relatively well quantified by a modified Bagnold type expression. The details of aeolian transport are quite complex, especially in the zones where there are steep cliffs. Such cliffs are typical after a winter storm (Figure 1) and for the chosen beach nourishment configuration of sand storage berms in front of the dyke.

Providing sufficient sand on the beaches not only strengthens the beach itself, but also contributes to strengthening the dunes. The increased replenishment efforts of the past years have realized permanently wider beaches on nourishment locations. Like with all beach nourishments, erosion rates increase initially, yet after a few years return to the long-term average. The wider beaches enhance the coastal safety level, the touristic use and resilience with respect to sea-level rise.
After a storm, our beaches recover at least partially, and this within a period of barely a few months. The storm Dieter in 2017 caused severe erosion and large sand cliffs at several locations along the Belgian coast. It is well known that beaches recover at least partially after storm disruption. This was also observed on a beach with dike section that was monitored more intensively during CREST. Five months later already one third of the eroded volume was recovered.

THEME 3: physical processes and innovation in modelling

Taking fundamental processes better into account is a good basis for understanding and simulating the patterns of coastal sediment transport. Sediment transport modelling in coastal areas remains a challenge, for example because of the variation in sediment characteristics (e.g. sediment size, sediment composition, cohesive properties, consolidation state) and variation in forcing conditions (storm conditions versus calm weather conditions). Many empirical transport formulations exist, each with its own range of applicability. It is believed that the next real step forward should be a better representation of fundamental processes in the sediment transport formulation. One of these processes is the energy dissipation due to sediment motion, which usually is not taken into account in turbulence closure models. During CREST, it has become clear that modeling of the particle-turbulence interaction needs a physics-based turbulence closure to model accurately sediment transport rates (sediment fluxes) in flows with high concentrations typically found close to the bottom.
It became also clearer that the road to efficient and accurate design of the optimized coastal defense systems of tomorrow involves a variety

Figure 2. Aeolian sand transport campaign. On the foreground three Modified Wilson And Cook (MWAC) sand traps are visible. Author: Glenn Strypsteen.

of tools. When dealing with wave overtopping processes such as overtopping volumes or wave forces on structures, there is no optimum model which can deal with the multi-scaled aspects at the same time. In order to provide a solution for real applications, coupling between numerical models can be employed, which enables complex modelling in an efficient and accurate way, taking advantage of the strengths of an individual model while avoiding limitations of the others. For example, the SWASH model can simulate wave transformation in very efficient way while it cannot deal with complex wave-structure interaction. The coupling of DualSPHysics and SWASH allows modelling both the wave transformation and the wave-structure interaction and attains a compromise between results accuracy and computational effort.

The FLIAT (Flood Impact Assessment Tool) model developed under CREST provides a solid basis for hinterland flood risk calculations (Figure 3). The model is cloud based with an object relational approach and allows a more accurate cost-benefit analysis of infrastructure adaptations for flood protection compared to other currently available approaches. It includes special features such as recognition of critical infrastructure and vital functions.

THEME 4: wave-dike interaction

Extensive laboratory tests to study wave impact on beach-dike configurations typical of the Belgian coast have been carried out (Figure 4).

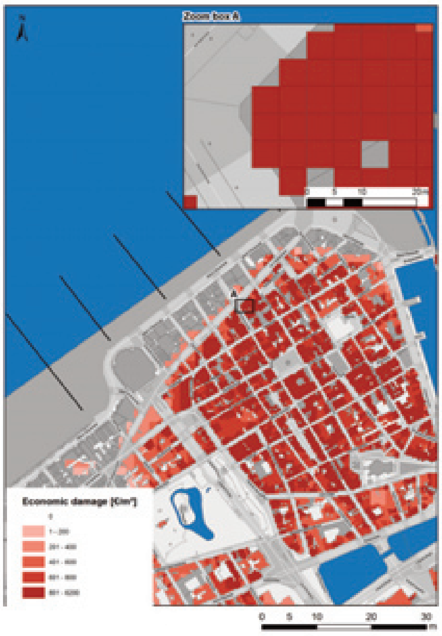


Figure 3. Flood risk calculation using the FLIAT model

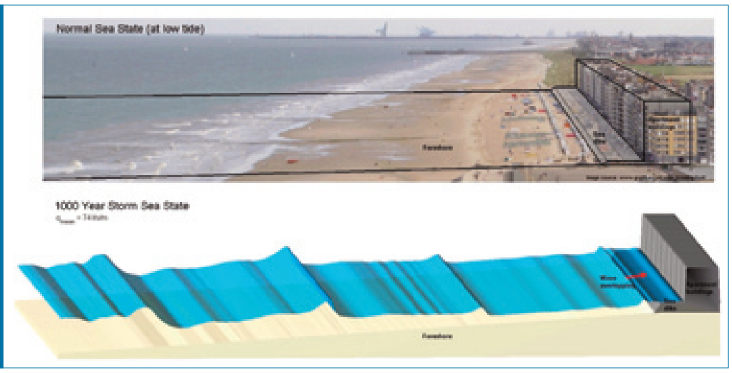


Figure 4. Testing the impact of a 1000-year storm event on a typical beach-dike configuration at the Belgian coast.

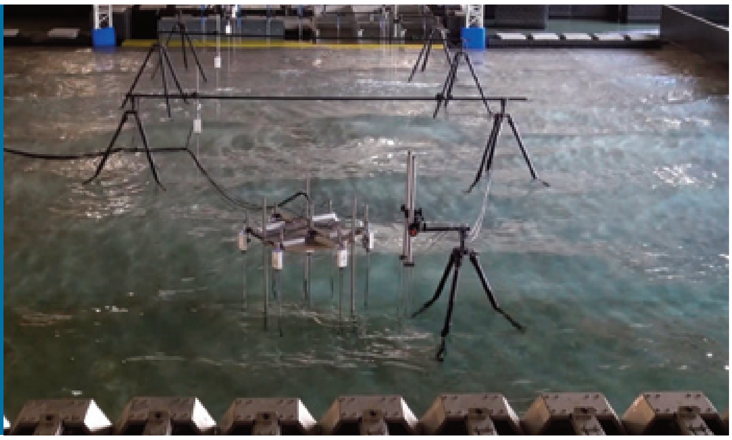


Figure 5. Directionally spread and oblique wave experiment in the wave basin at Flanders Hydraulics Research

In the wave flume of Ghent University (L x W x H: 30.0 m x 1.0 m x 1.2 m) storm conditions have been tested for four different beach slope angles (from mild to steep: i.e. 1/80, 1/50, 1/35 and 1/20) to investigate the effect of the foreshore slope angle and infragravity waves on the response (wave overtopping, wave impact) of sea dikes with very shallow to extremely shallow foreshores. For the same storm conditions a lower wave impact was measured for wider beaches and *it was concluded that wider beaches (lower slopes) reduce the impact of waves on dikes.* Infragravity waves play an important role. More energetic infragravity waves increase the wave impact and this further intensifies with steeper foreshore slope angles.

In the wave basin of Flanders Hydraulics Research (with an effective model area of L x W x H: 20.0 m x 12.0 m x 0.55 m) the effect of directional spreading and oblique wave incidence on wave overtopping and wave impact was tested for several storm conditions (Figure 5). Directional spreading was found to significantly reduce the wave overtopping and impact.

A large-scale experiment performed in the Deltares Delta Flume within the Hydralab+ WALOWA project allowed to investigate scale effects and provide experimental data for the validation of numerical models. Scale effects were found to be negligible compared to the uncertainties related to non-repeatability and model effects. Such large-scale experiments are invaluable for the validation and the inter-model comparison of numerical models. Measurements of flow velocity on the promenade and pressure array and load cell force measurements along the dike mounted vertical wall are currently being compared to output of three numerical models (OpenFOAM, DualSPHysics and SWASH). ■

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COASTBUSTERS: NATURE INSPIRED SOLUTIONS FOR ECOSYSTEM BASED COASTAL MANAGEMENT

BY TOMAS STERCKX, EMILE LEMEY, MARC HUYGENS, JAN FORDEYN, BERT GROENENDAAL, ALEXIA SEMERARO, THIBAUD MASCART & KOEN VAN DOORSLAER

Conventional coastal protection solutions such as dykes and embankments are increasingly being challenged by changes in sea level rise, more aggressive climatic conditions, land subsidence, beach erosion etc. Maintenance of these conventional structures is becoming challenging; hence, innovative alternatives are necessary to guarantee coastal resilience.

The Coastbusters project aims to develop three nature-based solutions for sustainable coastal protection. These solutions will create new habitats based on known 'biobuilder species' in the form of biogenic coastal reefs. The purpose of the reefs is to induce natural accretion of sand, attenuate storm waves and reinforce the foreshore against coastal erosion, thus, adding to coastal protection. Three key biobuilding concepts were identified to be tested to strengthen conventional coastal engineering: (1) Tube-building polychaete worm reefs (Lanice conchilega), (2) Marine flora fields (seaweed and seagrass) and (3) Bivalve reefs (mussels and oysters).

Based on a critical assessment of the actual state of the art, adapted innovative designs were evaluated in an integrated feasibility analysis prior to further step up pilot projects in the field. The created biostabilisation power of the biogenic reefs was tested in both laboratory experiments and in-situ pilot projects along the Belgian Coast. For each of the three concepts, the goal is to find environmentally friendly ways to stabilize the shoreline and minimize local erosion by using an ecosystem approach. As for each of the three concepts the same ìsuccessî criteria are formulated, a uniform monitoring and evaluation approach is set up in an integrated way.

Introduction

Adverse effects of global changing conditions associated with natural disasters and climate change are currently indisputably present. Under current climate change scenarios, it has been estimated that along low coastlines, almost 30% of residences, if sited within 200 m from the sea, may be severely affected by erosion-related property losses over the next 50 years [15]. Societies across the world are facing the need to adapt to safeguard valuable resources and to reduce the vulnerability of communities to an increasingly uncertain future. To this end, classical engineering solutions, such as conventional hard coastal protection solutions (e.g. dykes, breakwaters and embankments) to attenuate waves and reduce erosion, have been applied. In the context of coastal protection, these hard stabilization structures are currently severely challenged in many locations and their value is questioned due to their costly and continual maintenance requirements, as well as, their relative lack of flexibility to any widening and height increase to keep up with the increasing coastal erosion risk. Additionally, such structures significantly alter the natural adaptive capacity of any coastline.

Under present and future environmental conditions, the world requires smart coastal protection strategies that are, sustainable, multifunctional and economically viable to help solve immediate and predicted coastal erosion and inundation problems. Coastal lowlands such as Belgium and the Netherlands are considered among the most vulnerable to sea level rise and related inundations. Moreover, sea level rise and the increased likelihood of severe storm surges are projected to be the highest in the tidal North Sea region, where both countries lay. These climate change effects may also worsen coastal erosion, a problem which already affects a large part of the Belgian coastline. In addition to these morphological aspects, the socio-economic characteristics of the Belgian coastal zone make the area vulnerable to flooding due to the increasing numbers of people and economic assets near the coast.

The Belgian coast until the late 1960's has been protected by hard coastal defence schemes (sea walls, groynes, breakwaters). Since then, awareness has grown that these hard structures have a negative effect on the stability of the dynamic coastal system and can induce erosion of the foreshore. Gradually, soft engineering solutions, such as beach nourishments have been adopted to safeguard the natural dynamics of the coast giving the beach a typical profile prone to dune erosion and subtidal beach accretion during storms events.

Newly developed policy frameworks on innovative engineering solutions supplementing existing conventional coastal protection solutions are being promoted. Amongst others, this has led to recommendations to create or restore natural habitats, providing coastal protection in place of (or complementing) artificial structures [4]. Such ecosystem inspired approaches are based on the creation and restoration of existing coastal ecosystems, such as natural vegetation (e.g. mangroves, salt marshes, seagrass beds and dune vegetation) and biogenic reef structures (e.g. corals, oysters, mussels and tube building worms). Natural coastal ecosystems have some resilience capacity for self-repair and recovery, and can provide significant advantages over traditional hard engineering approaches against coastal erosion (Gracia et al 2017).

This global need of novel ecosystem-based coastal defence solutions to protect shore communities and associated infrastructure is inevitable [10], [11]. The above mentioned naturally occurring ecosystem engineering or biobuilding species have the capacity to reduce storm waves [1], [12] and storm surges [14], [16], [17], and can keep up with sea-level rise by natural accretion of mineral and biogenic sediments [5], [9]. Henceforth, the Coastbusters project, presented in this article investigated three ecosystem-based coastal stabilisation solutions using biobuilder species, which have the capacity to positively influence their surrounding environment through their own biogenic structure [3].

This project fits within the vision for further development of the Belgian coastal zone, which is under way, aiming at the integration of safety, natural values, attractiveness, sustainability and economic development including navigation and sustainable energy. The project was awarded an innovation grant from the Flemish government in March 2017 and runs for 3 years. This article describes the selection process of the concepts including their design, development (from laboratory tests into a pilot scale setup in front of the Belgian coast), deployment and monitoring.

Nature based solution design

The Coastbusters consortium leading this 3-year project consists of Dredging experts (Jan de Nul and Dredging International - DEME group), a textile manufacturer (Sioen industries), a marine consultant (eCoast) and a research institution (Institute for Agricultural and Fisheries Research, ILVO). The Southern part of the North Sea at the Belgian Coast, nearby the Broersbank sandflat (ca. 51°07,11'N – 002°34,45') has been chosen to test the concepts of biogenic subtidal reefs using "biobuilder species". The dimensions of the installations within the testing zone will be approximately 100m² per concept.
The Coastbusters project tests the ecosystem resilience, survivability and reef building capacity of three biobuilder types: (1) Bivalve reefs (*Mytilus edulis*), (2) marine flora reefs (seaweed and seagrass) and (3) reefs of tube-dwelling sand mason worms (*Lanice conchilega*) (Figure 1).

To test those nature-based solutions, suiting substrates or sockets are being used or specifically developed. The following innovative designs have been put in place to speed up/stabilize the formation of each biogenic reef type:

1 For the bivalve reef field test, a specific socket method (based on aquaculture technique) was used in combination with a string of 40 shellfish bags (artificial structures) as a substrate for colonisation. The deployment can be seen in Figure 4A.
2 For the flora reef field setup Coastbusters installed three reef concepts, parallel to the coastline, using bags and frames with innovative seeded textile bags (Algaetex ®Sioen) as a substrate. The in-field setup comprised four bags and two frames per reef as shown in Figure 2 and Figure 4B).
3 For the *Lanice* reef concept ex-situ tests in laboratory conditions were performed prior to in-situ tests. In the laboratory *Lanice* juveniles were cultivated to test several recruitment substrate prototypes in a Kreiseltank (see Figure 4). For the in-situ tests several artificial structures with protruding tubes at the beach were used, simulating a *Lanice* reef for efficient recruitment adding to coastal protection (See Figure 4C).

The main goal of this project is to find alternative, environmentally friendly ways to stabilize the shoreline and minimize local erosion by using an ecosystem approach. The use of biostabilisation – biological processes to increase sediment stability – or to reduce the potential for erosion by tidal currents and wave action can be a cost efficient and sustainable way to obtain a safe and resilient coastline. This alternative or addition to recurrent sand nourishment will influence the natural ecosystem of the beach in a positive way.

For each of the three concepts, the following goals were identified: (1) the organism survives the dynamic conditions of the foreshore and maintains its ecological functions, (2) the reef, built as a specific biogenic structure, is stable and creates ecological added value within the local coastal ecosystem (ecosystem services), and (3) the natural reef develops in such a way that local sedimentation and natural stabilisation of the foreshore occurs (adding to coastal protection).

A uniform monitoring and evaluation approach is set up to verify for all three concepts whether the goals are being reached.

Three ecosystem based coastal stabilisation solutions

Coastbusters tests three concepts of biogenic subtidal reefs using "biobuilder species" as an alternative to conventional coastal engineering in the field, where up to now theoretical concept-validation is lacking and where ecosystem services will be used to validate the tested field setup. In 2018, all three reefs were successfully put in place (see Figure 7 illustrating the deployment) and monitored over the duration of the 3 year project.

Bivalve reef

The on-seabed present *Mytilus edulis* reef building socket and detached clumps of organisms are currently modifying the erosive character of the foreshore stabilizing the bed and attenuating the hydrodynamic energy of the waves, whilst accumulating sediment on the foreshore. In addition, mussel beds or other reef building species beds enhance biodiversity by providing shelter and nesting area for fish and crustacean species (e.g. crabs and shrimps). Further, mussels and, for instance, oysters are filter feeders filtering algae from the water column for food. By doing this they clarify the water by removing not only algae, but also silt and organic particles from the water column [2]. This additional ecosystem service makes the bivalve reef a worthy ecosystem based coastal stabilisation solution.

Flora reef

Sugar kelp (*Saccharina latissimi)* supports high primary productivity, magnifies secondary productivity, and creates a three-dimensional habitat structure for a diverse array of marine organisms, many of which are commercially

Figure 1. Coastbusters' logo (l) and 3 conceptual reef building ecosystem engineers

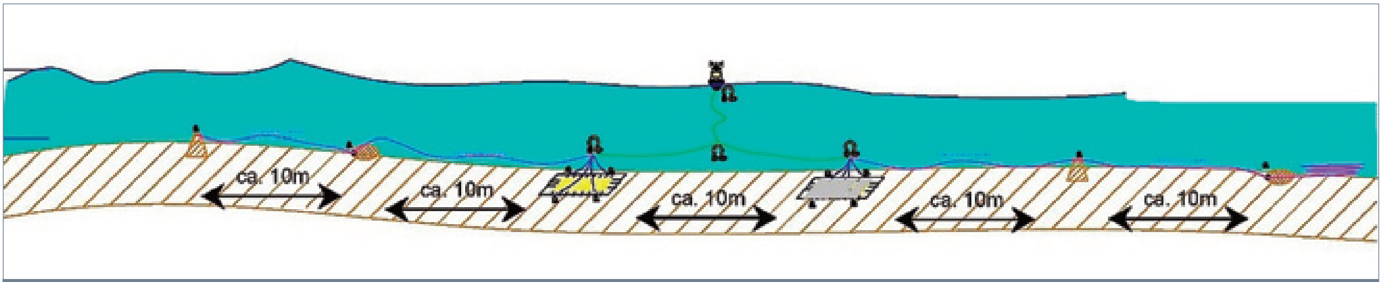

Figure 2. Flora Reef in-field test setup of impregnated seaweed Saccharina latissima seed bags and frames (m)

important. In addition, it has bio-remediation potential through filtering dissolved nutrients from the water column. These ecosystem services make the flora reef a good bio-builder, however it exhibits pronounced spatiotemporal variability and does not consolidate sedimentation. Kelps (and in extension seaweeds) need a hard substrate (natural or artificial) to develop. Consequently, the ecosystem services from the kelp flora reef are not primarily coastal protection but in combination with other reefs, these reefs can increase the overall ecosystem services delivered. In contrast, other types of flora reefs, like seagrass-based reefs have added value by enhancing sedimentation, hence, coastal protection. However, seagrass-based reefs require specific physical conditions, which might not currently be present at the Belgian coast.

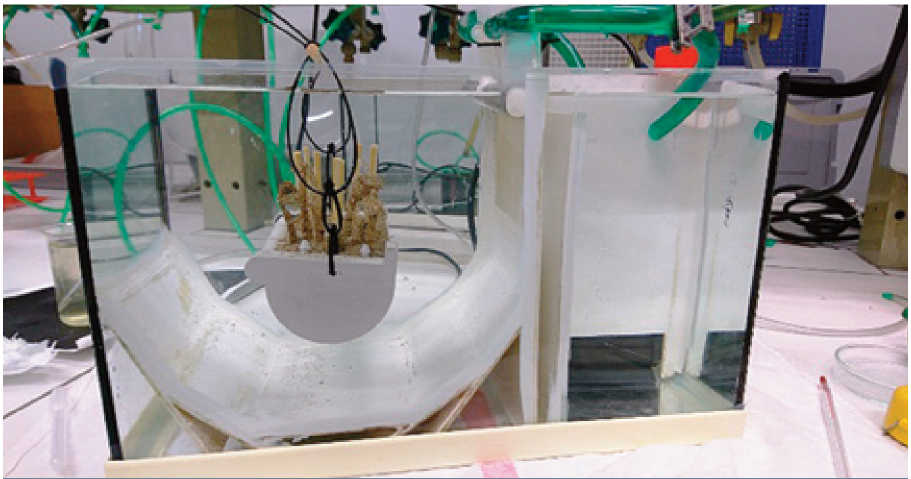

Figure 3. Lanice Reef laboratory set-up using Lanice juveniles in a Kreiseltank.

Lanice reef

The physical reef characteristics of *Lanice conchilega* have been proven to consolidate sediment deposition within the biogenic reef and thus provide coastal protection. In addition, the biological community structure of associated fauna will presumably increase within the aggregations, thus showing a positive correlation and increase of macrobenthic fauna, which are feed for adult and/or juvenile fish in commercial fisheries. However, those biogenic aggregations are ephemeral, unless existing aggregations are renewed annualy through juvenile settlement. Hence, the spatial extent and patchiness of the biogenic reefs might fluctuate over time, presenting varying ecosystem services over time. Therefore, site selection is primal to ensure continuous juvenile settlement to create large self-sustaining *Lanice* reefs with optimal densities to fulfil their ecosystem services.

Conclusion

This work presents examples of three nature-based pilot projects aiming to enhance coastal protection by making use of bio-builder species. The drawback is that most suitable ecosystem engineering species depend on the specific site characteristics, for instance location, wave action, tidal height and sediment grain size, and other biological characteristics, such as species life-traits and ecology. Thereby, not all coastal locations are suitable for each type of reef. In addition, extreme events such as storm surges, might harm ecological systems to such an extent that returning to a state valuable for coastal protection can prove troublesome, or impossible. Information on resilience of specific engineering functions of species is lacking [8], meaning that use of engineering species for coastal protection requires systematic and continuous monitoring, to support and quantify claimed ecosystem services on longer spatial and temporal scale.

Figure 4. In-field installation of mussel *Mytilus edulis* socket (A), impregnated seaweed *Saccharina latissima* seed bags (B) and sand-mason worms *Lanice conchilega* (C) for induction of biogenic reef formation, respectively, Bivalve, Flora and *Lanice* reef.

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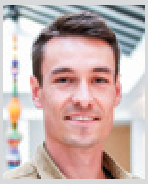

Emile Lemey works as Project Development Engineer at Jan de Nul Group. His background is in Bioengineering and Marine conservation. At Jan De Nul he has focused on nature based solutions projects in which ecological considerations are an essential part of the design phase. He worked as Environmental Engineer on the Coastbusters project during the realisation phase.

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Jan Fordeyn studied at the University of Ghent and graduated as a naval architect in 1994. Since 2007, he helps develop projects around the world that fall outside the classic canon of marine construction and whose result relies on the symbiosis of different disciplines. As such he maintains close relations with experts, consultants, universities and manages several innovation projects.

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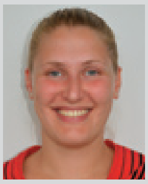
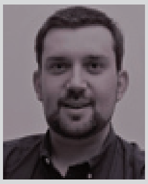
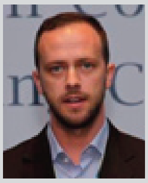


Alexia Semeraro studied Marine Biology at the University of Ghent (International Master of Science in Marine Biodiversity and Conservation). She's a young researcher at Flanders Research Institute for Agriculture, Fisheries and Food (ILVO) in Ostend working on the Coastbusters project.



Dr. Thibaud Mascart works as Environmental Engineer Marine Ecosystems within the DEME group. He is currently implementing environmental enhancements & mitigation measures for dredging contracts, deep-sea mining and off-shore installations across the globe. As marine seagrass biologist he advocates smart environmental protection and restoration of sensitive marine environments through innovative nature-inspired solutions. Within the Coastbusters project, he facilitates the academic-private partnership and focusses on the design and modularity of the biogenic reef, enhancing multiple ecosystem services.



dr. ir. Koen Van Doorslaer works as a design manager coastal engineering within the DEME group. He is currently involved in the project 'New Lock Terneuzen' where he is responsible for the design of the flood protection, dredging works and scour protection. He graduated his PhD on the reduction of wave overtopping to improve the stability of our coastlines. In Coastbusters, dr. Van Doorslaer is involved in the technical team designing the stability of the reefs and focusing on the impact of the reef on waves, currents and beach stability.

The main advantage to traditional (soft or hard) engineering is that the latter are generally over dimensioned and static, hence not responding to fast changing conditions. Integration of nature-based solutions into coastal protection allows a dynamic interaction between organisms and the natural evolution of the coastal system. In case of sea-level rise, nature-based solutions may be used to avoid if possible, and if not, delay the need for massive engineering measures for coastal protection.

Thereby, organisms that trap sediment to keep up with long-term sea level rise may provide a long-term sustainable protection and might, at least locally, reverse or delay ongoing trends. Moreover, given the adaptive abilities of ecosystem engineering or bio-builder species, solutions could be less over-dimensioned compared to traditional engineering solutions, which reduces costs during deployment, monitoring and maintenance. Thorough knowledge of ecosystem functioning, and ecosystem-based management is needed to make this approach successful [7].

To conclude, Coastbusters tests ecosystem-based coastal stabilization solutions to demonstrate their coastal protection efficiency and ecological added value on a large scale and long term. Nevertheless, Coastbusters is sharing best practices on design, development, deployment and monitoring adding pioneering knowledge in terms of emplacement, hydrodynamics and life-trait requirements of proposed nature-based solutions. In addition, Coastbusters aims to answer existing and future coastal protection challenges, driving to promote nature-based coastal engineering as the way forward to integrate multiple social, economic and environmental functions into innovative coastal resilience management. ■

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A HOLISTIC APPROACH TO COASTAL PROTECTION FOR THE PRINS HENDRIK POLDER

BY JAN FORDEYN, EMILE LEMEY & LUITZE PERK

The Prins Hendrikzanddijk project on the Dutch island Texel is an integral project where flood defence is combined with nature development, public services and recreational appeal. Seaward of the existing dike, a dune is landscaped to act as primary coastal protection. The existing dike thereby loses its main function but remains in place as a scenic element.

Instead of using a classical engineering design approach, the inclusion and enhancement of public, recreational and ecosystem services were the focal point of the design.

A unique and dynamic nature reserve with dunes, salt marsh and beach in front of the current dike was designed, with the goal of upgrading some 200 hectares of the Wadden Sea coastal area (UNESCO World Heritage Site). Central to the design are the interactions between ecology and sediment dynamics. In traditional hydraulic engineering, there is a trade-off between safety and ecological value, and between sediment stability and dynamics. Coarse sand resists erosion better, but provides a less suitable habitat for benthos, which makes the area less attractive to wading birds.

Therefore, the target species and habitats were analysed, and sediment characteristics chosen accordingly. A specific strategy of including fine sands to stimulate benthos growth was applied. Other strategies for habitat creation included salt marsh recuperation and seashell patches. The design further dealt with the trade-off between recreational opportunities and the natural habitat disturbance, and between the dynamics of soft coastal protection and the lifetime of public functions. Project specific key performance indicators are assigned and monitored during construction and a five-year maintenance period.

This paper presents a nature-based solution for enhancing a coastal defence system while maximizing the ecological value of the area. A soft design is laid out, where safety, nature, recreation, agriculture and public services come together.

Introduction

Need for action

Primary water defences (dikes, dunes, storm surge barriers, etc.) absorb the forces of the sea and can protect urbanized coastal areas against floods. In the Netherlands, these structures must satisfy the safety standards defined in the Waterwet (the flood defence act). The design conditions of these standards are periodically adapted to recent knowledge and insights (Loucks & Van Beek, 2005).

The Dutch administrators for water defence structures check the strength of the primary water defences against the safety standards every 6 years. When certain sections are no longer compliant with the standards, corrective measures are implemented. During the review process in 2007, more than 70% of the 24-kilometre-long Wadden Sea dike on Texel Island failed to meet the standards. 14 km of the dike had been upgraded without altering the visual aspect of the dike. Width and height increased, and a new asphalt and stone cover was applied on the seaward slope. The subject of this paper is the refurbishment of section 9, the 3.2-kilometre-long dike, that protects the Prins Hendrikpolder, which harbours agricultural land, houses and nature reserves.

Hard versus soft coastal protection strategies

(Sub-) littoral sandy sediments, sandy beaches, and sand dunes offer natural coastal protection. Despite their importance, these sandy 'soft' defences have been lost in many European coasts due to the proliferation of coastal development and associated hard engineering. They also face further losses due to rise in sea-level, subsidence, storm surge events, and coastal land claim due to urban development (Hanley et al. 2014).

In order to protect the coastal erosion, hard coastal protection structures are often used. They consist of rigid or semi-rigid structures constructed along or in front of the coastline to resist deformation from wave or current action, either at the dune foot, intertidal beach or seabed. Hard coastal protection structures fall into the categories of sea dikes, seawalls, revetments, groynes and offshore breakwaters (IADC, 2017).

Although these hard-coastal protection structures are effective in stabilising the coastline, they offer a one-sided solution focussing only on protecting the land behind it from water action, while largely ignoring the characteristics of the water system (Van Slobbe et al. 2013). They have an immediate impact on local biodiversity and alter local hydrodynamic regimes, which in turn affects sediment supply, deposition and grain size. These alterations have an impact on both the soft-bottom sublittoral ecosystems and the beaches (Hanley et al. 2014). Existing dike revetments are classic examples of hard coastal protection.

Soft coastal protection strategies replicate the natural defence systems with locally available natural material to secure and restore the coastal dynamics and their flexible nature (IADC, 2017). They are based on careful observation and replication of these natural defence systems (Fordeyn et al, 2012). Restoring or reintroducing soft coastal defences was an opportunity to use a nature-based solution to upgrade the coastal protection capacity of Texel island.

Materials & methods

Project Location

The primary protection of Texel's Eastern coast has a total length of circa 24 kilometres and consists of ten sections. Section 9 is the Prins Hendrikdijk with a total length of 3.2 kilometres between the ports of Oudeschild and NIOZ. The Prins Hendrikdijk protects the Prins Hendrikpolder, which consists of agricultural land, farmhouses, and two nature reserves, Ceres and Molenkolk. Two water pumping stations discharge into the project area (Gemaal Prins Hendrik and Gemaal De Schans). These stations pump brackish water into the project area, mimicking biogeochemistry processes of an estuary system. Halfway along the dike, near the Prins Hendrik pumping station, several public services cross the project area: two water supply pipes, two high-voltage- and two data cables. In the south, the project area is bordered by the NIOZ (Royal Dutch Institu----te for Sea Research) port breakwater.

Jan Fordeyn studied at the University of Ghent and graduated as a naval architect in 1994. Since 2007, he helps develop projects around the world that fall outside the classic canon of marine construction and whose result relies on the symbiosis of different disciplines. As such he maintains close relations with experts, consultants, universities and manages several innovation projects.

Emile Lemey works as Project Development Engineer at Jan de Nul Group. His background is in Bioengineering and Marine conservation. At Jan De Nul he has focused on nature-based solutions projects in which ecological considerations are an essential part of the design phase. He worked as Environmental Engineer on the Coastbusters project during the realisation phase.

Luitze Perk is director Coast&Sea at WaterProof BV. Luitze is hydraulic engineer working with hydrodynamic and morpho-dynamic numerical models for studies in coastal areas and estuaries in different places in the world. He has contributed to different port and coastal development projects in which he quantified the effects of inter-ventions on currents, waves, salinity and morphologic or sedimentation/ erosion effects.

Characteristics of the environment

Since the Middle Ages, dikes have been erected and reinforced to protect arable land from the forces of the sea. They are mostly hard structures made up of sand and clay with an asphalt, concrete and grass cover. These dikes are in contrast with the dynamic, soft transitions that naturally occur in the Wadden Sea and with the focus of the NATURA 2000-management plan Wadden Sea 2016-2022. The core assignment of the project was to maintain or restore the spatial cohesion of deep water, gullies, creeks, shallow water, salt marshes, tidal flats, beaches and dunes, and the related sedimentation and erosion processes, as well as the related biological communities.
Situated east of Texel island, the Texelstroom is one of the important tidal channels connecting the Wadden Sea with the North Sea. In between the Prins Hendrikdijk and the channel lies a shallow plateau between MSL+0 and MSL-2 meter of circa 400 meter wide. The largest waves hitting the project site originate from the North Sea, propagate through the Schulpengat and Marsdiep narrows and refract toward the coast. The site is therefore relatively sheltered with a 4,000-year return period design wave height of maximum Hs = 2.7m at MSL-5m (Van Vledder, 2016).

The project area mainly consists of NATURA 2000 habitat type H1110A (permanently submerged sandbanks). This habitat type refers to shallow, relatively flat areas and gullies, where the tidal influence is more important than the wave influence from the sea. Because of the low hydrodynamic action, the sea bottom sediments are mostly muddy to fine sands. A much smaller part of the project area is composed of the important NATURA 2000 habitat type H1140A (tidal flats). This habitat type is relatively sheltered and protected from wave action. Close to the sea channel, the sediment is mostly sandy and shelly, while the sediment is very muddy at the upper end of the tidal range and close to the shoreline. The characteristics of the project area - the shallow seabed, the sheltered location and the absence of tidal flats - made it an ideal location to apply a soft coastal protection strategy.

Results

Acknowledging the potential of the site, the project owner, Hoogheemraadschap Hollands Noorderkwartier, issued a tender for the design and construction of a soft coastal defence solution in December 2016. The project was awarded to the Jan De Nul team (JDN) in September 2017. Notably the synergy of competences of both inside and outside the dredging world was vital for fitting together all the pieces of the puzzle: hydrodynamics and morphology (Waterproof and LVR sediment), marine construction (RPS), landscaping (Feddes & Olthoff), ecology (Altenburg & Wymenga), geotechnics (Wiertsema & Partners), hydrology (Artesia) and visual appeal (John Körmeling). The JDN-design is a unique and dynamic nature-based solution creating a reserve with dunes, salt marshes and beach in front of the current dike, adding some 200 hectares to the valuable Wadden Sea area that will protect the Prins Hendrik polder and provide a high quality ready-made environment for target habitat types and endangered species.

Prins Hendrikzanddijk reference design

The JDN-design did not start from scratch. Together with a list of 74 requirements, the tenderers were provided with a reference design devised by HHNK's advisor Witteveen+Bos. The reference design features a rectilinear dune that functions as the new primary defence, a nature zone with beaches and a sand spit creating a low dynamic zone north of the Prins Hendrik pumping station. On the seaward slopes a buffer layer of coarse sand is included to minimise the erosion caused by yearly average conditions. In order to minimize aeolian transport, the 20-ha surface of the safety dune is to be covered with marram grass.

Optimized design

The price correction system in the tender procedure allowed for a fictive reduction of the tender price up to 30% for initiatives that would increase the quality of the offer. Therefore, numerous changes to the reference design were considered, evaluated and implemented to maximize the added value for safety, ecology, recreation and public functions.

In the small playing field that is the project area, any change that adds value to a certain aspect has an immediate effect on other aspects. Therefore, a holistic approach to the design optimisation was chosen that was also central to the Vlaamse Baaien design (THV Vlaamse Baaien, 2009). Optimisations were dimen-sioned and evaluated based on their merit for the totality of the project objectives.

Layout and location of elements

The sand spit was shifted offshore in order to accommodate the relocated pumping station outflow and increase the size of the ecologically important sheltered zone. By shifting the outflow construction southwards, the length of the tidal stream within the sheltered area was increased, thereby increasing the size of the rare habitat where sea and fresh water meet. Two bulges were introduced in the sheltered area to guide

Figure 1. Visualization of the low dynamic zone behind the sand spit (Feddes & Olthoff)

the outflow and tidal stream into a narrow gully while simultaneously creating gently sloped salty pioneer vegetation (habitat H1310A).

Safety dune height

The crest of the safety dune was designed to the lowest allowable level for a number of reasons. First, the Wadden landscape differs from the high and steep North Sea dunes. Secondly, lower dunes do not present a visual barrier for walkers and cyclists on the dike who want to see the horizon. Furthermore, a lower crest height will induce less sand blown over the dike towards the polder. Building a low and wide dune is a robust solution for the future; if it is decided to provide increased safety in the future, the wide base of the dune could be easily heightened without further disruption to the Wadden Sea nature. However, because the two water supply pipes, data- and power cables will be buried under the Prins Hendrikzanddijk, the settlement of the surrounding soil due to the added surcharge of the safety dune, which reaches up to MSL +11 m, would cause additional stresses in pipelines and cables. To avoid this condition the design of the area of pipelines and cables was therefore adapted to the lowest allowable height from a safety perspective.

Natural character

In the optimised design the safety dune is overlain with an undulating layer that replicates the character of natural dunes. The height and size of the relief varies, creating a changing character along the length of the dune. Inspiration was drawn from the existing natural dunes at the Wadden Sea coasts of Texel and the other islands (so-called Nollen). It was found that they were different from the North Sea dunes on the islands that face dominant westerly winds, in terms of slopes, form, size, microrelief and vegetation.

Careful thought was given to variations in the transition from dune to dike. At two sections, the dune was moved seaward to create a dune valley between the safety dune and the existing dike. The first valley is located halfway along the dike near the Prins Hendrik pumping station. The increased distance between dike and dune will soften the change in surcharge and decrease tension on the waterline and cables. The second valley is located at the Ceres nature zone to enhance the visual appeal of the footpath that leads to the observation platform. Finer sand can be applied in these valleys because the wind will have little influence there. At two other locations, a connection was made between dike and dune just beneath the dike crest to accommodate the cycling path access.

The dune base and seaward slope of the safety dune was given natural contours. Along a part of the dune base, small embryonic dunes with fine sand, which can be colonized by vegetation, were added. These embryonic dunes will form the natural transition from dune to the mudflat and tidal flat. The dune will reach its maximum level near its southern and northern end in order to both increase the visual appeal to hikers and cyclists and to create a physical barrier between recreation on the dune and nature in the low dynamic zone.

Minimize Sand drift

Most state-of-the-art calculations for beach erosion in the Netherlands are developed and calibrated with the experience of North Sea beach maintenance, where wind and wave direction are close to perpendicular to the beach. Sites with a dominant offshore wind and oblique incident waves, like the Prins Hendrikzanddijk project area, are rare and therefore poorly accounted for in these formulas. Therefore, cross-shore and longshore transport was calculated with different available models such as X-Beach 1D, X-Beach 2D, Delft 3D and Longmor and supported by expert assessment.

The models predict a significant northward longshore transport along the sand spit that may in time create a sandbar across the mouth of the sheltered area. The beach at the northern edge of the project area was therefore reshaped to maximize the tidal in- and outflux of the sheltered area. The beach level was lowered to increase the area of valuable H1140 habitat and minimize drifting sands. Two measures were taken to minimize erosion and future maintenance during the lifetime of the primary defence: the Dutch shallow North Sea was combed to find the coarsest sand available and seaward slopes were adjusted to approach the natural slope for the encountered grainsize.

Minimize negative effects on groundwater

The presence of a sand body seaward of the existing dike has a beneficial long-term effect on the saline/freshwater balance in the polder due to the increased hydraulic resistance and lower seepage through the dike. In the construction phase however, temporary overpressure on the groundwater may cause instability of the dike and the nearby buildings. In the polder, the seepage of saline water may displace the fresh rainwater layer at the surface of the agricultural land, causing damage to growing crops. At Prins Hendrikzanddijk, an extensive real-time measurement system monitors changes in groundwater pressure and salinity in the dike and the polder. The surface water is captured at the seaward side of the dike by a horizontal drain installed close to the mean high-water level. At the landward side of the dike, seeping water is extracted from the first permeable layer by a series of vertical drainage wells. The depth and spacing of the wells vary along the length of the dike in accordance with the local geology. The final drainage design was based on trial tests done before the start of the project.

Safeguard operational Public Services

The water pumping station outflows were redesigned in order to ensure undisturbed drainage. The requirement of a lifelong operation of the pumping station is however at odds with the dynamic nature of the soft coastal protection and the natural aspect of the area. The outflow protection measures are made from natural materials (wood, rock) that provide a favourable habitat to marine life and allow for adjustments during their lifetime.

Conclusions

Seaward of the existing Prins Hendrikdijk coast on the Dutch island Texel, a dune was landscaped to protect the polder. The Prins Hendrikzandijk project integrates coastal protection with nature development, public services and recreational appeal. Instead of using a classical engineering design approach, the inclusion and enhancement of public, recreational and ecosystem services are made the focal point of the design. This example of a soft coastal protection strategy illustrates how many design initiatives that can be introduced to increase overall project value are often overlooked during project design. Key to this design was to steer free of the traditional engineering practice of splitting a complex project into a number of individual specific problems in different fields of competence, whose solutions are then brought together at the end. Instead, a holistic approach was chosen where every measure was evaluated in its own merit for safety, ecology, recreation and public functions and integrated into the whole solution during the design process. ■

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RESEARCH PERSPECTIVES ON ECOLOGICALLY-WISE MEANS OF COASTAL PROTECTION – CURRENT DEFICITS AND FUTURE DEMANDS

BY NILS GOSEBERG, MAIKE PAUL, DAVID SCHÜRENKAMP & TORSTEN SCHLURMANN

Throughout history and continuing into the modern age, coastal and estuarine zones have been a place of preferred settlement, for its abundant food sources, yield-rich soils, trade opportunities, and favorite climatic conditions. Population in these areas has grown significantly, hence exacerbating the negative effects that dense settlements have on the surrounding environment and coastal communities.

New elevation data, employing artificial neural networks to improve upon coastal digital elevation models (SRTM products[1]), yield a population of up to 630 million people at risk from extreme coastal water levels under a high emission scenario[2]. Numerous problems related to higher rates of population growth and stronger trends of urbanization along coastlines have been addressed revolving around waste management, sustainable transportation solutions, air/water quality, soil degradation, and so forth, applying to mid-size and mega-cities alike. The benefits coastal locations offer are balanced by the challenges driven by population growth and rapid urbanization. The onset of emission-induced climate change and related sea level rise tendencies have though aggravated the situation along the world's coastlines, since efforts to maintain and develop existing coastal defense infrastructure turn more and more costly. Coupled with sea level rise and increased storminess is the observation that up to 24% of our globe's coastlines are eroding at a rate of 0.5 m/yr or higher[3], thus increasing the pressure exerted on coastal defenses.

Ever-growing evidence suggests that sea level rise will continue for the decades to come. Depending on the effectiveness of human intervention through cuts in greenhouse gas emissions, the world's coastlines will see mean SLR relative to the mean sea level of 1986-2005 ranging between +43 cm in 2100 (RCP 2.6, "Paris scenario") to +84 cm (RCP 8.5, "business as usual scenario"). Global mean sea levels have been recently reassessed, confirming trends of 3.1±1.4 mm/yr consistent with satellite altimetry (1993-2012)[4]. The debate about the definition of "Coastal Squeeze"[5],[6] has brought attention to the detrimental effects that anthropogenically-enforced coastal landward defense and SLR plus increased storminess on the ocean side have on ecosystems and their associated services. In recent years, research has hence started to investigate the status and services of coastal and estuarine ecosystems, as well as

Figure 1. Dynamic development of natural mudflats and salt marshes in the re-opened summer polder Langwarder Groden, Lower Saxonian coast. Access is provided by log paved paths (credit Jan Visscher).

their functioning mechanisms. These questions are increasingly relevant, as communities and academia have started to debate choices of robust adaptation measures varying from “hold-the-line” to “managed retreat” approaches. Adaptation to SLR along coastlines requires a more fundamental understanding of system-wide, holistic functionalities and feed-back mechanisms, without which sustainable coastal engineering design and integrated coastal zone management cannot be done.

In this context it remains unclear how much coastal defense infrastructure benefits from regulating ecosystem services, how the interconnections between engineered structures such as dikes and natural dune systems with adjacent salt marshes and tidal flats actually depend on each other, and how co-benefits could be efficiently resourced with respect to future coastal defense developments. This article hence attempts to provide insight into a current research approach in Germany, along its North Sea coastline, aiming at *ecologically-wise means of coastal protection* that is conducted in close contact with research partners in governmental agencies, local stakeholders, and nature conservation groups in order to derive a *co-design* to implement adequate nature-based solutions in coastal protection. It covers the interrelation between existing ecosystems located in close vicinity of the coastal defense infrastructure, and also encompasses an emerging, but invasive ecosystem – a Pacific Oyster reef - in the German Wadden Sea, that has started to thrive extensively to the extent that it starts altering incoming waves and currents.

Examples of German Coastal Research

In this context, two recent examples of German coastal research showcase the increased necessity to strive collaborating across science fields. Addressing research questions that extend the scope of traditional engineering interest and contexts, such as wave run-up or subsequent overtopping on coastal dikes, demands the inclusion of relevant disciplines that provide fundamental knowledge of ecosystem functioning and species-related response to typical wave and current-induced loads and impacts. Coastal Engineering research has gradually undergone a transformation, as the following two examples of research projects testify to the change taking place.

- ***Real-world laboratories along the Lower Saxony coastline – “Gute Küste Niedersachsen”***

Scientists and decision makers in the federal State of Lower Saxony mutually agree that the named challenges can only be faced by combining coastal defence with habitat conservation and strengthening of ecosystem services and thus addressing all aspects of the socio-ecological system. “*Gute Küste Niedersachsen*” (in English: Good Coast Lower Saxony) addresses the question how such a state of well-being, i.e. a good coast, could look like and provides baseline data and process understanding to transform traditional technical coastal defence and its strategies towards a sustainable integrated management solution. Figure 1 provides an aerial impression of a typical northern German coastline with salt marsh-lined foreshores adjacent to a traditional grass-covered dike[7]; in many instances, secondary lines of coastal defence have been retained, now adding to the complexity that such protection systems exhibit.

Previous work has shown, that consideration of regulating ecosystems services such as wave attenuation and soil stabilization in coastal defence strategies is generally feasible as coastal vegetation has been proven to provide such a service under a wide range of conditions[8],[9],[10]. The required next step undertaken in the project “*Gute Küste Niedersachsen*” is to parameterise these processes for their integration in forecast models and design equations. For an *exemplary coast*, however, other habitats and ecosystem services need to be considered that may not directly be associated with coastal defence. Given the competition for space along the coast, multi-functionality needs to be considered for all parts of the coastal defence belt including dike revetments[11]. Dikes in Lower Saxony are dominated by monoculture grass revetments and solutions will be sought to improve their ecological value by adapting seeding-mixtures and maintenance routines towards a higher supply of food for insects and higher aesthetics due to increased diversity in flowering colours. The challenge is to maintain the high resistance against mechanical stress from wave run-up and breaking as requirement for a dike revetment.

Finally, coastlines requires reliable planning and approval procedures which allow efficient implementation of necessary management and construction solutions. Next to short communication pathways between and among science and decision making in this context is the communication with the civil society which needs to support the decision-making process and its results. To integrate solutions to the above challenges on the way towards an

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exemplary coast, "*Gute Küste Niedersachsen*" operates a set of real-world laboratories. Designated field sites serve as joint and sustained research work spaces in which scientists from all relevant disciplines work together with local stakeholders and decision makers to assess the efficacy and effect of novel coastal defence and management concepts in order to establish transformatory knowledge based on enhanced system understanding[12].

- ***Introduced species and their impact on the German Wadden Sea – BIVA-WATT***

The Pacific oyster *(Crassostrea gigas)* has populated most of the former existing blue mussel beds *(Mytilus edulis)* in the German Wadden Sea[13]. As ecosystem engineer, oysters build reef structures which provide food and habitat for other species (Figure 2) and ecosystem services for coastal engineering[14]. There is a strong link between energy reduction through rough seabed, shallow water conditions provided through the reef systems and local dampening of sea states, eventually impacting mainland dike infrastructure, thus ecosystem services co-regulating coastal defense functioning. Oyster reefs are extremely resistant to mechanical stress exerted through waves, currents and ice drift; their impressive growth rates hence are not slowed by mechanical disturbances. The effects of reef formations on hydro- and morphodynamics in the Wadden Sea have been so far largely ignored in research. Oyster reefs are hypothesized to have an influence on the ecological composition of the Wadden Sea, on the bathymetry of shipping lanes, as well as on the long-term terrain elevation or vertical diversity in the light of climate change. Field and laboratory investigations on the Pacific oyster and the blue mussel under hydrodynamic load are the focal point of a current research project including experimental investigations, focussing on the effects of oyster reefs on waves and currents. Methodologically, the research questions are addressed using field studies to determine relevant distribution patterns and geometric parameters, laboratory investigations on wave and current effects, as well as conceptual work on the future numerical modelling of relevant processes. Considerations are made on the parameterisation of rough reefs and blue mussel beds for the experimental investigations. To this end, ecological parameters, such as abundance distributions, coverage rates as well the location of selected oyster reefs and mussel beds are determined and digitalised by 3D scanners. Based on this data and a parameterised characterisation, appropriate production methods for manufacturing laboratory specimen involving a digital building fabrication laboratory (i.e. a CNC-controlled milling and printing of concrete) for the models are investigated in terms of their suitability. Roughness and wave dissipation parameters are obtained for use by coastal engineers and authorities in numerical modelling including the growth state variation and spatial distribution of oyster reefs, which are necessary to answer hydrodynamic and morphodynamic issues.

Figure 2. Pacific oyster patches and close-up of individual oysters functioning as ecosystem engineer (credit: Nils Goseberg)

Conclusions and Outlook

Ecologically-wise means of coastal protection are required along densely populated and urbanized coastlines and demand answers and insights that are not yet available. Through two current research examples it has been shown that a deeper understanding of processes and effects is needed to provide timely and accurate knowledge-based policy recommendations, which requires multi-facetted research. In that regard, it is paramount to overcome currently existing disconnections between the general public, responsible stakeholders and the science community, which offers well-researched future scenarios in delivering a co-design of either effective coastal protection or managed re-allignment of (over) exposed coastlines. Effective communication between the involved and responsible parties is more important than ever before in history. Ecologically-wise means of coastal protection has a potential that has yet to be lifted, with joint efforts between traditional engineering measures in combination with strong insight into ecosystems provided by natural science disciplines. Social sciences are equally important as stakeholder processes and science-based research dissemination is nowadays critical to the overall success of implementation measures. Harmonizing design guidelines and standards with spatio-temporal effects of ecosystem contributions to coastal defence will require continued trans-disciplinary research and openness of all stakeholders and the public, ideally combined with real-world laboratory approaches combining co-design and co-living aspects of local communities at risk.

Future research in the coastal realm will continue to deepen our understanding of the abiotic nature of the coastal dynamics, however it will have to capitalize on a more holistic understanding of the biotic aspects of coastal systems. Examples of future research scope – and that list is by no means exhaustive – could be the stabilizing/destabilizing effects of biogenic activity on coastal sediment dynamics, holistic-functional modelling of food web-ecosystem-physical feedback, and ecologically-wise combinations of innovative coastal defence infrastructure effectively complemented by regulating services of ecosystems. ■

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DURCWAVE "AMENDING THE DESIGN CRITERIA OF URBAN DEFENCES IN LECZS THROUGH COMPOSITE-MODELLING OF WAVE OVERTOPPING UNDER CLIMATE CHANGE SCENARIOS"

BY XAVIER GIRONELLA & CORRADO ALTOMARE

Coastal zones are exposed to a series of hazards, such as sea-level rise (SLR) and intensified storminess[1], which are estimated to increase due the effects of the climate change. According to IPCC[2], the sea water level has been rising about 3.2 mm/year since 1993 - three times faster than the rates observed over most of the 20th century! - and this increase is expected to continue. At the same time, population in coastal zones is expected to grow into the future[3]. This is true especially in low elevation coastal zones (LECZs) - areas contiguous with the coast that are 10 m or less in elevation - where population will grow from 625 million to nearly a billion people by 2060[4], 56 million of which in Europe. Two-thirds of world's largest cities are located in LECZs; in Europe, urban areas represent actually the 40% of the population in LECZs, values that will reach the 58% by 2060. Will coastal cities and urban areas in LECZs survive the SLR and flood events in the near future? How much the risk for people living in LECZs will increase? How to tackle it? Over the last century, the growing number of extra-tropical cyclones led to more frequent and disastrous flooding events: waves overtopped and breached coastal defences, causing major economic damages and loss of life. The "1953 North Sea flood" was one of these events, considered the worst natural disaster of the 20th century in The Netherlands, the U.K. and Belgium, recording over 2,500 lives and widespread property damage (around 10,000 buildings were destructed). Unfortunately, similar severe storms are likely to occur again as a result of climate change. A clear evidence is the intensive stormy weather that is affecting Europe over the last 10 years (e.g. the "2013–14 Atlantic winter storms"), causing severe flooding and casualties from Scotland to Spain, from Sweden to Poland (Figure 1). Very recently, between January and February 2017, storms characterized by exceptional wave heights (>6-7m) hit the southern coast of Spain, washing away entire parts of the coastal protections and causing major damages (≈36.131.000€) to ports, promenades and other infrastructure. Under these scenarios, the performance of coastal defences in the next 20-100 years will become increasingly important to prevent flooding due to extreme overtopping events.

Recently the DURCWAVE project (https://cordis.europa.eu/project/id/792370) was granted within the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie (grant agreement No 792370). The project is ongoing at the Maritime Engineering Laboratory of Universitat Politecnica de Catalunya-BarcelonaTech (LIM/UPC). Its scope is to contribute to long term solutions *to cope with climate change in terms of requirements regarding coastal safety for LECZs*.

Figure 1. Examples of winter storms that struck the northern Europe over the last 6 years (a & b) and damages to the sea frontages (c & d)

The main scientific objective of DURCWAVE project is to define new design criteria for wave action by modelling wave overtopping and post-overtopping processes of these urban defences. Specific objectives (*SOs*) are defined as follows:

1. To study post-overtopping processes by characterising overtopping flows on urban defences.
2. To explore the influence of structural geometries on post-overtopping processes.
3. To relate overtopping flow characteristics to maximum exerted loads.
4. To determine the most appropriate overtopping flow characteristics in terms of design purposes.
5. To define new design criteria for overtopping wave action as upgrade of European Standards.

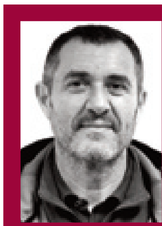
To reach these objectives, the project is implementing a composite-modelling approach: physical modelling (hereafter "PM") and numerical modelling (hereafter "NM") are combined and applied to wave overtopping and overtopping loading assessment. The complementary use of PM and NM is essential since each approach counterbalances the drawbacks of the other. On the one hand, PM is an established and reliable method for studying wave loads and wave overtopping of arbitrary coastal structural geometries. However, PM is often a costly and time-consuming solution with further practical shortcomings due to limitations in measurement techniques. On the other hand, NM is less restrictive in structure configurations and provides much more detailed information on the overtopping and post-overtopping flows (velocities, pressures, forces and overtopping volumes). However, NM requires high computational effort and preliminary validation phases. Hence, a composite- modelling allows overcoming the aforementioned limitations and attaining a level of detail of the analysis that, otherwise, would be partial or incomplete.

PM focusses on *sea dikes and vertical quay walls with main defence elements (storm walls, still wave basins, parapet walls)* and *secondary elements (buildings located behind the main defences)*. Overtopping discharge, individual overtopping volumes, thickness and velocity of overtopping flows, pressure and forces exerted by the overtopping waves are measured.
The *NM* employs the meshless DualSPHysics model[5]. DualSPHysics is based on the Smoothed Particle Hydrodynamics method and is released open-source under a LGPL licence. The code has been already proved to provide accurate and realistic modelling of wave-structure interaction phenomena (see Figure 2).

The project is organised in 5 synergic Work Packages (WPs) that focus on science development, dissemination and public engagement and project management. The WPs are listed as follows:

- **WP1: Physical modelling of post-overtopping processes**
- **WP2: Numerical model development and application to new case studies through secondment**
- **WP3: Integration of PM and NM data**
- **WP4: Dissemination and public engagement**
- **WP5: Project Management**

Physical modelling is carried out at LIM/UPC and comprises both large and small scale modelling. LIM/UPC experimental facilities were considered well suited for accomplishing all PM



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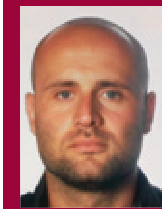

Dr. Corrado Altomare is a Marie Curie Postdoctoral Researcher at UPC (Spain) and voluntary postdoctoral researcher at Ghent University (Belgium), with activity focussing on coastal safety and analysis of countermeasures to the climate change. He has 13 years of experience in experimental and numerical modelling of wave-structure interaction problems. He is co-developer of DualSPHysics numerical model. Moreover, he contributed to the EurOtop manual (2nd Edition) and to the Guidelines for Safety Assessment of the Belgian Coast.

proposed in this project as they include two different and complementary wave flumes. On the one hand, the **large-scale flume "CIEM"** (Canal de Investigación y Experimentación Marítima), has been recognized since 1996 as a "Large Scale Facility" by the European Commission and since 2006 as an ICTS (Infraestructuras Científicas y Técnicas Singulares) by the Spanish Ministry of Science and Education. The participation of the CIEM flume in the Infrastructure Network HYDRALAB and in the Spanish ICTS programme allows other Spanish and European researchers to access this infrastructure and share know-how and equipment. The flume is 100m long, 3m wide and 7m high. On the other hand, the **small-scale flume "CIEMito"** (18m x 0.38m x 0.56m), represents the perfect complement for CIEM, maximizing the typology test variability while minimizing costs, without affecting the quality of the results.
A first experimental campaign has been carried out in the CIEMito flume. The geometrical layout used for the experimental campaign resembles the beach and costal protection in the area of Premià de Mar, municipality in the comarca of the Maresme in Catalonia, Spain. In particular, the area nearby the railway station has been studied. This stretch of the coast, in fact, has both railways and a bike path very exposed to possible sea storms, being located at a few meters from the shore (see Figure 3). Besides issues related to people safety, the vicinity of the railway to the sea has already caused in the past several problems and service interruption of public transport for a line that is strategic for the zone, connecting it directly to the metropolitan area of Barcelona. Close to the railway station, the dike slope has been estimated equal to 1:1. In the physical model tests, the effect of the rubble mound has been neglected, considering a smooth slope, instead. Due to lack of bathymetric data in the area, two different foreshore slopes were considered, namely 1:15 (steep) and 1:30 (gentle). Different widths for the promenade between the dike edge and the station were considered to be representative of the different stretches along the coastline.

Preliminary results from small scale modelling show that overtopping flow velocities and flow depth turn to be significant parameters to

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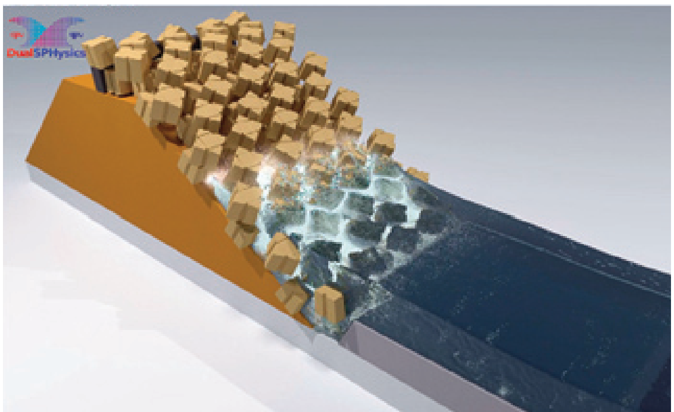

Figure 2. Run-up on a breakwater with DualSPHysics

Figure 3. Bike path and railway in Premia de Mar

CLIMATE CHANGE AND COASTAL DISASTERS (A REVIEW)

BY NOBUHITO MORI & TOMOYA SHIMURA

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Ocean, Cryosphere in a Changing Climate (SROCC) [1] states that climate change may exacerbate sea level rise (SLR) up to 1.1 m for worst case scenario RCP8.5 at the end of century. The SROCC [1] also warns that extreme sea level changes, sea level plus waves and storm surges, and hazards in coastal regions would increase to various degrees under different Representative Concentration Pathway (RCP) climate scenarios. Impact assessment and adaptation of coastal regions to climate change considering regional effects are important for future coastal protection.

Introduction + Sea level rise

The impacts of climate change in the coastal regions depend on both the magnitude of changes and spatial distributions of hazards (i.e., sea-level-rise (SLR), waves and storm surges). On the other hand, adaptation to changing climate in coastal regions also differ depending on changing hazards. It is therefore important to consider the regional characteristics of changing hazards over time and the preferred protection strategy.

SROCC [1] states that climate change exacerbates global mean sea level up to 0.59 m and 1.10 m for the RCP2.6 and RCP8.5 scenarios at the end of this century, respectively. The regional differences of SLR are up to about 30 %, i.e. up to 33 cm relative to the global average. Climate change due to global warming is expected to have major impacts on tropical cyclones (TCs), monsoons and seasonal storms. Understanding future changes of ocean waves and storm surges is also important for assessing and adapting to the impact of climate on coastal, marine and ocean environments, and on engineering problems [2].

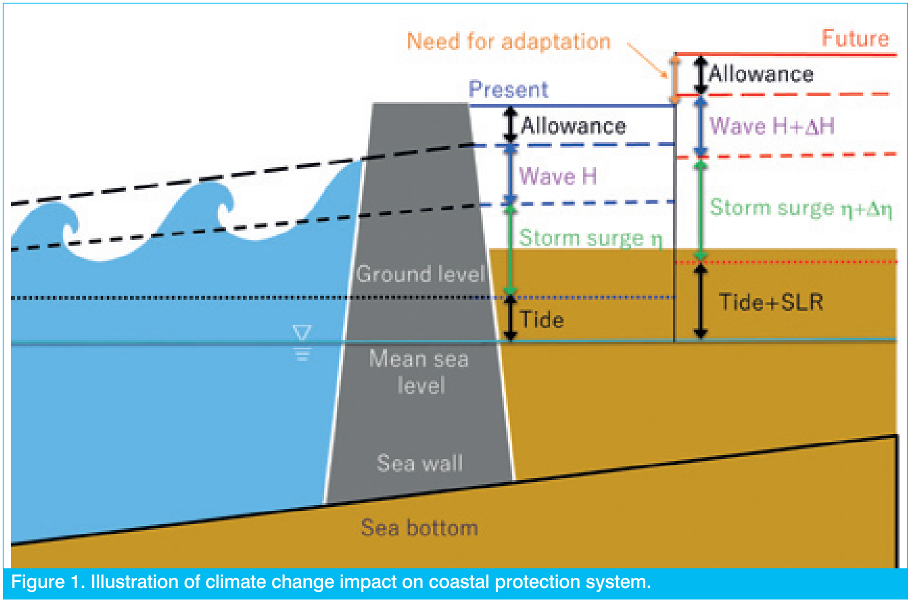

Figure 1. Illustration of climate change impact on coastal protection system.

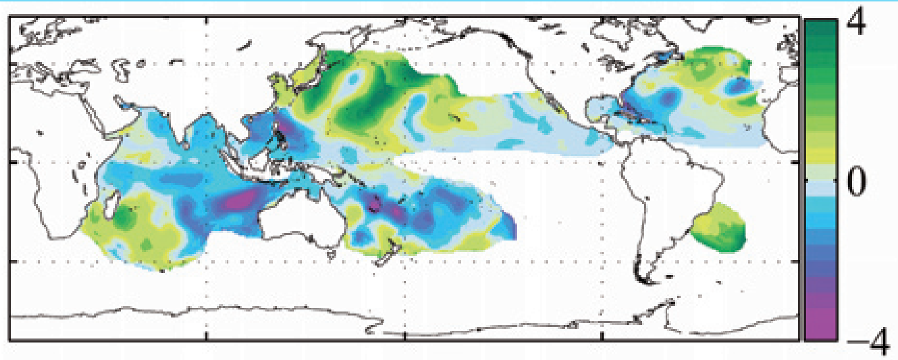

Figure 2. Future changes in 10-year return wave heights of TC-induced waves (unit: m). [8]

Sandy beaches and coastal dunes are major nature-based coastal protection features and need to be maintained as defenses against SLR and wave run-up. On the other hand, coastal urban areas are protected by hard engineered systems such as breakwaters, sea walls or storm surge barriers. Figure 1 illustrates the impact of climate change on key levels considered in the design of a typical coastal protection system. A coastal breakwater is designed accounting for the combination of maximum astronomical tidal level, maximum storm surge level and the pressure from the maximum wave condition, the so-called design wave, during the predetermined design lifetime. Coastal urban areas expected to be heavily affected by increases in storm surge include the heavily populated mega-delta regions of East Asia, South-East Asia, South Asia, Northern Europe and the Gulf of Mexico. Extreme waves are the main threat for locations which are open to ocean. Going beyond the current coastal protection level, it is important to project future SLR, extreme storm surge and wave heights (or wave run-up) considering regional characteristics. Future changes in SLR, ΔH and $\Delta\eta$ in Figure 1 are different by country and by region. Although areas of natural beaches may be affected by climate change gradually, sea wall protected areas are likely to be suddenly in danger when the total sea level becomes higher than the protection level in Figure 1. Combined projections of SLR,

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wave heights and storm surge heights are important for understanding and preparing coastal protection.

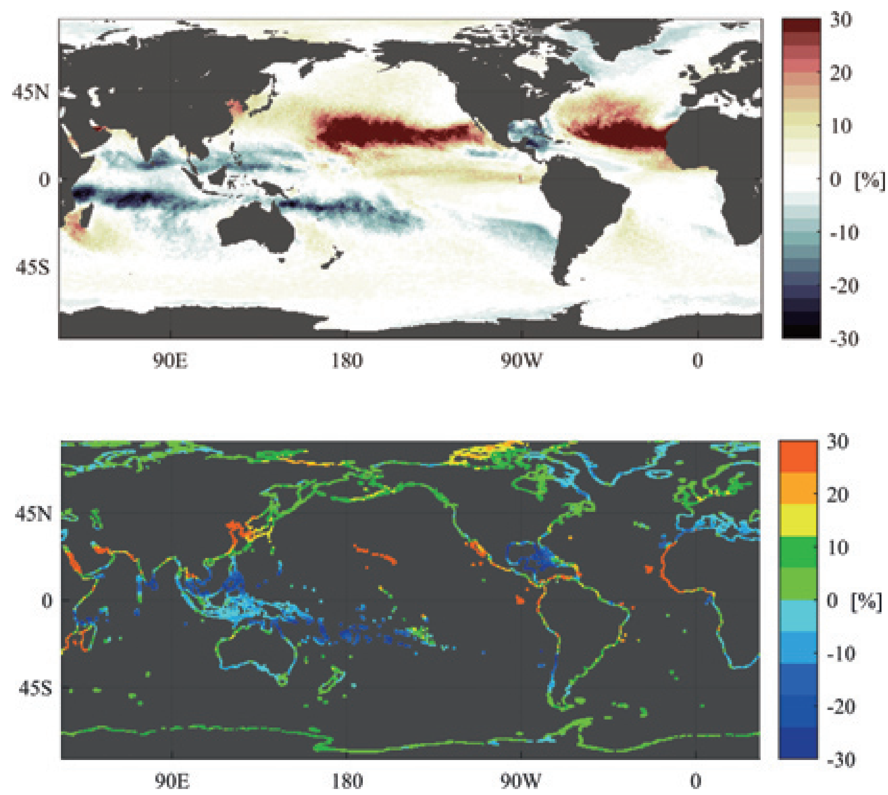

Figure 3. Example of future percent change in sea surface wind speeds (upper panel) and storm surges (lower panel) in 100-year return periods. (unit: percentage) [9]

Waves

Long term characteristics of ocean waves, called the wave climate, can be modulated by the changes in tropical cyclones (TC) and extra-tropical cyclone characteristics (frequency, duration, intensity and storm track). The wave climate can be represented by the long-term mean and extreme values of wave height, and the wave period and direction. Extreme wave conditions are important for coastal protection as indicated in Figure 1. The importance of the wave contributions, in addition to storm surge and tide, to extreme sea level change has been emphasized in recent studies. For example, Melet et al. [3] concluded that wave contributions can strongly affect long-term water-level change and variability. The mean wave climate is one of the main drivers of beach morphology and coastal ecosystem. Historical wave climate changes have been observed globally by satellites over the past three decades, showing that extreme wave heights have increased in the Southern and North Atlantic Oceans by around 1.0 cm yr^{-1} and 0.8 cm yr^{-1} over the period 1985– 2018 (IPCC, 2019)[1].

Future projections of the global wave climate have been conducted by several research groups since IPCC-AR4[4]. Based on the average of projections by different research groups, first community-derived ensemble global wave climate projection has been summarized in the Coordinated Ocean Wave Climate Project (COWCLIP) [5] and reported in IPCC-AR5 [6]. At that time, future expected increases in wave height in the Southern Ocean were described as "*likely*". A second community-derived ensemble global wave climate projection has been conducted more recently [7]. The number of ensemble members was 148, which represents a great increase compared with the first ensemble that had only 20 members. It is *highly likely* that significant wave heights are projected to increase across the Southern Ocean and the tropical Eastern Pacific and decrease over the North Atlantic and the Mediterranean Sea under RCP8.5 by 10 % of the present climate value [1]. The knowledge of expected changes in wave period and direction is currently more limited compared with that of changes in wave height,

In terms of extreme wave climate, TC intensity is projected to increase in the future climate and thus TC-induced extreme wave conditions are expected to be more severe. There is no quantitative assessment of projected changes in TC-induced extreme waves yet (see SROCC, Chapter 4) [1]. The reason is that realistic TC intensity and the related extreme winds cannot be represented well in the Atmosphere-Ocean coupled Global Climate/Circulation Models (AOGCMs) which have been used generally for wave climate projection studies. However, based on high-resolution Atmospheric GCM climate simulations [8] predicted changes in the 10-year return period wave heights of TC-induced waves (Figure 2). The simulations showed that global TC waves would tend to decrease over the lower latitudes and increase over the higher-latitude regions. The 10-year return wave heights of TC-induced waves over the western North Pacific would either increase or decrease by 30 % maximally depending on the region. The spatial distribution of future changes in TC waves can be explained by an eastward shift of TC tracks. However, the number of extreme wave climate projection is limited. Therefore, even though a prediction of global mean wave heights is available, a quantitative assessment of expected changes in mean period, direction and extreme wave conditions, which are important for developing coastal protection measures, remains a future challenging task.

Storm surges

The impact assessment of the impact of climate change on storm surge at regional scale is difficult due to the scale differences between global/general circulation models (GCMs) and storm surge scales (less than O (1–100 km)). The impact of climate change on storm surge was discussed in the SROCC (2019) [1], which only used empirical projections based on observed data. A quantitative summary of the climate change impact at regional scale storm surge is expected to be included in the next assessment report. Assessing the impact of climate change on storm surge risk requires accounting for a number of factors besides the nature of the storm event itself (e.g. TC or extra-TC); storm surge at a particular location is affected by several storm characteristics such as the moving speed and incident angles not only frequency and intensity of storm. Therefore, assessing the storm surge risk in a particular region is difficult even when considering the historical climate alone because landfalls are not very frequent (happening in many areas only once every few decades).

Figure 3 shows an example of the future percent change in storm surge heights and sea surface winds for 100-year return period events [9]. Extreme storm surges were obtained from over 5000-year GCM simulations [10] and a simple storm surge model. Future 100-year return values of storm surge increase about 20% along the East Asian eastern coast and the US western coast, although future 100-year return values of wind speed increase by only 10% due to TCs in these areas. A moderate, future change in storm surge within 10% increase is found in the higher latitudes; which is due to a change in polar circulation in both hemispheres. Changes in wind speed by extra-tropical cyclones will be stronger in the higher Western North Pacific, but they will not be significant in the higher Northern Atlantic. As such, it is necessary to analyze how extra-tropical cyclones and related storm surges will change in the near future. These changes in extreme storm surges depend on the length of return periods. The results in Figure 3 show one such example.

Conclusion

SLR and changes in wave heights and storm surge heights in coastal areas can have a significant impact on the development of coastal protection measures.
Combined projections of SLR, wave heights and storm surge heights are important for understanding and preparing coastal protection from the present to middle or end of this century. ■

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DURCWAVE "AMENDING THE DESIGN CRITERIA OF URBAN DEFENCES IN LECZS THROUGH COMPOSITE-MODELLING OF WAVE OVERTOPPING UNDER CLIMATE CHANGE SCENARIOS"

BY XAVIER GIRONELLA & CORRADO ALTOMARE

continued from page 19

assess stability for pedestrian and vehicles in the vicinity of the sea dike, demonstrating that design criteria based just on average overtopping discharges and maximum individual overtopping volume are necessary but not sufficient conditions to be met. It is therefore necessary to investigate further the overtopping and post-overtopping processes taking into account the particular dike layout and protection countermeasures (e.g. storm walls) and go beyond or amend the current design methodology for wave overtopping. This will be achieved by the end of DURCWAVE project, foreseen for April 2021. ■

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DEVELOPMENT AND FEATURES OF THE NEW COASTAL AND OCEAN BASIN IN OSTEND, AS SUPPORTING RESEARCH INFRASTRUCTURE TO TACKLE CLIMATE CHANGE ISSUES RELATED TO URBANIZED COASTAL ENVIRONMENTS

BY PETER TROCH, VICKY STRATIGAKI, JAAK MONBALIU & FRANK MOSTAERT

The new Coastal and Ocean Basin (COB, cob.ugent.be) in the Flanders Maritime Laboratory, Ostend (Belgium), is the latest tool that will support the scientific community in their effort to tackle climate change and come up with countermeasures to protect coastal communities and offshore investments. The COB will be able to reproduce wave, current, and wind conditions, offering an unprecedented opportunity for researchers and consultants to take a closer look at ocean hydrodynamics, and the structural response of coastal and offshore structures. Also, it enables them to advance marine renewable energy technologies, and to validate numerical models. Construction of the COB started in 2017, and the facility is expected to be operational by end of 2021.

Acceleration in sea level rise and increased intensity of storms [1] have put coastal populations at risk, and pushed the scientific community to come up with better solutions through: designing coastal protection structures, developing new ocean renewable energy technologies, or implementing nature-based solutions. In any case, designers have to go through the so-called integrated research methodology, which combines both numerical and physical scale modelling. Flanders is no stranger to this long-lasting quest and already has experimental infrastructures at Ghent University (UGent) and Flanders Hydraulics Research (FHR), with a limitation to relatively small-scale experiments. Therefore, and to cope with the emerging needs, a consortium led by the Civil Engineering department at UGent, and in partnership with KU Leuven and FHR secured funding for a new state-of-the-art test facility, the new Coastal and Ocean Basin (COB).

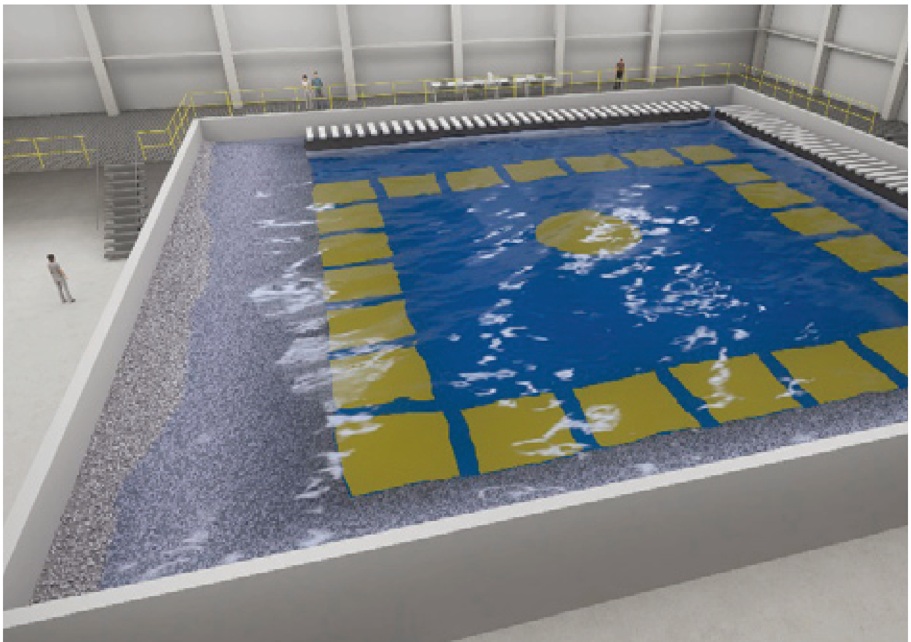


Figure 1. Artist impression of the Coastal and Ocean Basin

The COB, as depicted in Figure 1, is designed to cover a wide range of physical modelling needs while minimizing operating costs. This has resulted in a large range of opportunities for academic research, and for governmental and private sector projects. Users of the new test facility are expected to come from different backgrounds and fields. Starting with coastal engineering, scale experiments will offer valuable data on the wave impact loading of structures, the prediction of wave overtopping over dikes and breakwaters and damage to coastal structures. Emerging marine renewable energy technologies including offshore wind, floating photovoltaics and tidal and wave energy converters will be also tested in the COB.


Figure 2. Front view of the facility hosting the COB and a towing tank (Ostend, Belgium).

Moreover, interdisciplinary work that combines marine ecology with engineering will help shape the role of seagrass vegetation and natural reefs with their habitants. The Civil Engineering department from UGent focuses on these applications. Traditionally it has focused on wave overtopping [2], wave energy converters and scour protection [3], [4], and is a pioneer in coastal defenses and wave attenuation by vegetation [5].

Strategic hub connecting coastal and offshore research universities and governmental institutes with the private sector

The COB is hosted within the Flanders Maritime Laboratory, Ostend, Belgium (shown in Figure 2), a newly built research facility that houses alongside the COB a towing tank, which is also commissioned under a joint initiative between FHR and UGent [6]. This offers a unique opportunity to perform multipurpose tests within the same facility, which will create strong research synergies. Additionally, the laboratory provides a spacious workspace and modern offices to support operations.

What are the components of the COB and how does it work?

The COB laboratory will consist of a large technical facility housing the basin and the accompanying systems to operate it (see Figure 3). The main wave/current basin (see current view in Figure 4) will cover a total area of 900 m^2 (30 m x 30 m), and operate through four components: (i) wave generator, (ii) current generator, (iii) wind generator and (v) water transfer system. Additionally, a fully automated Data Acquisition System (DAQ) will ensure smooth and perfectly controlled set-up, start-up and management of all testing scenarios. Auxiliary systems that improve the efficiency of the experiments have been also installed; these include an access bridge, a crane, an operation control room, and a workshop.

The Wave generator

The wave generator is the most crucial mechanical system of the COB, and the design has been made bearing in mind the typical physical modelling scenarios that will be performed. To generate realistic waves, the wave generator ideally spatially covers two sides of the COB basin, forming an "L"-shaped corner (as presented in Figure 5.A). The wave generation system is composed of relatively narrow wave paddles capable of generating waves in any direction. This "L"-shaped configuration will

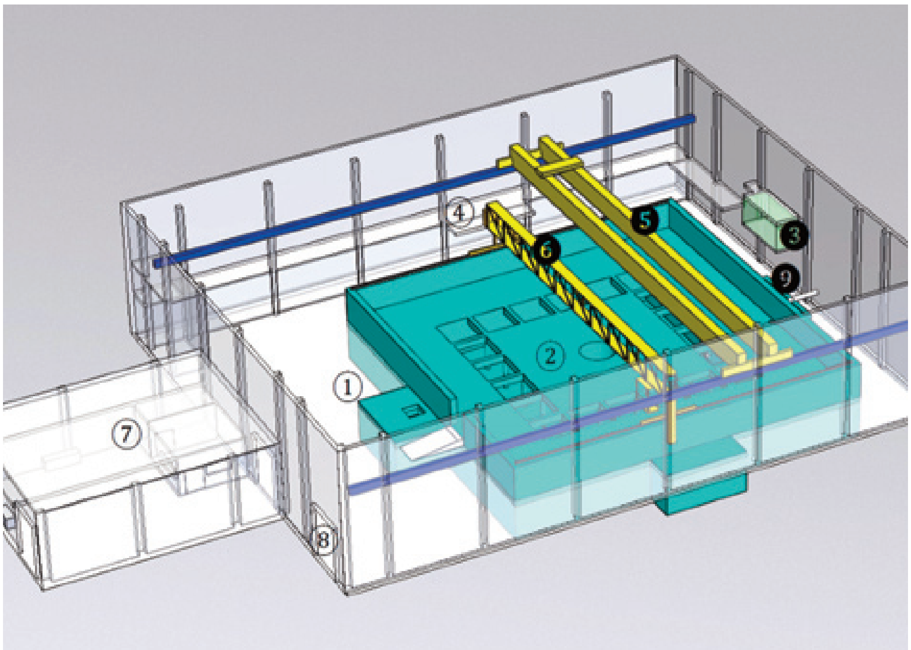


Figure 3. Overview of the layout of the components of the COB facility: 1) main hall, 2) COB basin, 3) main operation control location and office, 4) secondary operation and observation control location, 5) bridge crane, 6) carriage (access bridge), 7) workshop, 8) external access, and 9) water transfer system.

Figure 4. Work progress at the COB: the construction phase of the COB basin structural elements has been completed

Table 1. Selected examples of existing wave basins in relation to the COB

Name and location	Dimensions (length x width x water depth) (m)	Maximum Wave height (m)
COB (Belgium)	30.0 x 30.0 x 1.40 (with 4.0 m deep central pit)	0.55
Portaferry (Queen's U. Belfast, UK)	18.0 x 16.0 x 0.65	0.55
DHI shallow basin (DK)	25.0 x 35.0 x 0.80	est. 0.40
U. of Aalborg basin 1 (DK)	15.7 x 8.5 x 0.75	0.20
U. of Aalborg basin 2 (DK)	12.0 x 17.8 x 1.00	est. 0.50
Delta basin (Deltares, NL)	50.0 x 50.0 x 1.00	0.45
Pacific basin (Deltares, NL)	22.5 x 30.0 x 1.00	0.40
Atlantic basin (Deltares, NL)	75.0 x 8.7 x 1.00	0.45
Tsunami wave basin (Oregon State U., USA)	48.8 x 26.5 x 1.37	0.75
Coastal basin (U. of Plymouth, UK)	15.5 x 10.0 x 0.50	0.30
HR Wallingford (UK)	27.0 x 55.0 x 0.80	0.25

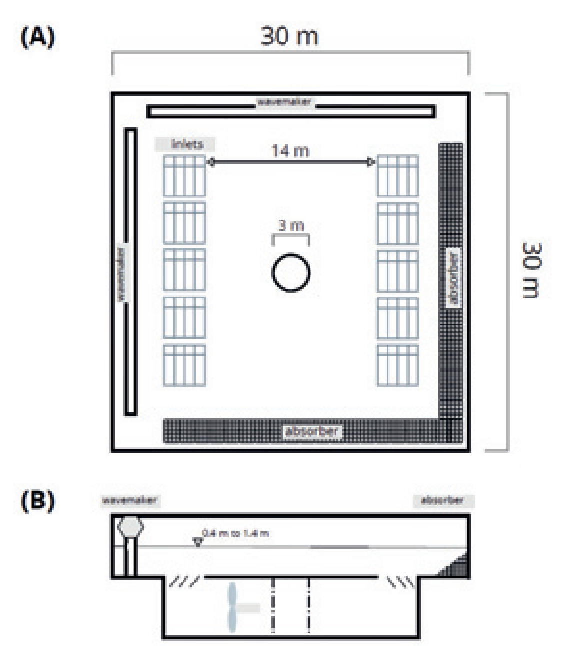


Figure 5. COB schematic (not to scale) including the wave generators at both sides (areas indicated as 'wavemaker') and the current generation system (A: plan view; B: cross section).

make it possible to test a large spectrum of oblique (short-crested) wave angles, and when coupled with the reversible current generation system, to achieve any desired relative angle between the generated current and waves.
The dimensions of the COB basin combined with the wide range of hydrodynamic conditions to be reproduced, will place the COB in a leading position on the global scale in terms of both coastal and near offshore experimental setups. The COB offers a variable water depth ranging from 0.4 to 1.4 m, enhanced by a central pit with a maximum water depth of 4.0 m. Multi-directional wave generation with a maximum height of 0.55 m is targeted, together with a full spectrum of wave-current interaction, with currents of up to 0.4 m/s as described in the next section. Table 1 presents a list of operational wave basins at different hydraulic laboratories; the COB stands out clearly with regard to the relationship between maximum water depth and capability to generate large waves, emphasizing also on the practical aspects for easy, yet accurate, operation of the facility. Moreover, the COB offers the additional capability to test offshore scale models for applications in the fields of marine renewable energy and offshore engineering like monopile wind turbines, floating platforms and offshore devices, mooring applications, etc.

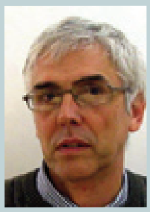
Current generator

One of the unique characteristics of the COB is its capacity to generate combined waves, currents and wind loads. To our knowledge, there are very few facilities reported in literature which offer combined wave and current generation at any relative angle of propagation. As a result, experiments regarding combined waves and currents are also scarce [7]. With no "off-the-shelf" solution available for the current generation system, a tailor-made solution that takes into account the basin layout and target flow rates has been developed and implemented. The target current flow velocity is based on the dominating flow conditions in the Belgian coastal waters, characterized by tidal currents with a typical depth-averaged flow velocity of about 1.0 m/s in full scale. Considering a maximum scaling factor of about 1:8, the flow velocity in the model is scaled down to 0.4 m/s, requiring a total discharge of approximately 11 m^3/s. These design parameters place the COB in a leading position with flow velocities that are almost as twice as the average of the maximum velocity at many other similar facilities of 0.25 m/s. Current and wave testing facilities mainly operate through three systems: jet induced flows, pump and pipe systems, and flow chambers. The first two systems are compact but lag in high power requirements due to the presence of high velocities in multiple sections of their components. To stay within reasonable operating costs, the use of a flow chamber below the level of the wave tank floor, namely a current tank, has been selected. Sketches of the current generation system are shown in Figure 5. The current is introduced in the basin through a set of guiding grids flush-mounted in the basin floor. Each grid can be replaced by a lid when the current system is not being operated.

Prof. Peter Troch is the department chair and director of the Coastal Engineering Laboratory at UGent and coordinator of the Coastal and Ocean Basin, Ostend. He has 25 years of academic experience and focuses on wave induced response of coastal structures, on wave propagation and harbor penetration modelling, and on eco-hydraulics of vegetated lowland rivers. Prof. Troch coordinates a large team of researchers focusing on wave energy converters and coastal engineering. He has published in various international peer reviewed journals and conference proceedings, and he is member of the Editorial Board of Coastal Engineering. He is chair of the management committee of the COB.

Dr. Vicky Stratigaki is a Senior Research Engineer at the Civil Engineering Department of Ghent University (Belgium) with PhD in Civil Engineering, MSc in Civil Engineering, and an additional MSc in Environmental Sciences. Her numerical work with wave models focuses on wave transformation and penetration into harbors, diffraction around breakwaters/coastal structures, marine renewable energy devices and resources. Her current research topics focus on Coastal & Offshore Engineering, Nature-based techniques for coastal protection, and interdisciplinary ocean research topics including Aquaculture, Maritime Engineering and Marine Renewable Energy with a focus on Blue Growth and Blue Economy. Dr. Stratigaki has published her research on experimental testing and validation of numerical models in numerous international peer reviewed journal and conferences. Dr. Stratigaki is a team-leader in national and international research consortia and is Chair of the pan-European COST Action WECANet CA17105 of 31 countries. She is member of the design team of the COB.

Prof. Jaak Monbaliu is the chair of the Department of Civil Engineering and also teaches several courses including Coastal Engineering and Advanced Mathematics for Water Engineering. His sphere of research lies in (but is not limited to) wind waves, sediment transport under waves and currents, and remote sensing coastal zone and estuaries, with several publications in international peer reviewed journals. He is management committee member of the COB.



Prof. Frank Mostaert currently works at the Flanders Hydraulics Research as division head and is a part time lecturer at Hasselt University and Ghent University. His interdisciplinary experience bridges the academic sector of Belgium with the public and private sectors in Flanders. In his work he focuses on research in water management and water science and environmental science, holding publications in international peer reviewed journals. He is management committee member of the COB.

Data Acquisition System

Since the quality of acquired measurements and data is the most vital outcome of any experiment, special attention to detail has been put in the selection of the measurement instrumentation and the design of the Data Acquisition System (DAQ). The COB laboratory will have a large inventory of traditional and state-of-the-art instrumentation for measuring e.g. the water free surface (i.e. capacitive, resistive, ultrasonic wave gauges), the wave orbital and current velocities (Acoustic Doppler Velocimeter, Acoustic Doppler Profiler, micro-propeller velocimeter), loading pressures, loading stresses (axial load cells), wind parameters and loads (ultrasonic anemometer, cup anemometer, barometer, air temperature sensor), and water depth. In addition, 3D motion capture systems and a 3D laser scanner for topographic mapping are foreseen. The collected measurements information will be transferred to a local processing unit, which will be in turn connected to a server that provides real-time remote access.

Conclusions

Emerging challenges in the coastal sector due to sea level rise and higher storm waves, alongside the transition towards clean energy through wind, wave and current energy illustrate the importance of the COB in providing a test ground for prospective solutions and emerging technologies.

In the field of offshore renewable energy, there is a significant potential for exploitation of wave, wind and tidal energy worldwide which results in ample research opportunities focusing on all relevant technologies at various stages of development. Yet there is a clear need for new infrastructure to move from concept to open sea as recognized in various Research and Development and Innovation (R&D&I) roadmaps at European level. At the same time, and to tackle climate change impacts, there is also a clear need for physical modelling infrastructure within the fields of coastal engineering and marine ecology, where updated knowledge on coastal resilience and ecosystem protection methods, especially under 3D conditions and wave-current interaction, is still needed. The Coastal and Ocean Basin (COB) is serving these critical present-day and future needs by providing a versatile facility that will lead to the technologies and methods of the future.

Acknowledgements

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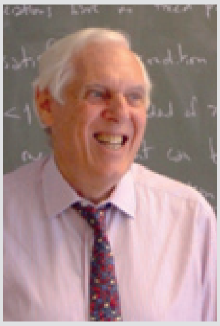
MICHAEL B. ABBOTT (1931-2019)



Michael Abbott, Honorary Member of IAHR, sadly passed away on Thursday 19th December 2019, at the age of 88. IAHR mourns the loss of a 'Giant' within our community. Mike (as he was known to all) was a scholar, a visionary and a pioneer of computational hydraulics, hydroinformatics and, more recently, the water knowledge initative. He was always ahead of his time; his book on Computational Hydraulics in the early 1980s ushered in the new era of numerical modelling of free surface flow problems in hydraulic research and engineering. His lectures and work on hydroinformatics have guided the development of the global water industry, as big data and computational modelling provide everyday tools to manage water systems in numerous countries. His captivating teaching has inspired generations of students from all over the world - many of whom are now in leadership positions in academia, government and industry. He was an avid reader and a deep thinker who liked to share his philosophical views alongside the technical feats. In recent times he introduced IAHR members to the spiritual dimensions of the water world and encouraged IAHR to reach out for a global vision of water management, beyond a regional or country-specific context. Mike was a dedicated promoter of IAHR and a most revered and beloved friend to numerous IAHR members. He was an IAHR institution.

Mike Abbott was born in Barnet, UK, in 1931. He studied civil engineering at the University of London, graduating in 1953. He then studied fluid dynamics and computer programming at the University of Southampton (1957-58), followed by a diploma at the International Course in Hydraulic Engineering (IHE) in Delft (1958-59), and completing his PhD at Southampton in 1960. He was then appointed as a NATO Fellow at the University of Amsterdam (1963-64), followed by a Lectureship at the Technical University of Denmark (1964-66). In 1966 he returned to IHE (currently IHE Delft Institute for Water Education), where he advanced rapidly to become Professor in Computational Hydraulics and subsequently Hydroinformatics. In 2001 he was appointed Emeritus Professor in Hydroinformatics and continued working closely with many of the existing staff at IHE. Throughout his career Mike wrote 7 texbooks on computational hydraulics and hydroinformatics – these are widely cited classics that have been translated into many languages, including Chinese and Russian. He published over 100 seminal journal papers; many have won prestigious awards, such as the Journal of Hydraulic Research Best Paper Award (1979-80), the ASCE Karl Emil Hilgard Hydraulics prize (1988) etc. In 2002 he was awarded an Honoris Causa Doctorate ('Hon Dr') from the University of Thessaloniki. Througout his life in Europe Mike learnt and spoke 5 languages – a rare accomplishment for a UK national.

Mike Abbott was also an outstanding practitioner. In particular, Mike worked closely with the Danish Hydraulic Institute (now DHI Group) as a consultant (1970-2000). During that period he designed and led the first 3rd generation simulation software tools for hydraulic and environmental applications, project managed the System Hydrologic European (SHE) consortium, designed and constructed software for pipe-laying operations that became standard for Det Norske Veritas and, in particular, led the design, development and marketing of DHI's 4th generation modelling systems: Mouse, MIKE 11, MIKE 21, MIKE SHE etc. The MIKE software tools, powered by DHI, form one of the most widely used suite of software tools developed to help tackle water environmental challenges worldwide. One of Mike's most fascinating projects was the application of the MIKE software system in the hydro-environmental design of the Oresund Bridge project, linking Denmark and Sweden. In addition to reporting on the computational modelling of this project, he went on to publish seminal papers on using the internet and telephony to design real-time monitoring of such large-scale infrastructure projects, for which he received the ICE Telford Gold Medal (2017) for one of these papers. These principles are now widely used by international consultants and project managers worldwide.

In 2001 Mike Abbott returned to WL Delft Hydraulics (now Deltares) as a consultant, where he remained active throughout the early years of his retirement – although he never really retired. Alongside this move, Mike also co-founded the European Institute for Industrial Leadership (EIIL). Steven Price of EIIL writes: "in 2003 Mike wrote 'European Industrial Leadership' providing EIIL with a curriculum and value set for leadership, which was unrecognisable with those discussed in most business schools of the day and with some of these values only just starting to trend some 17 years later".

Michael Abbott will be remembered as an outstanding academic and scholar, a visionary intellectual, and a practitioner with an immense appreciation of multi-disciplinarity. Above all, those that knew him well and had the pleasure and honour of working closely with him, will always remember him as a true and immensely valued friend – nulli secundus. He is survived by his devoted wife Louise and his daughter Jette.

By: Roger Falconer (Past President of IAHR), Peter Goodwin (Immediate Past President of IAHR) and Joseph Lee (President of IAHR).

IAHR HONORARY MEMBER PROF. LI GUIFEN PASSED AWAY ON JANUARY 5, 2020 AT THE AGE OF 89.

With deep sadness we pay tribute to Professor Li Guifen - a distinguished and devoted member of the IAHR family over several decades. Professor Li Guifen was a highly esteemed researcher who played a leading role in promoting international cooperation, international student exchange and the development of the IAHR China chapter in its global role.

Professor Li Guifen was a member of the IAHR Council during 2001-2005, and before that served in the Technical Committee on Ice Research and Engineering (1996-2001) and the Technical Committee on Hydraulic Structures (1997-2003). She was elected IAHR Honorary Member in 2007.

Professor and Senior Engineer Mrs. Li Guifen graduated from Shandong University, China in 1952. After graduation, Prof. Li joined the Huaihe River Conservancy Commission of the Ministry of Water Resources, China. Starting in 1956, she spent two years as a Visiting Scholar in the Department of Hydraulics of VNIIG, Leningrad, U.S.S.R., and then she joined the Institute of Water Conservancy and Hydropower Research (IWHR, now the China Institute of Water Resources and Hydropower Research) where she was the Director of the Department of Hydraulics and Director of the Division of International Cooperation. Since 1958, she had been engaged in scientific and engineering research on hydraulics in the fields of water resources and hydropower. Her research covered a wide range of topics that include hydraulic structures, high speed flow, flood discharge and dam safety, energy dissipators, wind-induced waves in reservoirs, river ice, effects of plant-barriers on debris flow, and prototype measurements. She published 30 scientific papers and 8 research monographs, as well as hundreds of reports. In particular, her book on “Flood Releasing Structures in High Dams with High Discharge” (in Chinese) was a landmark that served as a valuable reference for designers and researchers in China.

Professor Li Guifen also acted as consultant for many water engineering projects in terms of planning, assessment, laboratory design and construction, and capacity building. Due to her excellent work and achievements, she received many awards at national and ministerial levels. Professor Li was a Visiting Professor of Sichuan University and Shandong University, an advisor to the State Key Laboratory of High Speed Flows in Sichuan University and to various monumental hydraulic projects. Over the last two decades, she had been very active as a Council Member of the Chinese Hydraulic Engineering Society (CHES) and the China Society for Hydropower Engineering (CSHE).

Prof. Li Guifen had devoted herself to communication and exchange of water science between Chinese and international groups since the beginning of the 1980s. She had been actively involved in IAHR activities since the XXII Congress in 1987 (Lausanne, Switzerland). Owing to her introductions, dozens of Chinese hydraulic scholars and experts joined IAHR. She was Chairperson of the IAHR National Committee of China from 1987-2005. In 1988 she organized the first International Symposium on Hydraulics in China. Since then she and her Chinese colleagues had organized more than 10 conferences and symposiums, including the 7th IAHR-APD Congress (1990, Beijing, China), the 13th IAHR Ice Engineering Symposium (1996, Beijing, China), and was Chairperson for the highly successful 29th IAHR Congress in Beijing, 2001. She also led many delegations to attend IAHR congresses and events overseas.

Professor Li Guifen was a true leader who helped to advance the mission of IAHR and the international water engineering community. In addition to her outstanding contributions to hydraulic research and practice, Madame Li has been a quiet and important guiding force in international collaboration over the past three decades. She had a keen interest in the professional development of younger colleagues and often provided mentorship and encouragement to them to be engaged in various IAHR committees and academic activities. She supported many conferences organized by APD researchers and provided valuable opportunities for them to experience the excitement of water in practical engineering projects.

Professor Li will be remembered as an outstanding hydraulic engineer and an empathetic lady who had the rare gift of connecting researchers - particularly students and early career researchers across the globe. She was a warm and wonderful ambassador for China and IAHR in international networks – a role model instructive to young engineers and scholars, friendly to colleagues from abroad, gentle to partners from home and abroad, and helpful to all the visitors.

Professor Li Guifen, a devoted hydraulic engineer and a distinguished member of our IAHR family, will be always in our hearts.

2020-2023 IAHR STRATEGIC PLAN

Since 1935 the mission of IAHR has been clear: to build an international community of top scholars and researchers in water science and engineering. To effectively address many global challenges - in which water is often at the center - IAHR is making a Society-oriented step forward to be part of the solution for a better water future.

In 2009 IAHR changed its name to become the *International Association for Hydro-environment Engineering and Research* to reflect its diverse activities beyond traditional Hydraulic Engineering and its contributions to sustainability. *Hydro-environment Engineering and Research* refers to the continuing expansion of our knowledge about water flow and management in engineered structures and natural water bodies and the use of such knowledge to serve the needs of people and in harmony with the environment.

As suggested by the above definition, IAHR helps boost knowledge through our network of expertise all over the world and this knowledge should be proactively disseminated for the service of people of all nations.

It is my honor and pleasure to present the new IAHR Strategic Plan which embodies the extensive deliberations of the IAHR leadership on where IAHR should be in the next four years and the milestones to achieve that vision. This plan is the product of an initiative by Past President Peter Goodwin and Executive Director Tom Soo in 2019. I would like to extend special thanks to them and the task force that also included James Ball, Angelos Findikakis, Silke Wieprecht for their time, creative thinking and passion. I am proud to have been part of this venture from the beginning. Thanks are also due to the comments of the council members, division and technical committee chairs and journal editors for their input which invariably found their way into the final document.

The Strategic Plan (SP) is based on the following four pillars:

1. Provide a world class international networking platform and great member experience
2. Inspire, disseminate and catalyse state-of-the-art knowledge and thinking
3. Institute events that set agendas, harness and amplify the collective knowledge of the global Hydro-Environment community
4. Act as a global voice on behalf of the Hydro-Environment engineering industry and research communit

This strategic plan will help guide us, monitor and evaluate goals and results to achieve new levels of excellence and reputation as the premier and a truly international association in water. We only can do this if we share this new vision and look beyond our own narrow interests.

We do hope that you feel proud of being part of IAHR!

Joseph Hun-wei Lee, IAHR President

You can read and download **2020-2023 IAHR STRATEGIC PLAN** on the IAHR website

Preview of some pages from the strategic plan

Prince Sultan Bin Abdulaziz International Prize for Water

Recognizing Innovation

Invitation for Nominations

10th Award (2022)

Nominations open online until 31 December 2021

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