Delft University of Technology

The Sand Motor: A Nature-Based Response to Climate Change
Findings and Reflections of the Interdisciplinary Research Program NatureCoast

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Publication date
2019

Document Version
Final published version

Citation (APA)
Luijendijk, A., & van Oudenhoven, A. (Eds.) (2019). *The Sand Motor: A Nature-Based Response to Climate Change: Findings and Reflections of the Interdisciplinary Research Program NatureCoast*. Delft University Publishers.

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THE SAND MOTOR: A NATURE-BASED RESPONSE TO CLIMATE CHANGE
RESEARCH PROGRAM NATURECOAST – Luijendijk and Van Oudenhoven (eds)

THE SAND MOTOR: A NATURE-BASED RESPONSE TO CLIMATE CHANGE

FINDINGS AND REFLECTIONS OF THE INTERDISCIPLINARY RESEARCH PROGRAM NATURECOAST

EDITED BY
Arjen Luijendijk
Alexander van Oudenhoven

Arjen Luijendijk (right) was active in the NatureCoast program as a postdoctoral researcher at Delft University of Technology from the start in 2013 until the end in 2018. He focused on setting up the interaction between the PhD researchers and end-users, as well as integrating the research findings. He worked on developing integrated model forecasts and developed the world's first global beach erosion map. He is currently working as a Specialist at Deltares and as a researcher at the Delft University of Technology on predicting the future behavior of the world's beaches.

Alexander van Oudenhoven (left) was active in the NatureCoast program as postdoctoral researcher at Leiden University between 2015 and 2018. He focused on integrating the program's scientific findings, thereby looking at the potential benefits that nature-inclusive coastal management can generate and how these are perceived. He is currently working as an assistant professor at the Institute of Environmental Sciences at Leiden University, working on the interface between biodiversity, ecosystem services and societies' quality of life. In the spring of 2018, he became Co-Editor in Chief of Ecosystems and People, an interdisciplinary open access scientific journal.

THE SAND MOTOR: A NATURE-BASED RESPONSE TO CLIMATE CHANGE

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Edited by

Arjen Luijendijk
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TU Delft

DELFT UNIVERSITY PUBLISHERS 2019

Henk Ovink

MITIGATE TO ADAPT AND BUILD WITH NATURE, 1.5 DEGREES IS MORE THAN ENOUGH!

PREFACE

Henk Ovink is Special Envoy for International Water Affairs and Sherpa to the UN/WB High Level Panel on Water.

The in October 2018 presented report "Global Warming of 1.5 degrees" of the Intergovernmental Platform on Climate Change (IPCC) is very clear: we are on track towards an inhabitable planet. Limiting it to 1.5 degrees will make the world more sustainable and more equitable. But it will not be easy to keep us all within that threshold, since we are heading towards a much larger than 2.0 degrees increase. This will demand systems' changes on all levels. Climate change impacts are already here. We lose millions of people and billions of dollars. Every year is record-breaking with more intense disasters, casualties, damages and despair; ripping apart families, societies and our ecosystems.

I was born optimistic with an engineering architect father and a community leader school teacher mother: believing that every challenge is an opportunity as long as we include everyone - and combine all our will, energy and talent. The IPCC is also hopeful that it can be done. If only we dare to do it, and do it boldly. We have no time to waste! In 2015, we set down a climate agreement and endorsed the United Nations Sustainable Development Goals. But paper alone will not change the world. Across the globe, we still repair the damage caused by disasters, responding to the past instead of preparing us for the future and building. The Netherlands has been engaged in the latter for more than thousand years. Ever since the institution of our first regional water authority, water has become embedded in our culture and landscape, in legislation, governance, businesess and academia. Along with the Netherlands, a majority of the world's population is living in cities along rivers and coasts and growing. Prosperous places, but increasingly vulnerable due to climate change.

Adapting to climate change is the way to bend the curve. The choice between prevention and prepairing is false. Both are essential. We need to start at the source: to reduce greenhouse emissions, and make sustainable use of our planet and all its resources. And at the same time we need to prepare boldly, comprehensively and inclusive for tomorrow's extremes. The Netherlands' coast is worth protecting, an amazing deltaic coastline. Protecting the country means working on our coast and looking ahead systemically while merging natural and human strengths. Nature has always been better in adapting to change. However, with the speed and intensity of mankind's interventions and the massive pressure we put on our planet we have to help nature progress, help nature help us.

With Henk Nieboer from EcoShape I wrote about nature-based solutions and their critical capacity to answer to these challenges: "Nature-based solutions require a comprehensive approach to engineering. They address societal needs for flood protection, infrastructure and food production while providing additional benefits in increased biodiversity, CO^2 sequestration, recreational and economic values. Furthermore, nature-based solutions are adaptable to changing circumstances, often cost effective and more impactful than our traditional solutions."

The Sand Motor is such a nature-based solution par excellence. It required innovative governance, plus institutional, business and finance models and frameworks. It also required an inclusive collaboration between various disciplines and sectors, and the engagement of all relevant stakeholders from the initiation phase of the project all the way towards final implementation. The Sand Motor now inspires the world that nature with its capacity to destruct is actually our best friend in building sustainable and resilient coasts, safeguarding our coastal towns and economies while improving the environment, the ecology, and mitigating climate change.

I think it is time to learn, replicate and scale up these nature-based solutions globally. We must start to educate the new generation of engineers, designers, ecologists, policy makers, politicians and managers on the principles of nature-based solutions. We must develop credible narratives and the business cases and examples of successful projects. Implement larger scale projects worldwide, evaluate them and disseminate the experience and knowledge gained. Involve communities in the planning and implementation and equip them with knowledge and financial means in order to scale up and sustain such solutions, working side by side with governments and private sector. Scale up existing pilots and replicate these in international consortia across the globe, in partnership with the financial sector - multilateral development banks, the Green Climate Fund, governments, private sector and pension funds.

We have no time to waste; the disasters of this world will not stop. They have become the "new normal", more extreme year by year. The need for fast results is also an opportunity: ideal for setting up good business cases combined with political and societal action. Ambitious enough to be attractive, and short and fast enough for targeted actions, with results and with hope. We can and we must act now.

Marcel Stive

FROM COASTAL GENESIS TO NATURECOAST

Marcel Stive was program leader of the NatureCoast research program. He is professor emeritus of Coastal Engineering and former chairman of the department Hydraulic Engineering at Delft University of Technology.

Allow me to share my observations of the fascinating development in our thinking about and coping with coastal challenges in the Netherlands. Specifically, this will cover the time following the completion of the Delta Works in the *Oosterschelde* in the 1970s until the present, in the context of the emerging role of multidisciplinary research.

Coastal Genesis (*Kustgenese*; 1985-1987)
In the mid-1970s a transition took place when *Rijkswaterstaat* shifted from funding fundamental research to funding more applied research. In the middle of the 1980s, it became clear that that a further shift, towards more multi- and interdisciplinary research was imminent, resulting in the Coastal Genesis project. But what was in fact the result of the Coastal Genesis project? I would argue that the first Coastal Bill (1990), the Dutch Centre for Coastal Research (NCK), which was established in 1994, and the current coastal policy (1990-present) all are indebted to the Coastal Genesis project.

First Coastal Bill (*Eerste Kustnota*; 1988-1990)
The results of Coastal Genesis were an almost seamless, logical input to the rather remarkable first Coastal Bill. In 1987 all Delta works in Zeeland were close to completed, and so the time had come to reflect on the future. Then Minister Smit-Kroes decided that the time was ripe to introduce a structural policy on coastal erosion. The coastline of 1990 was chosen to be maintained as the benchmark coastline. The type of interventions that were intended to achieve this goal were as innovative as the policy, especially "soft" interventions as sand nourishments.

Water management in the 21st century
In August 2000 the *Commissie Waterbeheer 21e eeuw* (Water Management Committee 21st century) published advise on the future of water policy in the Netherlands. Its main message was that water needed more room and its management needed an organizational principle. The *Unie van Waterschappen (*Union of Dutch Water Authorities) endorsed the main principles, including the principle of combining water management with other interests, such as nature conservation, spatial quality and recreation.

Weak coastal links (*Zwakke Schakels*; 2004-present)
To bring this multifunctional principle into practice, Minister Schultz van Haegen presented the "Process plan weak links of the Dutch coast" in 2004. One of the eight weak links was the coast near *Kijkduin* and *Hoek van Holland*. Deputy Dwarshuis of the province of South Holland established a carefully composed Advisory Committee that included all relevant stakeholders. Their advice: no elongated, uniform dunes and widening of the beach, no permanent buildings, but a concentrated mega-nourishment where natural processes would facilitate a dynamic dune and beach landscape. At that moment the concept of the Sand Motor was born.

Delta Committee 2.0 (Committee Veerman; 2007-2008)
Quite unexpected, the Delta Committee 2.0 was established at the request of Minister Huizinga. A remarkable decision, given that no flood disaster had occurred recently, but most probably Hurricane Katrina in 2005 played a role. The composition of the committee was unusually multidisciplinary and strongly confirmed the prevailing policies of room for the rivers and water, and a natural, resilient coast.

Sand Motor realized (2011)
Amazingly, the Sand Motor was realized only five years after its inception. The challenge at that moment was to generate enough budget to monitor at least the morphological development in a time when formally nothing had been put in place to do so, let alone the ARGUS video tower. Delft University of Technology was able to solve this in a flexible way, using various sources including the EU-funded project NEarshoreMOnitoring (NEMO), while *Rijkswaterstaat* joined later.

NatureCoast (2013-2018)
The pilot project Sand Motor was born as a multifunctional answer to realizing a large number of functions, such as safety, nature values, recreation and innovation. Both from an academic, technological and socio-political point of view, it was clear that the Sand Motor offered a unique "living lab" to conduct interdisciplinary research. This triggered a broad consortium of Dutch institutions and industries to prepare an interdisciplinary NWO-STW (now TTW) research proposal. This proposal became the NatureCoast program, in which disciplines have interacted in an unprecedented way.

Cor de Boer

SCIENTISTS AND END-USERS WORKING TOGETHER TO CONTRIBUTE TO SOCIETY

Cor de Boer is head of the Department Life, Environment and Health, NWO Domain Applied and Engineering Sciences.

Just like the sea has tides, raging waves and lapping water, the NatureCoast program also has its storms and periods of calm. In the ten years of *Perspectief* programs, I have come across almost no other consortium that consists of such a wide range of parties, and that has developed into such a tight-knit group over the years. It did cost the group a considerable effort to keep everybody on board. Yet that is also the challenge for multidisciplinary projects like these: everybody looks at the subject in his or her own way and takes other interests into account. A success like this requires considerable commitment to and focus on the joint end result.

One of the successes in this regard was the involvement of end-users right from the start of the program. During *Rijkswaterstaat's* Sand Motor Congress in 2016, and NatureCoast's own final symposium in 2017, it also became clear just how successful NatureCoast was in seeking that connection with the end-user.

You can be rightly proud of what you have achieved: a consortium that has yielded a new innovation with societal impact. This innovation is now gaining a firm international footing too, which is securing economic impact for the Netherlands. It is a fantastic showcase that still manages to interest the media and the wider public. This ensures that a wider public also experiences the importance of applied and engineering sciences.

So, in my opinion, the program also does precisely what the *Perspectief* program intends: creating an intensive collaboration between scientists and industry to solve innovation bottlenecks and contribute to societal issues.

The knowledge acquired in NatureCoast is of a superb level, as evidenced by the follow-up in various other NWO program including the "Open Technology Programme" (OTP) and the "Talent Scheme." I look forward with considerable interest to the fantastic results that this will yield. It is high tide for the researchers and end-users of NatureCoast, and I hope that the intensive relationships that have developed, will also lead to fantastic collaborations in the future. Maintain those close links!

Photo (left page): Cliff formation at the most seaward part of the Sand Motor revealing layers of shells (Photo by Sierd de Vries)

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ONE | **INTRODUCTION**

Alexander van Oudenhoven, Ewert Aukes and Arjen Luijendijk

TOWARDS MULTIFUNCTIONAL COASTAL MANAGEMENT

Alexander van Oudenhoven was active in the NatureCoast program as a postdoctoral researcher at Leiden University between 2015 and 2018.He focused on integrating the program's scientific findings, thereby looking at the interactions between nature and people, the potential benefits that nature-inclusive coastal management can generate. He is currently working as an assistant professor at the Institute of Environmental Sciences at Leiden University, working on the interface between biodiversity, ecosystem services and societies' quality of life.

Ewert Aukes was active in the NatureCoast program as a postdoctoral researcher, shortly after obtaining his PhD within the same program in 2017 at the University of Twente. He currently works at the department of Science, Technology and Policy Studies at University of Twente, as a postdoctoral researcher.

Arjen Luijendijk was active in the NatureCoast program as a postdoctoral researcher at Delft University of Technology from the start in 2013 until the end in 2018. He focused on setting up the interaction between the PhD researchers and end-users, as well as integrating the research findings. He worked on developing integrated model forecasts and developed the world's first global beach erosion map. He is currently working as a specialist at Deltares and as a researcher at the Delft University of Technology on predicting the future behavior of the world's beaches.

Photo (left page):
The Sand Motor being constructed, as seen from the dunes of Ter Heijde. The sand is being sprayed on through so-called rainbowing. (Photo by Arjen Luijendijk)

Climate change is the most formidable challenge that our ever-increasing world population faces, and it poses special problems for those living near coasts. People have always been attracted to the coast, as a place to live and work, and to relax. By 2050, around half of the world's population is expected to live near the coast, the vast majority in developing countries. How will we cope with rapidly rising sea levels and more intense and frequent storm surges?

Although retreating from coastal areas might not be such a bad idea, this is an unlikely option for most coastal settlements. This means that active protection of urban areas and infrastructure against flooding will remain our primary focus. Artificial protective barriers, such as concrete dikes, dams and breakwaters have traditionally been the go-to way to deal with coastal protection. However, such hard structures have always had the single aim of providing coastal protection, without considering their impact on the coastal ecosystem. In other words, traditional coastal management solutions were treating symptoms; building coastal protection structures in nature often created new problems or moved existing problems to other places.

Throughout history, the fate of the Netherlands has always been intimately linked to the sea. Without our coastline protection and inland water management, two-thirds of the country would be under water. However, we have also realized that just treating symptoms is no longer sufficient. Protecting people and infrastructure will always remain the main aim of coastal management, but the impact on the environment must also be considered, as well as the wider societal context. This means that we need to fully understand how coastal ecosystems function, as well as their societal context. This knowledge is crucial if we are to create integrated multifunctional coastal protection solutions that have minimal environmental impact and are widely appreciated.

The shift away from treating symptoms towards integrated, multifunctional designs requires a new approach. Throughout the Netherlands, the Building with Nature approach has been adopted. The key to this innovative approach is using prototype pilots to develop new knowledge and insights. In this book, we present the findings of a multidisciplinary research program, called "NatureCoast", which studied a full-scale coastal protection pilot project, the "Sand Motor".

Building with Nature
Building with Nature (BwN) is a proactive approach to surface water management. The approach advocates an integrated approach that harmonizes coastal management solutions with the requirements of ecosystems. Decisions must be taken about desired societal and ecological functions, which means that the state and the functioning of the ecosystem has to be studied and understood before a design can be proposed.

The BwN approach maintains that this knowledge is crucial if environmental and nature concerns are to be integrated into coastal infrastructure projects. By considering how the local ecosystem can become part of the solution, project managers anticipate legal opposition and avoid having to create alternative nature areas. This is almost directly opposite to mainstream infrastructure approaches,

Photo (left page): NatureCoast researchers sharing their findings during an excursion of the Rijkswaterstaat Sand Motor conference in 2016. Throughout the years, our researchers have provided numerous excursions to the Sand Motor. Excursions, discussions and guest lectures are just some of the ways through which NatureCoast has been in dialogue with end-users and society. (Photo by Alexander van Oudenhoven)

which tend to focus on the current situation rather than the future and build in nature, rather than with nature. Besides being proactive, the BwN philosophy attempts to maximize the use of natural processes in infrastructure projects. The Sand Motor is one of the first large-scale applications of the BwN approach.

The Sand Motor
The Sand Motor is a large sandy peninsula, constructed in 2011 on the Dutch North Sea coast near The Hague. This unprecedented pilot project involved placing 21.5 million m^3 of sand on and in front of the beach with the aim that it would spread along the coast. Sand nourishment itself is not a new method to prevent coastline erosion. In fact, the Netherlands has had a structural nourishment program since the early 1990s. However, the Sand Motor is a unique beach nourishment due to its size, the design philosophy behind it, and its multifunctionality. The volume of sand used for the Sand Motor is about five times that of an average nourishment. The Sand Motor is intended to feed the adjacent coasts by using the natural forces of tides, waves and wind; in a way, it is built to "disappear". Another unique aspect of the Sand Motor is that it combines the primary function of coastal protection with the creation of a new natural landscape that also provides new leisure opportunities. From the outset, "learning by doing" has been a crucial part of the project. Because of its innovations, the Sand Motor has triggered considerable political and scientific interest from all over the world. Large research consortia such as the NatureCoast program were formed to conduct interdisciplinary research on the Sand Motor.

Interdisciplinary research: NatureCoast
NatureCoast is the largest research program that focused on the Sand Motor. The program was carried out by a large consortium of knowledge institutes, and the research was conducted in cooperation with end-users from private companies, research institutes and governmental organizations. The Dutch Technology Foundation (NWO-TTW) supplied the largest share of the project funds. The research in NatureCoast focused on six themes: coastal safety, dune formation, marine ecology, terrestrial ecology, hydrology and geochemistry, and governance. NatureCoast researchers collaborated actively with researchers from the NEMO project (Page 19), who studied the behavior of the Delfland coast, including the Sand Motor.

The purpose of this book
Interdisciplinary research is crucial to support integrated coastal protection solutions and to put the lessons learned into practice. In this book, we will to tell you more about both the innovative mega-nourishment, the Sand Motor, and about the uniquely interdisciplinary NatureCoast program. We share concrete research findings about the Sand Motor's behavior and about the societal context of the pilot Sand Motor. We also reflect on the merits of collaboration and integration within a multidisciplinary research program.

Table 1.
Project structure of the NatureCoast program.

Project	Purpose	Personnel	Organizations
Utilization	Further articulate research questions in close collaboration with end-users	1 professor	Delft University of Technology
Integration	Search for synergies between science projects; produce interdisciplinary research questions	3 postdocs	Delft University of Technology, Leiden University, University of Twente
Data	Facilitate data storage, sharing and dissemination	1 staff member	Delft University of Technology
Science *S1 Coastal Safety* *S2 Dune Formation* *S3 Marine Ecology* *S4 Terrestrial Ecology* *S5 Hydrology and Geochemistry* *S6 Governance*	 Interaction and adjustment of the seafloor and effect on coastal defense Sea currents and effect on swimmer safety Effect of organisms on dune formation Sediment exchange between beach and dunes Marine food webs in the shallow coastal sea Effect of organisms on the shallow coastal sea Vegetation succession in existing dunes Impact on community assembly in beach ecosystems Interaction between hydrology and geomorphology Chemical composition of nourished sand Freeridership & ecosystem services Societal acceptance of large nourishments	12 PhDs, 7 non-scientific personnel, 6 principal investigators	Delft University of Technology, Utrecht University, University of Twente; Wageningen University, VU University, Royal Netherlands Institute for Sea Research

MONITORING AND RESEARCH ON THE SAND MOTOR

Monitoring and Evaluation Program (MEP)
The Dutch Ministry for Infrastructure and Environment commissioned an extensive monitoring and evaluation project (the so-called MEP study). The MEP study evaluated the performance of the Sand Motor in terms of the original three project aims: stimulating dune growth in the project area, developing additional recreation and nature areas, and knowledge development through "learning by doing." In addition, the MEP study evaluated the feasibility of using the Sand Motor at other locations in the Netherlands.

The MEP was always intended as a monitoring project, focusing on gathering data and answering that the Sand Motor works. Hence, it does not answer fundamental scientific questions regarding the Sand Motor, such as on how and why the Sand Motor works. This task was left to the research programs, of which NatureCoast was the most extensive. This book intends to shed more light on the underlying processes behind the Sand Motor.

NEMO
NEMO is short for "Nearshore Monitoring and Modeling." NEMO is an ERC-Advanced Researchers Grant project involving three PhDs and three postdocs, led by the Delft University of Technology.

NEMO aims to advance our ability to forecast the shape of our coast in the coming decades. The heart of this project was an intensive measurement campaign along the Delfland coast. Researchers simultaneously measured surf zone topography, beach position, dune profiles, current speeds, local wave heights, and even sediment transports at the highest resolution possible. This data provides a more complete understanding of the coastal environment and its evolution over time, which is why many of NEMO's findings will also be discussed in this book.

The NatureCoast program
The diversity of the topics and the complexity of their interrelations called for a coherent and interdisciplinary program. This interdisciplinary requirement was already recognized during the funding application process. The definitive program structure reflected this ambition. In addition to NWO-TTW, NatureCoast was financially supported by Boskalis, Deltares, the Province of South Holland, Rijkswaterstaat, Van Oord and Wageningen Marine Research.

NatureCoast was structured around four projects (Table 1). It included twelve PhD candidates as well as three postdoctoral researchers from six different Dutch universities and one research institute. While the PhD candidates were tasked with the fundamental knowledge questions in their research fields, the postdoctoral researchers guided the integration of the research results.

Note that all 12 PhD researchers and all other authors will be introduced briefly in the chapters to which they contributed. Besides the three postdocs (as introduced on Page 15) two other postdocs also contributed to the program. Timothy Price (predecessor of Alexander van Oudenhoven) was involved in NatureCoast from May 2013 to October 2014, after which he joined Utrecht University as an assistant professor. Vera Vikolainen (predecessor of Ewert Aukes) was a postdoc from January 2013 to March 2017, after which she joined the European Parliament in Brussels as a policy analyst.

NatureCoast was unique among nationally funded research programs. Two factors stand out. Encouraged by the funding organization, the program organized regular end-user meetings, in which NatureCoast researchers shared their findings with end-users and worked on scientific issues that cut across the disciplines. This ensured the strong involvement of end-users and took advantage of their practical knowledge, insights and experiences. In addition, three postdocs had the dedicated task of integrating the research findings and encouraging collaboration among the PhD candidates across scientific disciplines.

Figure 1.
Introducing the PhD's s in the NatureCoast scientific research program.

Top row from left to right: Iris Pit, Isaac Williams, Corjan Nolet, Emily van Loon van Egmond, Lotte Bontje, Ewert Aukes.

Bottom row from left to right: Jantien Rutten, Max Radermacher, Simeon Moons, Marinka van Puijenbroek, Sebastian Huizer, Marjolein Post.

READING GUIDE

Each chapter of this book can be seen as a dialogue between researchers involved in the NatureCoast program and the end-users of the information. In addition to presenting the key research findings of the involved PhD researchers, each chapter also features a personal reflection by the principal investigator(s), partly looking back at the combined research findings and partly looking forward towards future developments in the field and their application. Finally, each chapter also features reflections from end-users; practitioners, policy makers and other stakeholders who are interested in how to put the findings to good use. We note that NatureCoast has always embraced discussion and dialogue. The views expressed by the investigators and end-users in this book are their own and do not necessarily reflect the vision of NatureCoast.

The outline of the book is shaped as an hourglass – after this broad introduction, we zoom in on specific research findings, and zoom out again to integrate those findings and to reflect on broader applications. Chapters 2 to 5 highlight specific research findings of the NatureCoast PhD projects and, if applicable, of related projects. The chapters deal with the societal context in which the pilot Sand Motor came to be, the workings of the physical system of the Sand Motor, dune development at the Sand Motor, and the impact of the mega-nourishment on its animal life.

After this, in Chapters 6 to 8, we relate the research findings to broader, overarching issues, such as multifunctional management of our coastlines and the worldwide application of sandy strategies. We summarize the main overall findings and put them in the context of the original aims of the Sand Motor, to assess how the characteristics of the Sand Motor have contributed to expected outcomes and also created more surprising ones, and to consider how this will continue in the future. With that knowledge, we reflect on the potential application of new sandy strategies, both in the Netherlands and abroad (based on experiences with four international case studies that we have been involved in). In the final chapter we reflect on the NatureCoast program, before leaving with reflections from key experts and end-users on the program and the usability of its findings.

Former member of the Gedeputeerde Staten (Executive Council)

LENIE DWARSHUIS – PROVINCE OF SOUTH HOLLAND

INTERVIEW

In what way is the Sand Motor unique to you as end-user?
"The Sand Motor is unique because it serves multiple purposes. That was new at the time, because before we had mainly done underwater sand nourishments. With that you do increase coastal safety, but you do not contribute to other functions or demands from society. With the Sand Motor, there is also room for nature and recreation, and it serves an innovative way to increase safety by building with nature."

How do you see the role of scientific research at the Sand Motor, as end-user?
"Indispensable. Because, even with all the coastal knowledge and expertise present in the Netherlands, the Sand Motor was still an experiment. The question was: Will nature, which of course always finds its own way, do what the clever scientific minds had calculated with all sorts of computer models? That was interesting for two reasons. First, for technical reasons: are we ready to predict what will happen with this kind of interventions in nature, and with building with nature? The second reason is more future-oriented: if things do go as expected, and all this prior knowledge and expertise turns out to work in practice, what are we going to do next? Because for me, the Sand Motor has always been a pilot or an overture for the question what would come next. And that is what I am currently working on, so as an end-user, the research on the Sand Motor is also a stepping stone to new horizons for me."

How relevant is multidisciplinary research on the Sand Motor for you as end-user?
"One should of course try to bring together all knowledge, expertise and science in the Netherlands. In the field of water management, but also concerning ecology: how will the flora and fauna react? Because the Sand Motor is an experiment, but a "calculated experiment", we aren't just trying something. And with a calculated experiment, the more disciplines you can accommodate, the better you can connect to what you expect and what can be monitored. And, hence, the clearer it becomes what you can do with it afterwards."

What are the main findings of the NatureCoast program for you as end-user?
"For me, these are very broad and certainly not only technical. The point is that there is every reason to say, based on the current research, that we now have experience and knowledge on how this concept can be further applied. Not only in South Holland, but also internationally. As far as I am concerned, the Sand Motor has always been a commodity - Dutch knowledge and expertise on sustainability that is gained here can be marketed elsewhere. For me, the drive was to be able to take the next steps with much more knowledge and certainty."

"Another outcome of the program that has struck me greatly is that the resistance to the Sand Motor disappeared like snow in the summer. Coastal residents and other stakeholders are now extremely enthusiastic about the project. At first we saw many crowded rooms with a lot of upset people, and a lot of distrust. But apparently seeing is believing. People who were initially afraid that their business activities such as beach pavilions, boat rentals, and kite surfing would no longer have a future because of the Sand Motor, have seen that the opposite is true. The same goes for the nature organizations, World Wildlife Fund, *Natuurmonumenten*, *Stichting Duinbehoud*: they were all initially skeptical. Nevertheless, through mutual efforts, they ultimately stepped on board. Now they are also unrestrained in their enthusiasm, and have participated in new projects such as the *Hondsbossche Duinen* with a very different perspective, based on the knowledge, expertise, experience and public support for the Sand Motor. And that is great to see."

How does the Sand Motor and the knowledge and experience gained there fit within your vision of the future of the Delfland coast?
"I am still very active in coastal development, for instance as chairman of the *Stichting Nieuw Holland*, which also helped me at the time to get private partners involved with the Sand Motor. Our foundation is now working on a position paper concerning the follow-up of the Sand Motor - What can the coast mean for the Netherlands, and South Holland in particular? The four cornerstones are flood safety, large-scale nature development, metropolitan location policy, and innovation and sustainability. All from the central question: How can a good coastal policy be climate-oriented but also innovation-oriented? And this means building on the ideas behind the Sand Motor and the lessons learnt from it."

Project manager for the Monitoring and Evaluation of the Sand Motor

CAROLA VAN GELDER – RIJKSWATERSTAAT

INTERVIEW

In what way is the Sand Motor unique for you as end-user?
"The Sand Motor is unique for *Rijkswaterstaat* because it was a pilot project, and we had never carried out such a large-scale intervention before. One of the reasons we started this pilot was to see how the entire coastal system would respond to a mega nourishment. Our main objective is, of course, coastal flood safety. To keep the coastline in place, and to let the coastal foundation keep up with sea-level rise, we have a national program, *Kustlijnzorg* (Coastline Management). The Sand Motor project is thus unique because the method differs from our usual way of working, and furthermore because with this pilot we intend to look into future proof ways of coastline management considering sea-level rise."

How do you see the role of scientific research at the Sand Motor, as end-user?
"What I see is that the Sand Motor has given scientific research a huge boost, because it requires new lines of thought and new activities on the part of all parties. This allows research to be conducted on a range of new issues; beyond the many aspects of flood safety, the project requires research on nature and recreation. We are pleased about this, because this type of research also offers us broader insights for the future of coastal management and maintenance."

"Of course, at *Rijkswaterstaat* we mainly focus on monitoring and more applied research; and with the help of fundamental research by scientists, we are trying to take that a step further. We are interested in what additional knowledge we can gain from this pilot that can be used in our end-evaluation of the Sand Motor and in other projects "

How relevant is multidisciplinary research on the Sand Motor for you as end-user?
"The Sand Motor would not have been built if the project had not been multifunctional. First, it would have been far too expensive for flood protection alone. But when you combine multiple functions many stakeholders are interested, and the strength of this project is that it actually involved all those stakeholders. This generated more appreciation of a multifunctional solution and support for it. In order to coordinate, monitor and analyze all these functions, and to identify their added value, multidisciplinary research is necessary. For *Rijkswaterstaat* it was interesting to see how this added value related to flood safety, nature and recreation could be used on other parts of the coast, which also face sea-level rise challenges. Protecting the Delfland coast is just one of our tasks, and the multidisciplinary lessons we learned here are a real added value that the Sand Motor has brought to the rest of the coast."

What are the main findings of the NatureCoast program for you as end-user?
" We are interested in many aspects of NatureCoast's research, and intend to apply them. These include the governance research that Lotte Bontje and Ewert Aukes worked on. Their study showed that, in order to properly set up this kind of policy measure, you must not forget to do so in a narrative way: why are you doing this? What are the benefits for the various parties? This is not standard procedure for organizations like *Rijkswaterstaat* and the Ministry, and in my opinion this insight is crucial and needs to be included in the policy-making process. And from a technical perspective, I am thinking of the studies by Max Radermacher and Jantien Rutten. These deal with how swimmer safety can be considered when creating such a large-scale nourishment, how measuring devices can be optimally used, and what lessons we can learn. But the findings go beyond just the Sand Motor, as we have more large sand nourishment projects, and will have many more in the future. Currently, we are conducting a major project at the *Ameland* tidal inlet, and are applying the results from our own research and that of NatureCoast."

What findings from the NatureCoast study go beyond findings of the Monitoring and Evaluation Program (MEP)?
"This is a Monitoring and Evaluation Program that *Rijkswaterstaat* has set up for the Sand Motor. We use a large number of measuring devices, which were also used by NatureCoast researchers. Iris Pit for example, conducted research into the chemical composition of the water and sediment, and found naturally occurring heavy metals in the area of the Sand Motor. We then examined together whether this was specific to the Sand Motor or if it also occurs elsewhere."

"Another aspect is swimmer safety. This is a concern for both *Rijkswaterstaat* and the Province of South Holland, which is formally responsible for swimmer safety. Of course, we didn't know in advance how the area would react to a Sand Motor, and that is why *Rijkswaterstaat* developed a swimmer safety application to indicate dangerous situations at the Sand Motor. Max Radermacher's research contributed to the wider application of this app, as well as investigating how such a broad approach affects swimmer safety. Working together in this research program ensures that we can now incorporate the methods he used in other projects. This kind of added value certainly makes it relevant for *Rijkswaterstaat* to participate in scientific research programs as an end-user."

TWO | GOVERNANCE ASPECTS

Ewert Aukes

SANDY STRATEGIES IN SOCIAL CONTEXT

INTRODUCTION

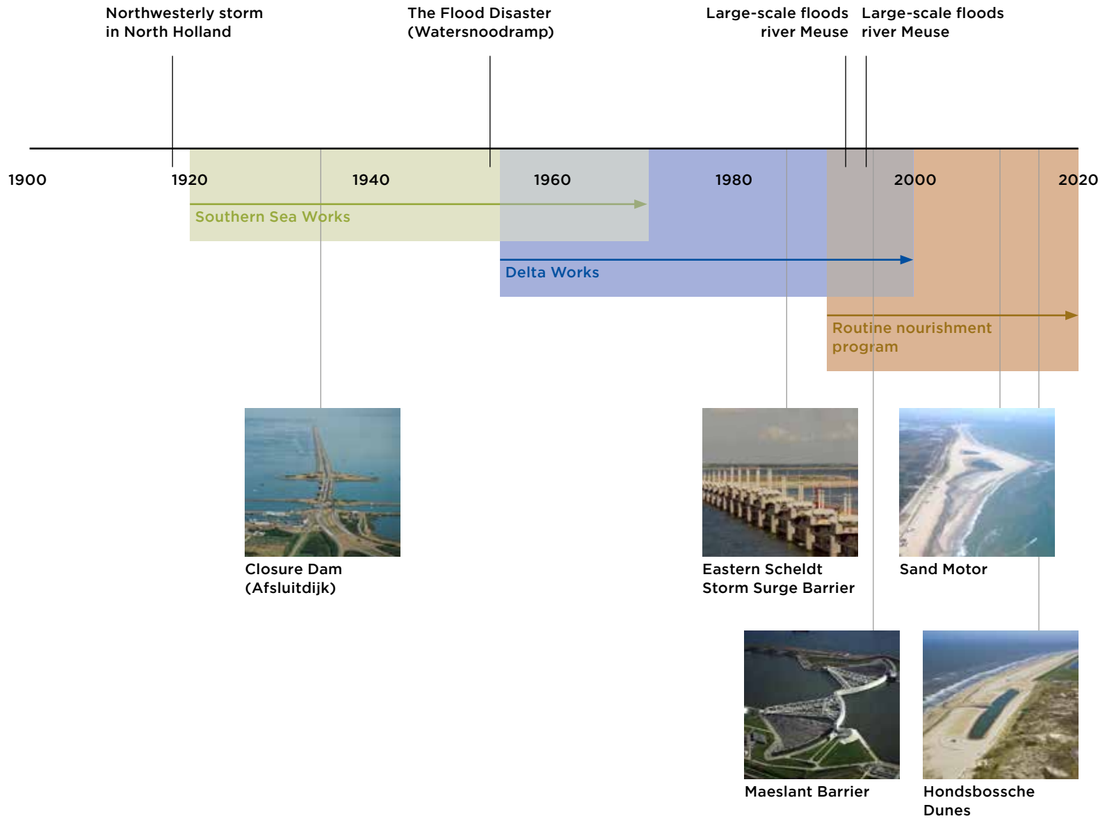
All over the world, climate change and sea-level rise are forcing societies to take action. They need to develop new and innovative approaches to adapt. But such technological innovations do not develop in a social vacuum; they are often closely linked to finding solutions to social challenges. The successful introduction of technological innovations, such as the Sand Motor, depends on whether a range of political and societal parties are willing and able to commit themselves to this solution. Considering the unprecedented scale, and thus potential social impact, of a project like the Sand Motor, it should come as no surprise that its introduction was not without challenges. In this chapter, we discuss why many political and societal parties came to support the Sand Motor pilot project.

We look at the social context of the Sand Motor from three related viewpoints. First, we place the Sand Motor in its social and political context. To understand the societal acceptance of the Sand Motor, we have to begin with the social and political background (Page 30), the history of Dutch coastal management. A specific set of spatial planning challenges along the west coast of the Netherlands guided the choice of location for the Sand Motor. In addition, Dutch coastal management reflects the democratic traditions in the country. This means that policy actors at many different levels can influence decision making, with citizens also having ample opportunity to participate.

Next, we consider aspects that affected the acceptance of the Sand Motor by organizations involved in the decision-making process. The second viewpoint explores how positive storytelling (Page 34) can become contagious and has contributed to the success of the Sand Motor. People tell stories all the time. The simple structure of a story – problem-development-solution – is a typical way of organizing our thoughts. We often communicate through stories, and so did decision makers and organizations dealing with the Sand Motor. The story element of multifunctionality linked the stories of many actors involved in the development of the Sand Motor.

The third viewpoint looks at how multifunctionality became an important argument, a successful frame to convince parties that did not yet support the idea of a Sand Motor (Page 38). These insights help us understand the importance of multifunctionality in coastal management as well as technological innovations in general. This multifunctionality, the fact that the Sand Motor had different perceived advantages that were appreciated by different groups of people, became important. It began to play a central role in how supporters talked about the Sand Motor, even though their stories were all slightly different. The Sand Motor's multifunctional character became its most important advantage, and multifunctionality became a key argument to convince others of its usefulness. Finally, our story would be incomplete without a view of the future (Page 42). It looks like multifunctionality as a frame or storyline is here to stay in societal and political discussions about sandy strategies and beyond.

Figure 1.
Timeline of Dutch flood risk management in the 20th century. (Photo credits: Eastern Scheldt, Closure Dam and Maeslant Barrier: beeldbank.rws.nl; Sand Motor: Rijkswaterstaat, Joop van Houdt; Hondsbossche Dunes: Boskalis)



Ewert Aukes

THE SOCIAL AND INSTITUTIONAL CONTEXT OF THE SAND MOTOR

Dutch coastal management history
Historically, socio-economic activities in the Netherlands have been mainly concentrated in the estuaries of the Rhine and Meuse rivers. The urban sprawl resulting from this activity is currently the home to a large share of the Dutch economic productivity, not to mention its population. In an area so close to the North Sea and with such socio-economic importance, coastal protection is a prime requirement. For centuries, the general principle of coastal protection in the Netherlands was building embankments to protect areas in danger of flooding from the sea.

Relying on embankments for coastal management continued in the 20th century (Figure 1). The last large-scale coastal management program in the Netherlands that relied primarily on embankments, were the *Zuiderzeewerken* (Southern Sea Works). As a result, embankments were built and fortified, as protection against nature. Necessitated by major flooding in 1916, this program intended to reduce the coastline of the Netherlands by closing off the *Zuiderzee*, which was subsequently called the *IJsselmeer* (Lake IJssel). Reducing the coastline would simplify maintenance of coastal protection works and decrease the protection needs in closed-off regions. Among other things, the *Zuiderzeewerken* included the construction of the *Afsluitdijk* (Closure Dam), a 32.5 km long causeway through the Wadden Sea connecting the Dutch provinces of Friesland and North Holland. With a main aim of coastal protection, the Southern Sea Works can be viewed as a monofunctional project. Limiting the coastal protection program to monofunctionality was possible, because the flood events triggered a heightened sense of urgency, while population pressure was still low in the first half of the 20th century.

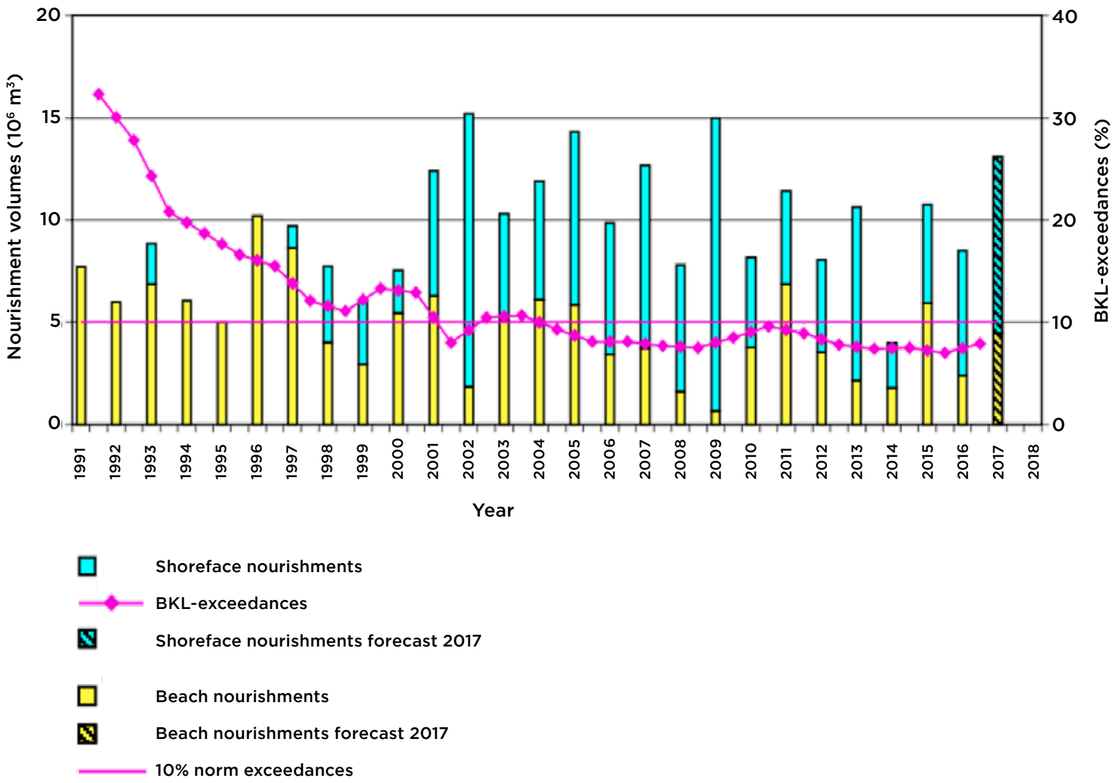
In 1953, the southwest of the Netherlands was struck by another major flood event: a Northwesterly storm combined with spring tide. Embankments in different places succumbed to the ferocity of the storm. As a result, 1,800 inhabitants perished and economic damage was high. The disaster came to be known as *De Watersnoodramp* (The Flood Disaster) and is a pivotal event in modern Dutch history. In the wake of the storm, the Dutch government convened a commission of high-ranking coastal management and civil engineering experts to draft a strategic plan to prevent a similar disaster from ever happening again. This so-called First Delta Committee Plan came to be known as the *Deltaplan*. It proposed closing off additional inland waters utilizing newly available steel-and-concrete engineering technology. Again, these structures were to be built *against* nature and serve the sole function of coastal protection.

Meanwhile, the Netherlands experienced rapid urbanization and population growth. As a result, competition grew among land uses in the increasingly crowded coastal areas. Coastal management could no longer focus exclusively on coastal protection. New ways of integrating land-use functions needed to be explored, sparking interest in land reclamation and integrated policies. From the 1980s onward, the effects of climate change, such as rising sea levels, further complicated the situation. These developments coincided with growing knowledge of ecosystems and their contributions to human wellbeing. Innovations in dredging technologies enabled sand dredging and nourishing beaches on an unprecedented scale. Gradually, a transition began towards more nature-friendly solutions in coastal management. Starting in 1990, *Rijkswaterstaat*, the Public Works Agency of the Ministry of Infrastructure and Water Management began maintaining a reference coastline, based on the Dutch coastline at that time. Annual, small-scale foreshore or beach nourishments became the new standard approach to maintain this *Basiskustlijn* (BKL; reference coastline, brown color in Figure 1).

In the 2000s, multifunctional space was still in high demand. By now, Dutch coastal managers had acquired considerable experience with beach nourishment. A combination of nourishment technology and Building *with* Nature was proposed. This spatial planning philosophy marked a subtle transition from aiming for one function to attempting to include as many functions as possible, moving from monofunctional to multifunctional land use. Building with Nature promotes an ecosystem perspective; not only minimizing ecological damage, but also developing nature and using natural processes for societal aims.

A pilot project was proposed that would experiment with many functions at once. And thus, the idea for a Sand Motor, in some ways a scaled-up version of previous nourishments, was born. The Sand Motor was designed to utilize natural North Sea currents. In that way, it would serve coastal protection on location and, by deliberate erosion and re-sedimentation, at other locations as well. In addition, the Sand Motor provided opportunities for developing nature, recreation and leisure opportunities, as well as promoting economic productivity. The Sand Motor is arguably the first

Figure 2.
Annual sand nourishment volumes in the Netherlands since 1991; the 21.5 million m³ of the Sand Motor is not included in the graph. (Figure by Rijkswaterstaat)



large-scale Building with Nature design put into practice.

It is no surprise that the Sand Motor was developed in the province of South Holland. This province is home to a large part of the urban conglomerate known as the *Randstad*, and the province is faced with significant spatial problems associated with population density. At the time, leisure areas for inhabitants of the growing cities were becoming scarcer. The European Natura2000 legislation required construction projects to include nature compensation, which was becoming more and more difficult to achieve. The Sand Motor offered an opportunity to innovate with spatial policies, and the provincial government seized this opportunity with both hands.

The arena of Dutch coastal management
The overall Dutch coastal management ambitions were stated in the 2009 National Water Plan. First, the coastal foundation is to grow proportionally to sea-level rise. Second, this process is to be stimulated using sand and the natural dispersal of this sand along the coast. Third, in addition to coastal protection, coastal management should focus on a balanced development of nature, economy and recreation.

The 2009 Water Act remains the main water and coastal management policy in the Netherlands. It relates water management to other policy areas, such as nature, environment and spatial planning. The Water Act distinguishes two water authorities. Water authorities manage coasts within their territory, while the State deals with coastal issues that overlap the boundaries of the water authorities. Water authorities have the task of planning, building and maintaining regional coastal management projects, as long as the coastal stretch in question is not a primary defense structure. The national government defines strategic policy and manages supra-regional defense structures.

Rijkswaterstaat is the national executive agency entrusted with the coastal management program. This has been in place since the formulation of a reference coastline in 1990, beyond which the Dutch coastline is not supposed to erode. *Rijkswaterstaat* performs annual inspections of the coastline, leading to nourishment activities, where necessary. Every four years, *Rijkswaterstaat* compiles a long-range nourishment plan, with an annual budget of 12 million m³ sand for immediate nourishment (Figure 2). *Rijkswaterstaat* also oversees applications for integrated water permits, which have to be requested when flood defense structures are constructed or modified. Such projects also need an environmental impact assessment, which evaluates the environmental impact of a preferred solution and compares it to alternative solutions.

Under the Water Act, provincial governments are not considered as water authorities. Nevertheless, they are thoroughly involved in water management, supervising regional water authorities and municipalities and coordinating their activities. Provincial governments have a significant influence on the coastal management process thanks to their role of approving project plans.

Like provincial governments, municipalities do not officially count as water authorities, although they do have certain water management tasks unrelated to coastal management. Although they are not responsible for coastal safety and spatial planning, municipalities are responsible for zoning plans. In the zoning process, other actors who might be affected by coastal management – such as drinking water companies, nature NGOs or knowledge institutes – can influence the decision-making process through the general public participation mechanisms in place. For example, final project plans have to be available to the public at the competent authority, where they can be inspected by everyone.

Besides these annual and multi-annual coastal management activities, the national Delta program is in place to guarantee long-term safety from flooding. The Second Delta committee established this long-term program in its final report in 2008, entitled *"Samen werken met water"* ("Working together with water"). The Second Delta committee advocates a coastal management approach that ensures long-term flood protection and freshwater management strategies.

Although this legal and political structure represents the legal blueprint for coastal management projects, this is certainly not the only way such projects can be organized. While non-experimental projects are generally initiated and managed by water authorities under the Water Act, experimental projects can be carried out by actors who are not water authorities, as was the case with the Sand Motor.

Figure 1.
Overview of the narrative research approach.

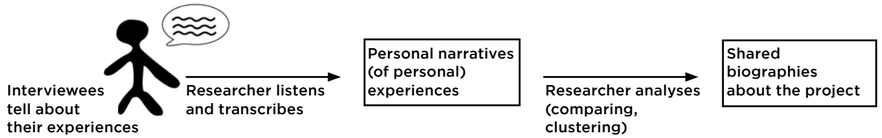


Figure 2.
Graphical representation of the narratives.

Lotte Bontje

NARRATIVES OF THE SAND MOTOR AND INSIGHTS INTO THE POSITIVE SPIRIT AROUND THE PILOT PROJECT

Lotte Bontje obtained her PhD at the Faculty of Technology, Policy and Management, section Policy Analysis at Delft University of Technology in 2017. She currently works at the municipality of Lansingerland, as an advisor for household waste and public space.

Dissertation title:
"Narrative perspectives on the development of coastal pilot projects."

PhD supervisors:
Jill Slinger (Delft University of Technology)
Wil Thissen (Delft University of Technology)

Pilots such as the Sand Motor are only possible with the cooperation of many organizations - represented by even more individuals. Each of these individuals will have experienced the process differently. Generally, people make sense of experiences through our so-called "narrative understanding", arranging our thoughts using stories. Through their context, characters, events and development, stories provide recognizable structures that help us organize our experiences. Research into the stories associated with a pilot project, such as the Sand Motor, is therefore research into the personal experiences of project participants.

In this section, we explore the personal narratives of the people involved in the start of the pilot Sand Motor. First, we describe the peoples' shared narratives distilled from the Sand Motor study. Second, we discuss the insights that these narratives provide.

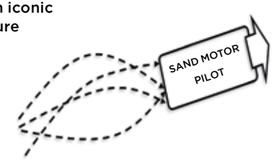
Three narratives of the Sand Motor
The starting point of our research were the personal narratives of the participants involved in developing the Sand Motor (Figure 1). Each personal narrative has a certain time span, spatial orientation, sequence of events and problem-solution structure. We revealed three commonly shared Sand Motor narratives (Figure 2). Each of these reflects how a group of people explained the realization of the pilot Sand Motor. Note that these biographies represent personal narratives and interpretations, not the official view of the agencies or institutions that the individuals work for.

The first narrative presents the Sand Motor as an unknown and unfamiliar thing thrust upon the region from a higher administrative level, which then had to be implemented (top row of Figure 3). This is how some local officials and local actors experienced the development of the Sand Motor.
The narrative covered several years and placed the Sand Motor in the local context. Interestingly, the novelty of the project and the associated uncertainties for the region were not necessarily interpreted as negative. The project offered several positive prospects, including the chances for large-scale natural processes along the coast, and opportunities for the region as a result of the uniqueness of the Sand Motor.

In the second narrative, the Sand Motor is viewed as an iconic outcome of a long evolving process. Starting in the seventies or eighties, this story has a far longer timespan. This narrative also has a higher spatial scale than the first; it simultaneously refers to regional and global processes, such as the development of Integrated Coastal Zone Management or global developments in coastal engineering. Interestingly, this narrative has at least two slightly different versions. Some interviewees from the field of coastal engineering consider the Sand Motor "a new step in the development of nourishment techniques" serving multiple purposes. Others view the Sand Motor as "a new step in the integrated development of coastal zones," because integrated development incorporates the idea of multifunctionality. In such a way, several mutually reinforcing stories about the Sand Motor became interwoven. The majority of the personal narratives fit into the category of "iconic departure biography."

The third narrative pictures the Sand Motor simply as a stage within an on-going and incremental process of

Figure 3. Overview of the three narratives on the development of the Sand Motor. Note that these are interpreted personal narratives, and do not represent the official positions of agencies or institutions.

Three biographies: The Sand Motor...	Details and varieties within the biographies:	Based on personal narratives from the:	Time-span	Spatial orientation
1 As something (unknown) that needed to be implemented in the region	**a** Providing opportunities for actors	Municipality, surfer association, nature development, water authority	Some years	Local to regional level
	b Potentially causing danger for actors	Drinking water company, municipality, village	Some years	Local to regional level
2 As an iconic departure 	**a** Emerged from coastal defence techniques/ nourishment techniques/ successor of the Delta Works	Dredging industry, RWS	Decades or some decades	Regional to global level
	b Emerged from knowledge development in coastal engineering (closely related to above)	Engineering science, RWS	Decades or some decades	Regional to global level
	c Emerged from Integrated Coastal Zone Development/ regional development	Province, provincial council	Decades or some decades	Regional to global level
	d Emerged from unwanted plan development (for economic activities which changes the area's character)	Village	Decades or some decades	Regional to global level
3 As a stage in an incremental process of coastal development	**a** Nourishment, not really new techniques, but with some improvements relating tender procedures and ecological impact	Consultancy	Some decades	Regional to global level

coastal development. In this perspective, the Sand Motor has the advantages of limiting disturbance to biodiversity and the ecosystem while promoting efficient interaction and collaboration between different actors, but the pilot is not necessarily an innovation. Although this narrative was initially based on only one interview, many from the coastal community later shared this view.

A positive spirit around the Sand Motor
The shared narratives reveal how many people have positive memories of the pilot Sand Motor. The "iconic" quality of the Sand Motor (Narrative 2) was emphasized by core participants in the pilot project. For others who were closely involved in the actual implementation and execution, the Sand Motor was an "exciting unknown project" (Narrative 1). The narrative that viewed the Sand Motor as neither an "exciting unknown project" nor an "iconic departure" (Narrative 3), had a narrow base in the interviews with the core participants, yet it enjoyed broad support from the coastal community.

It is no coincidence that Narrative 2 was common among core participants involved in the earlier phase, that of the realization of the pilot Sand Motor. After all, these people worked hard to communicate the project's unique and promising nature to make it a reality. Emphasizing the Sand Motor's "iconicity" in their personal and shared narrative is a logical consequence of their ambition. This type of communication could be identified early in the process. For instance, in their personal narratives several interviewees portray the project as "an impulse for the Dutch (dredging) industry," although they did not have any personal relation with this business. And some actors praise the "room for natural and morphological processes," even when they were not (primarily) concerned with this topic themselves.

These traces of early-phase storytelling are examples of how storytelling can resonate in such processes, generally increasing participants' inclination to commit themselves to the process. During the pilot Sand Motor, more and more people began to share elements of the positive stories. Discovering these elements in different personal narratives indicates how effective storytelling was during the development of the Sand Motor.

Did multifunctionality help the pilot project resonate?
But what made the idea behind the pilot Sand Motor so attractive for people to get involved in positive storytelling? One of the explanations is that the idea comprised so many ingredients that it could suit everyone's taste. At the same time, it retained key elements like the importance of coastal safety, something which is undisputed in the Netherlands. Its multifunctionality provided space for everyone to get involved in sharing positive stories; it allowed people from diverse organizations to endorse the unique and promising project in a way that fit their own organization. As a result, during the decision-making process and project realization, everyone could return to their own base with appropriate news. In this way, support could grow and was ensured among many participating organizations.

After the decision-making and project preparations, the Sand Motor was ultimately constructed. The Sand Motor was and is "doing well" and does indeed provide multiple functions for different users. Critical voices seem to have faded away. From the moment that the peninsula was created, people came from far and wide to explore and discover. The many nature-related excursions, sport and cultural activities that currently take place at the site show how different groups have taken possession of the new spot. Companies (e.g., dredging firms) organize tours for potential clients, as does the project team of the public works agency *Rijkswaterstaat*, which receives guests from foreign government organizations, from universities and from other educational institutions. So, after being subject of many (positive) stories, the Sand Motor itself functions as a place where experiences and stories are created and told.

In short, the multifunctionality of the Sand Motor has allowed actors to select and couple diverse aspects into their own narratives of the project. This has definitely helped to connect the initiators of the project and the many other organizations involved. The resonance of positive storytelling has contributed to the positive spirit with which the Sand Motor is still regarded within the Dutch coastal management community.

Figure 1.
Locations of Sand Motor and Hondsbossche and Pettemer Sea Defense

Ewert Aukes

UNDERSTANDING PROJECT SUCCESS THROUGH FRAMING CONTENT AND CAPABILITY

Ewert Aukes obtained his PhD at the department of Governance and Technology for Sustainability at University of Twente in 2017. He currently works at the department of Science, Technology and Policy Studies at University of Twente, as a postdoctoral researcher.

Dissertation title:
"Framing coastal squeeze: Understanding the integration of Mega-nourishment schemes into the Dutch coastal management solutions repertoire: An interpretive analysis of coastal management processes."

PhD supervisors:
Hans Bressers (University of Twente)
Kris Lulofs (University of Twente)

The overall consensus is that the Sand Motor has been a success. Although it is still too early to indicate the long-term consequences of this kind of large-scale beach nourishment, the success stories told about the Sand Motor tend to muffle the critical ones (Page 34). So, how did the Sand Motor come to be perceived as "successful"? And does the Sand Motor's proclaimed success serve as a promise for future large-scale projects using sand? As we shall see, "framing" can provide a valuable lens to understand how this general consensus developed, and why critical stories have had a hard time surviving in the political debate as well as in society.

Generally speaking, the Sand Motor can be characterized as a "smooth" project. Few disagreements among actors were so persistent as to significantly delay the project or even threaten its realization. This meant that the Sand Motor was quickly implemented (from the first ideas in 2006 to its construction in 2011) and helped to define it as a success. The province of South Holland led the Sand Motor project, which is unusual, since provincial governments are not formally responsible for coastal management in the Netherlands. However, a growing population and its demand for space presented a pressing spatial planning issue for the province. Consequently, the Sand Motor concept of a large, multi-purpose sand body went down well with the province.

Unfortunately, the Sand Motor is by no means a blueprint for future large-scale coastal engineering projects. A case in point is the coastal reinforcement project carried out at the *Hondsbossche en Pettemer Zeewering* (HPZ) (Hondsbossche and Pettemer Sea Defense, Figure 1), which took more than ten years to be implemented with disagreements and personnel changes (first idea was raised in 2004, but construction only occurred in 2015). In this project on the North Sea coast of North Holland, a proposed seawall reinforcement eventually turned into a large beach nourishment scheme. The evolution of the proposed solution coincided with changes in which organization was in charge of leading the project. To understand the role of framing, the transition period from one proposed solution to the next is especially telling. Comparing the smooth Sand Motor project and the rocky HPZ project helps us to understand how framing affects successful realization of large-scale projects using sand.

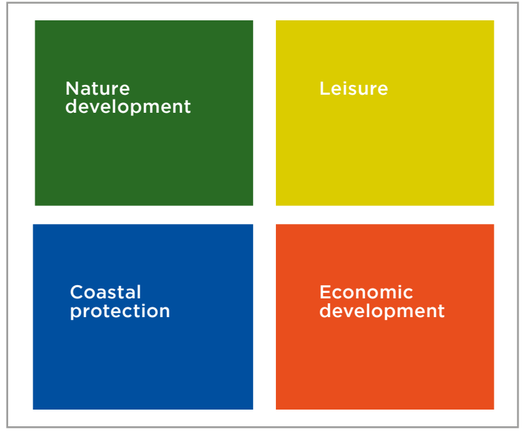
Let us first introduce the concept of framing. This concept assumes that interpretations of what happens differ from person to person and may depend on education, experience, or even the organizations people belong to. Applied to policymaking, framing theory states that actors interpret how desirable a policy and propose solutions based on their "frame." For example, one policy maker might recommend lowering taxes to encourage consumer spending, while another might argue for increase wages because they are viewing the problem from different perspectives. We will consider two aspects of framing here: the content of the frames and the actors' framing capabilities.

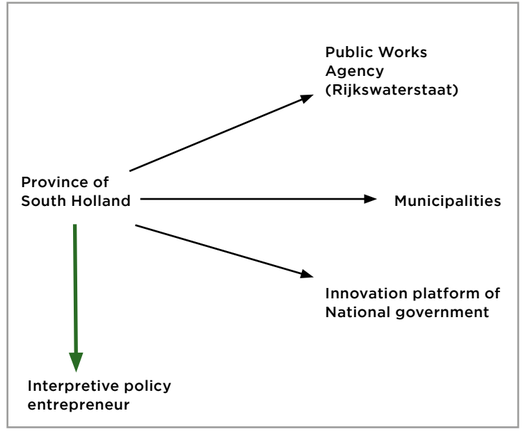
Content of the frames
Framing content refers to the ideas actors have about a policy situation. In coastal management, this could mean whether they advocate a traditional "hard" engineering solution or an innovative "soft" one (Figure 2, next page). If the goal of policy making is that an actor is able to successfully implement their proposal, being able to vary framing content is an advantage. Doing

Figure 2a and 2b. (below)
Illustration of "hard" versus "soft" engineering. The photo on the left shows the original "Hondsbossche en Pettemer Zeewering", a large dike in North Holland, whereas the photo on the right shows the same construction fortified by sand nourishment rather than additional hard structures. (Photo credit: Boskalis.)

Figure 3. (far below left)
The four functions of the Multifunctionality frame.

Figure 4. (far below right)
Framing capabilities and the result of a versatile framing content.





this allows an actor to tailor their message to resonate with other actors' framing content. This ability played a role in both the HPZ project and the Sand Motor, albeit in different ways.

In 2006, the province of North Holland proposed reinforcing the existing HPZ with an expensive traditional seawall, which would, however, have meant "sacrificing" half a village. This proposal ignored regional economic and demographic developments – both pressing matters in the region – and it did not create new recreational space. With its strong focus on coastal safety, the provincial government disregarded other framing contents. For actors with other frames, the proposal would make the situation even worse. In other words, framing the solution in terms of a traditional, monofunctional seawall reinforcement was too limited, and was unable to adapt to other framing contents. Omitting these other framing contents created a rift between the provincial government and other actors. The resulting political impasse was only overcome as another organization gradually took over as project lead, and as a more versatile, large-scale sandy nourishment scheme was chosen to reinforce the coast of North Holland.

How different was the Sand Motor project! From the start, the province of South Holland, which led the project, advocated for a project which would protect the coast, enable leisure activities and encourage economic development at the beach, while simultaneously sparking national and global interest for an unprecedented Dutch coastal innovation (Multifunctionality frame, Figure 3). Such an integrated vision had the potential to get many actors on board, even if their framing content represented only one of those elements. While some aspects, such as the precise location and shape of the Sand Motor, were thoroughly debated, its integrated design eventually facilitated a broad coalition in its favor. In the end, the Sand Motor was not only realized because of the versatility of its framing content (Figure 3), but also due to the framing capabilities applied in the project.

The actors' framing capabilities
Framing capabilities include the interactive components of framing: whom an actor chooses to communicate with and what they choose to communicate. This strategic use of framing depends on a sensitivity, permitting actors to adjust their framing content to the frames of other actors. So, framing is not something one does or does not do. Rather, we are all able to frame effectively to a certain degree, if we are able to develop this sensitivity. In the two projects, different framing capabilities resulted in different outcomes.

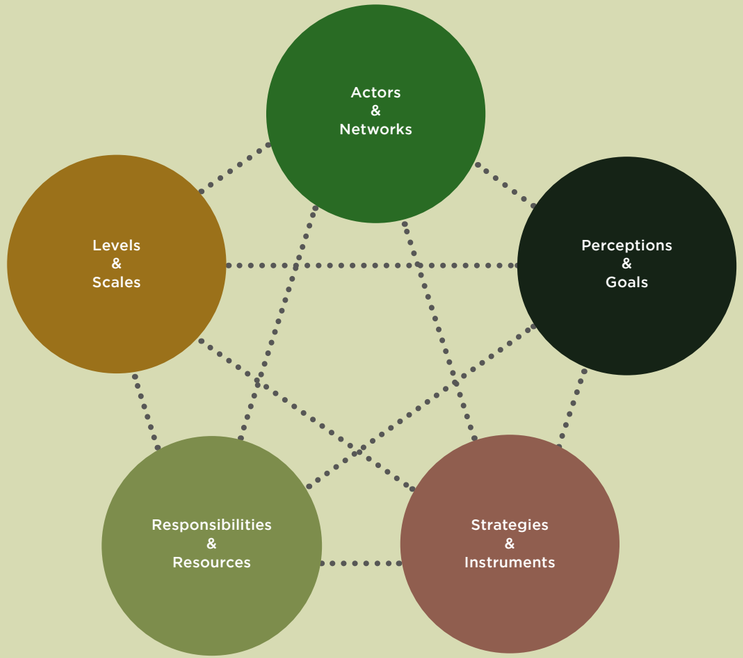
In the HPZ project, the rigid framing content present in the North Holland government's proposal reflected a low sensitivity towards other actors' framing content. The proposal showed insufficient understanding of other actors' perceptions and did not include measures to consider these. Additionally, the rationale for the monofunctional seawall reinforcement was not enough to convince the Ministry of Infrastructure and Environment to authorize the project. However, this was not only due to the provincial government's lack of sensitivity to other actors' framing content, but also due to the limitations of the proposed solution. The example of the HPZ project indicates the difficulty of convincing other actors to adopt a policy solution when they have different interpretations of the problem.

The versatility of the Sand Motor provided many more potential framing options – and the provincial government of South Holland seized these. It began by involving many actors in the process and trying to understand their interests. A broad advisory board was established for the project, including a high profile chairman and municipal delegates; this board provided information and permitted consultation. With a thorough understanding of the framing content of other actors, the provincial government began a kind of "promotion tour" to advocate for its proposal, much like a travelling salesman promoting a product at various doorsteps (Figure 4). It visited multiple political organizations – such as a national innovation platform and *Rijkswaterstaat* – and presented the project to the parliamentary forum for spatial planning projects. The province was able to gain the support of these organizations as a result of the versatility of the framing content, which allowed them to broaden or narrow the range of functions depending on whom they were trying to convince. Once the province found a way of framing the Sand Motor's functions that resonated with another organization's framing content, the added value would appear, and the other actors would become convinced of the project's usefulness. The ability to find the right tone and arguments resulted in a growing coalition of organizations supporting the Sand Motor through its construction in 2011.

It takes a creative, daring leader
The Sand Motor project not only shows that a versatile framing content helps an actor to convince others, but that these options have to be deployed skillfully to achieve an effect. This may be more difficult, especially in less experimental projects like the HPZ project, where pre-existing coastal safety criteria determine the response. In such cases, it requires a creative and daring project lead to move beyond pre-defined framing content and find innovative coastal management solutions that might be more suitable.

The Sand Motor and HPZ projects developed at a time, when mega-nourishment and multifunctional schemes had received enough attention to become dominant frames in Dutch coastal management. Arguably, the positive framing resulting from the Sand Motor project led to the revised, and successful, HPZ project, resulting in the *Hondsbossche Duinen*. The fact that large-scale projects using sand such as the Sand Motor can be framed as multifunctional makes them adaptable to a variety of frames. However, they do not frame themselves. Individuals or organizations need to have the sensitivity to know where and how such large-scale nourishments can be successfully promoted.

Figure 1.
Five interrelated dimensions of governance. (Source figure: Hans Bressers and Nanny Bressers (Eds.) (2015), Governance Assessment Guide, Almelo: Vechtstromen Water Authority.)



Hans Bressers

MULTIFUNCTIONALITY AS A SUPPORTING FRAME AND STORYLINE

REFLECTION

Hans Bressers is a professor of Policy Studies and Environmental Policy at the University of Twente. Within NatureCoast, he was the Principal Investigator for scientific research project S6, which focused on the governance aspects of the pilot Sand Motor.

This chapter deals with how the Sand Motor came about. This intriguing question led researchers Ewert Aukes and Lotte Bontje on a quest that provided many insights into the dynamics of the decision-making process leading up to the pilot Sand Motor. The researchers approached the issue from different, but related starting points: the frames that guided stakeholders to interpret the actual case (Page 30), and the storylines which stakeholders used to understand the whole project (Page 34).

Of course, there are other ways to approach governance questions. The term "governance" was first used in policy studies in the terms "multi-level governance" and "multi-actor governance." Multi-level governance means that a given issue is not dealt with at a single level, for instance national or municipal, but at multiple levels simultaneously (e.g., national *and* municipal). It rarely makes sense to look for the "best" level to arrange things. Instead, it is more useful to make sure that the various levels involved are well aligned. In the case of the Sand Motor that was not just true for the decision-making levels. The Sand Motor itself is a great example of a very local measure explicitly intended to serve much of the Dutch coastline.

Multi-actor governance means that a given issue is not just a concern for one actor, the "decision maker." It involves the interplay of many actors, both governmental and non-governmental, and often includes stakeholders within sectors. In multi-actor governance, the sector is not just the object of decisions, but actively involved in steering –and sometimes opposing– them. The Sand Motor was clearly a case of such interplay of actors.

Analyzing governance means identifying multiple goals and ways to achieve these. Goals can depend on different perceptions of what core issues are at stake – and they are often compromises. As a result, these goals are sometimes contradictory. Thinking in terms of governance rather than "policy" or "administration" also means that we need to recognize the variety of strategies and instruments proposed to achieve those goals, and the different responsibilities necessary to implement them. Few water projects would be feasible in the Netherlands without pooling resources, both financial and administrative. As illustrated in Figure 1, the key elements of governance are interdependent, interrelated and make governance and decision making a complex process.

Studies of the NatureCoast project approached governance from the point of view of "perceptions." A key result is the importance of "multifunctionality" as both a supportive storyline and a frame for the project. Multifunctionality refers to the multiple goals that were included in the Sand Motor pilot, but studies also show how multifunctionality made it possible to integrate various scales, actors, potential strategies, responsibilities, and resources. In other words, the emphasis on perceptions has not limited the studies, but has provided a starting point for considering all the "rooms of the governance house."

Considering the usefulness of concepts like frames and storylines, one cannot help but view the basic idea of "Building with Nature" as a powerful storyline and frame itself. While the name might change over time, the basic idea remains the same –aligning with nature rather than fighting it– and this has proven to be a compelling one that has opened many stakeholders' minds towards new and innovative options. The realm of its use has been rather quickly and vastly expanding.

The European Union already adopted the Building with Nature idea in the mid-2000s, promoting it as "working with nature." The World Association for Waterborne Transport Infrastructure also embraced the term in 2011. More recently, the United Nations placed this philosophy at the core of its report *Nature-based Solutions for Water* (2018), connecting it to other "framing buzzwords," such as circular economy, green growth, sustainable development goals and resilience.

On World Water Day 2018, the concept of Building with Nature was strongly supported in a position paper by the Dutch special envoy for international water affairs, Henk Ovink, and the director of EcoShape, Henk Nieboer (see Pages 3 and 187). Finally, the concept is also attracting attention for applications further inland, linked to climate adaptation measures. One can conclude by saying that Building with Nature is not just a frame for nature-based solutions, but an extremely successful one with a bright future.

Program director of the Sand Motor

HANS KLEIJ – PROVINCE OF SOUTH HOLLAND

INTERVIEW

In what way is the Sand Motor unique to you end-user?
"It is unique to us because it has enabled us to achieve three things at once. First, long-term coastal reinforcement. Second, it was a large contribution to the amount of recreational area in the southern part of the *Randstad*. We had a deficit of some 40,000 hectares of green space compared to similar regions such as London, Paris and even the Ruhr area in Germany. And third, we were also able to show something innovative, applying the principle of Building with Nature, and with all PhD candidates who studied the Sand Motor. This gives us a knowledge advantage over other countries; they might be able to dredge more cheaply, but we know more about the overall consequences and driving forces of mega nourishments."

How do you see the role of scientific research at the Sand Motor?
"I found that scientific research created trust in the concept behind the Sand Motor. Many parties were against it when we had just started. They were afraid that things might go wrong, swimmer safety would be at stake, and they argued that the current nourishments worked well anyway, and so on. But the scientists, who were represented in all kinds of groups, could give a considered response to these objections. For example, a number of Delft University of Technology professors were part of the steering committee: Marcel Stive and Huib de Vriend. And Suzanne Hulscher of the University of Twente took part in the innovation platform, chaired at the time by Prime Minister Balkenende. Those experts could tell the scientific story: "If we put the Sand Motor at that specific location at Ter Heijde, then we will really get a sediment flow to the north and to the south. Of course, we cannot predict everything, but most sand transport will function in the intended way, namely to strengthen the coastal foundation." And it was mainly this scientific foundation that made society and politicians feel good about the Sand Motor; we could explain the effects of 21.5 million cubic meters of sand deposited at once. Later on, when we had to appear before a committee, we could also respond to their questions with the help of scientific insights. Science was indispensable to us throughout the process."

How relevant is multidisciplinary research on the Sand Motor for you as end-user?
"Multidisciplinary knowledge is invaluable for achieving the multiple goals set by the Sand Motor consortium. When the Sand Motor was in place, we started the NatureCoast program with the NWO. All these young people have produced great research, which in turn positions the Netherlands in the forefront of hydraulic engineering. The multidisciplinary approach of NatureCoast ensured that not only was technology taken into account, but also ecology and governance: how do you tackle these kinds of processes, who are the stakeholders, why do you encounter resistance and who can help you? The combination of all disciplines made the project a success."

What are the main findings of the NatureCoast program for you as end-user?
"What I got out of it, besides all kinds of technical aspects, is that this way of carrying out coastal maintenance is much more cost-effective than the way we used to organize this in the Netherlands. In the past, *Rijkswaterstaat* placed small quantities of sand along the entire coast to nourish that coast. This had all kinds of effects, including the occurrence of quicksand. I used to be in charge of enforcement for the province of South Holland. We regularly had to close the beach during the high season, because these nourishments created dangerous situations in which people could drown. That is another advantage of the Sand Motor: it deposits every grain of sand where it should naturally be, through the principle of Building with Nature, via all the laws of nature."

How important was the understanding of each other's stories and ideas for the development of the Sand Motor?
"This is a very important aspect, because everyone operates from their own perspective, visions and dogmas. We engaged in intensive dialogues with all the different parties to understand their perspective. And sure, it is multidisciplinary and everyone can have an opinion, but the process must also be managed. Lotte Bontje, Ewert Aukes and Vera Vikolainen conducted this research, which clearly showed how different the stories of different stakeholders were. The fact that you know and understand each other's stories has brought important insights, but these differences also required guidance in terms of governance. In the end, things have to be concluded and decided, and I would argue that gaining those insights contributed to the success of the Sand Motor."

Advisor and specialist in chemical, environmental and civil engineering

RONALD WATERMAN – PROVINCE OF SOUTH HOLLAND

INTERVIEW

In what way is the Sand Motor unique for you?
"The Sand Motor is not unique within the Building with Nature idea. Building with Nature as a concept started in 1980, first with the *van Dixhoorn* triangle at Hoek van Holland, followed by the *Slufterdam*, the *Maasvlakte II*, the widening of the Delfland coast, Seaport Marina IJmuiden, and *Kennemerstrand* and *Kennemermeer*. After them came the Sand Motor, followed by other projects. The Sand Motor is just one star in that constellation; and, compared to the other projects, the one that is most difficult to export commercially or apply in other places."

"What is unique about the Sand Motor, however, is that it assumes that the coastline is not an equilibrium line at the beginning, but strives for it in the long term. All the other plans have tried to create an immediate dynamic equilibrium, where erosion and accretion are approximately in balance, with low maintenance and with a minimum of hard, defensive elements. The uniqueness of the Sand Motor is the process. Furthermore, it is very interesting as a pilot, and as a way to generate knowledge about sediment transport, dune formation, the emergence of pioneer plants, wind transport of sand, and so forth."

How do you see the role of scientific research at the Sand Motor, as end-user?
"I see scientific research as important for the Sand Motor, but that also applies to all the other projects that were initiated by Building with Nature. In fact, these projects always have to deal with what I call the 5 O's in Dutch (*overheden, onderwijs, onderzoek, ondernemingen* and *omgeving*): the authorities, education, research, private companies (both consultants and dredgers) and the surrounding environment. The latter means citizens, NGOs, and nature, environment and landscape in general. All five aspects need to be considered if we are to achieve our objective of creating the project and sharing the knowledge gained in making it. In this respect, education and research are the focal points for science."

How relevant is multidisciplinary research on the Sand Motor?
"The whole family of Building with Nature solutions requires an integrated and multifunctional approach, and that means multidisciplinary research. This is necessary to provide an answer to the question "How can we arrive at weighted and sustainable solutions for existing and future problems, while creating added value?" While doing so, we also need to investigate the relationships between problems, how they relate to the hinterland and to the adjacent lakes, rivers or sea. In my experience, applying the Building with Nature concept is not enough. I have therefore already developed the new concept, "Aquapuncture", which aims to revitalize waterways and their waterfronts. I believe this will become just as important as Building with Nature!"

What are the main findings of the NatureCoast program in your eyes?
"NatureCoast's research contributes to an enormous challenge: 80% of the world's largest population concentrations are located along coasts or in delta areas. This makes it imperative that we develop answers to questions about scarcity of space for living, working and recreating, and the infrastructure needed to support this. And all of this combined with the vulnerability of this infrastructure to climate change. Although NatureCoast's research has contributed, much remains to be done."

What does the Sand Motor mean for the future of sandy solutions or Building with Nature?
"In itself, the Sand Motor has an important function as an icon, because it has generated enormous attention. It is a special "baby" in the series of Dutch coastal developments. But in my opinion, we need to look beyond the Sand Motor and consider the entire range of Building with Nature projects so that we can export our knowledge and apply it abroad. I am raising this issue now, because this is not mentioned frequently enough!"

THREE | **PHYSICAL SYSTEM**

Photo (left page): Naming the key elements of the Sand Motor coastal area.

Arjen Luijendijk

IMPACT ON PHYSICAL CHARACTERISTICS

INTRODUCTION

The Sand Motor is located at the Delfland coast between the entrances of Scheveningen and Rotterdam harbors. This southern part of the Dutch coast is subject to structural erosion; the coastline migrated landwards about 1 km between 1600 and 1990. After the coast retreated about 300 m in the 18th century, rubble mound groins were constructed. As the coastline continued to erode despite the groins, sand nourishments were introduced as a mitigation measure in the 1970s. Since then, nourishments have been implemented more frequently, especially after the Dynamic Preservation Act of 1990 dictated that the 1990 coastline position had to be maintained at all costs. The first nourishment at the site of the Sand Motor occurred in 1986. Since then, the coastline was re-nourished eight times prior to the construction of the Sand Motor. In total, approximately 55 million m^3 of sand was added to the Delfland coast up to 2011, to mitigate erosion and reclaim land, with a new nourishment on average every 3 – 5 years. In the last years, the nourishment volumes in this stretch of coastline reached ~1.7 million m^3 per year.

In this chapter we will discuss the impact the Sand Motor has had on the various physical processes interacting with the sand nourishment. Some of these physical processes have caused the sand to spread along the coast, reducing the initial size of the disturbance and hence the impact over time. For a comprehensive understanding of the behavior of the Sand Motor we have adopted a multidisciplinary approach to study all relevant aspects. We will discuss the drivers that have shaped the Sand Motor between 2011 and 2018: i.e., the tidal currents, waves, wind, and sediment transport. In addition, we will look at the processes that are influenced by the changing Sand Motor, like the hydrology (freshwater reservoir) and geochemistry (chemical properties of the sand).

First, we will look at the observed behavior of the Sand Motor since its creation. In the next section (Page 53) we will look at the design and the rapid construction of the Sand Motor in 2011. We show that the spreading caused by the natural forces of tides, waves and wind resulted in a fascinating evolution of the bathymetry and topography. In particular, this chapter presents the unique setup and output of a multidisciplinary field campaign called MEGAPEX2014 (Page 74).

The placement of the large-scale nourishment has significantly changed the tidal and wave-driven currents at the Sand Motor and beyond. Extensive drifter experiments have revealed large-scale eddies around the Sand Motor. Max Radermacher shows how the changes in the tidal currents and the continuously changing bathymetry affect the day-to-day assessment of swimmer safety (Page 54).

Jantien Rutten illustrates that the interaction of the bathymetry with the incoming waves resulted in a dynamic bar system at the Sand Motor with sandbars and rips forming and reshaping (Page 58). Remote sensing techniques were used to capture this behavior in all seasons. We show that the bar dynamics make it difficult to predict the hazardous currents around the Sand Motor.

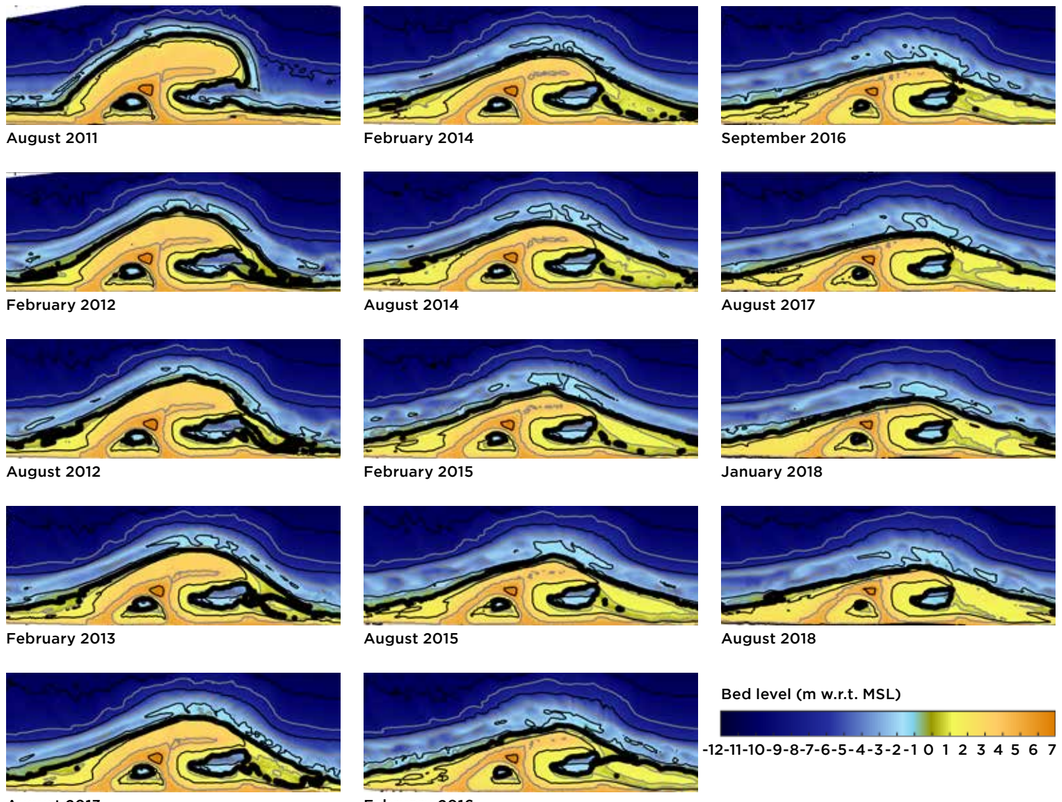
Extensive field measurements show that the currents around the Sand Motor deposited finer sand in deeper waters, while the sand at the erosive head of the Sand Motor coarsened considerably over time. Bas Huisman (Page 62) explains why, how and when this sediment sorting takes place. The numerical modeling that helps us understand this phenomena also allows us to make advanced forecasts of how the Sand Motor will evolve.

The placement of the Sand Motor had large effects on the fresh groundwater resources. Sebastian Huizer illustrates that this turned out to be strongly related to the tides, waves and the spreading of the Sand Motor (Page 66).

Iris Pit dives into the biogeochemical properties of the sediment which became exposed to the atmospheric conditions after placement (Page 70). We show that the variation in iron content and carbonate minerals found in the offshore-dredged sand originates from two different geological layers in the sand mining area. The environmental risks associated with the sediments used for the Sand Motor will be compared to other beach nourishments.

Finally, principle investigator Gerben Ruessink reflects on the chapter's findings and the implications for present and future coastal management (Page 74).

Figure 1.
Compilation of measured bed levels in the period 2011 – 2018, carried out by Shore Monitoring & Research.



Arjen Luijendijk

OBSERVED BEHAVIOR IN A NUTSHELL

Construction
The pilot Sand Motor involved constructing a large peninsula of about 2 km alongshore, with the most seaward position protruding about 1 km into the sea. The main part is a hook-shaped peninsula with the outer tip curved towards the north. The crest of the peninsula rises to 5 m above mean sea level. This design and location best fulfilled the multidisciplinary and multi-stakeholder requirements of safety in combination with recreation, development of nature, and scientific innovation. The cross-shore slope of the peninsula is 1:50, so that the toe of the nourishment is at -8 m NAP and -1500 m from the original coastline. The northern tip of the peninsula creates a sheltered area that nurtures different biotic species.
A small lake of about 8 hectares was designed to prevent the freshwater lens in the dunes from migrating seaward, which would endanger groundwater extraction from the existing dune area.

Sediment for the nourishment was mined offshore at two sites just beyond the 20 m depth contour at a distance of about 9 km. The sand was mined by Trailing Hopper Suction Dredgers and placed at the Sand Motor location by a combination of dumping through the doors in the hull, rainbowing (Page 14), and pumping onto the beach. The Sand Motor was constructed between March and July 2011 (page 186 shows a compilation of aerial images during the construction phase). Grain size analysis revealed the mean sediment diameter D_{50} was circa 280 μm, which is slightly larger than the mean sediment sizes found at the natural coast here (250 μm).

Evolution
Monthly surveys have measured the bathymetry and topography using a survey jetski, GPS on a wheeled pole and a quad bike. These bed level measurements show a rapid, predominantly alongshore redistribution of sediment in the first year after construction. The head of the peninsula eroded rapidly, leading to accretion both to the north and south. In the first half year after implementation, a spit developed from the northern tip of the peninsula, pinching the lagoon entrance (see photo on Page 50). The maximum elevation of the spit and shoal were slightly below the high water level, so they flooded during high tide (and storms). The channel landward of the shoal discharged the flow into and from the lagoon. This resulted in strong flow velocities of over 1 m/s during rising and falling tide in the spring of 2012, causing hazardous situations for swimmers (Page 55). In the first three years, the coastline developed into a Gaussian bell shaped curve. The curve widened over time, although after 2015 no further widening of the shoreline position was observed. Since 2016, the shoreline has developed an asymmetrical shape.

Although no sub-tidal bars were present after construction, these sand bars started to develop after about a year. The sub-tidal bars and coastline position seem to have been linked since 2013. Storms can sometimes cause a large-scale reset of the bar system (Page 59).

By 2018, about 3.5 million m^3 of sand had left the initial peninsula area. The erosion of the peninsula is predominantly caused by wave action, and where both daily conditions and high wave events matter. Analysis shows that the 12 largest wave events of the first year resulted in about 60% of the total erosion observed in that year. Milder wave conditions, which occur more often, are thus almost as important to the erosion of the Sand Motor as storm conditions.

The Sand Motor can be seen as a sand sorting machine. At the seaward part of the peninsula, we found much larger sand diameters than those initially placed, with sediment diameters up to 540 μm. During erosion events, the fine sand particles are washed out and transported away, while the larger sand particles remain behind, as the seabed is lowered. The eroded finer sand particles are deposited in areas northeast and southwest of the head of the Sand Motor, forming patches of fine sand at water depths of 8 – 12 m. How these patches are relevant for marine ecology will be discussed in Chapter 5. In the longer term, this coarsening of sand at the head of the Sand Motor may affect its overall shape and the rate of change.

In the first year after construction, the Sand Motor changed shape faster than expected based on long-term model calculations performed as part of the environmental impact assessment. Conversely, subsequent changes were slower than predicted. In 2018, the head of the Sand Motor had retreated about 300 meters since its creation in 2011. At the same time, the Sand Motor extended up to 6 km alongshore. This shows that the intended feeder function works well. The adjacent beaches are gradually fed by the Sand Motor as the sand is spread by natural forces. Both data extrapolation and recent modeling suggest that the lifetime of the Sand Motor will easily exceed twenty years and could be as much as 40 - 50 years.

Figure 1.
Aerial image of the Sand Motor just after construction. The sediment clouds at the water surface clearly show the presence of a tidal eddy as a result of flow separation.

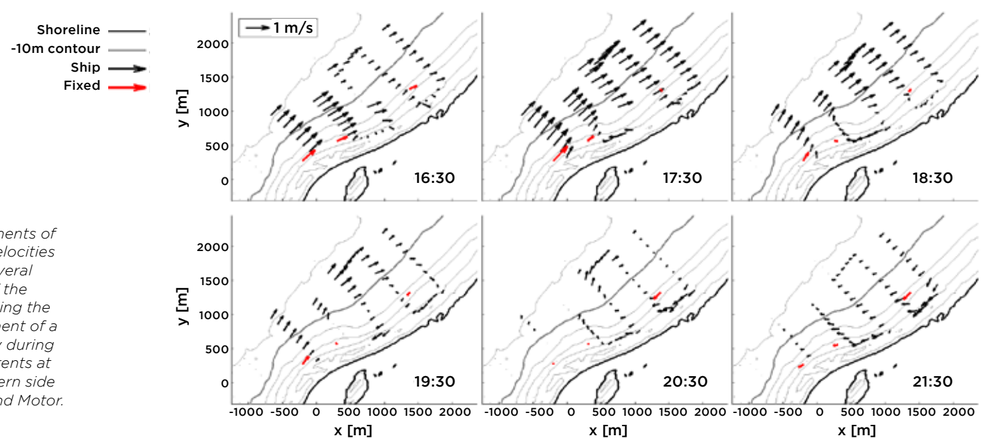


Figure 2.
Measurements of current velocities during several phases of the tide showing the development of a tidal eddy during flood currents at the northern side of the Sand Motor.

Max Radermacher

THE IMPACT OF LARGE-SCALE NOURISHMENTS ON NEARSHORE HYDRODYNAMICS

Max Radermacher obtained his PhD at the Faculty of Civil Engineering and Geosciences, section of Coastal Engineering, at Delft University of Technology in 2018. Max is the founder of WaveDroid, a start-up company that has developed an innovative, low-cost, light-weight wave measurement buoy.

Dissertation title:
"Impact of sand nourishments on hydrodynamics and swimmer safety."

PhD supervisors:
Marcel Stive (Delft University of Technology)
Ad Reniers (Delft University of Technology)
Matthieu de Schipper (Delft University of Technology)

From a physical perspective, the Sand Motor is a large, protruding body of sand along the Delfland coast. Modifying the coast on a kilometer-scale inherently has an effect on coastal hydrodynamics, which involve currents and surface waves. These will behave differently due to the presence of the Sand Motor. In turn, the modified nearshore hydrodynamics will influence the morphological development of the Sand Motor.

Apart from their role in morphodynamics, the altered hydrodynamics around a nourishment may also affect recreational safety. The Sand Motor has been constructed to stimulate many different functions of the coastal zone, one of them being recreation. Although absolute safety can never be guaranteed when designing coastal engineering works, a negative impact on swimmer safety is generally considered unwanted and unacceptable. Due to the unprecedented character of the Sand Motor, its exact impact on hydrodynamics, morphodynamics and swimmer safety was difficult to predict ahead of time. Therefore, our research aimed to determine and understand the ways in which a large-scale beach nourishment can affect nearshore hydrodynamics and swimmer safety. Three different flow phenomena were identified which are directly or indirectly caused by the Sand Motor: tidal eddy formation, rip currents, and tidal dynamics around the artificial lagoon. All three will be discussed here.

Tidal eddy formation
First of all, the Sand Motor can cause tidal currents to separate and generate new tidal eddies (Figure 1). Relatively strong tidal currents are present along the Dutch North Sea coast, running from south to north during the flood stage and from north to south during ebb. These tidal currents can reach peak velocities up to 1 m/s near the head of the Sand Motor. The Sand Motor acts as a large-scale perturbation to the tidal currents, forcing them to contract around the head of the nourishment (the most seaward point). On the downstream side of the head, the flow cannot follow the strongly curved coastline. The tidal current is diverted offshore, creating a large-scale tidal eddy adjacent to the nourishment. We observed this phenomenon at the Sand Motor in 2014 during the MEGAPEX2014 measurement campaign (Page 74).
The generated tidal eddy had a diameter of more than one kilometer and extended further offshore than the tip of the nourishment (Figure 2).

These tidal eddies were also predicted by our computer model of the Sand Motor. By changing the size and shape of the nourishment in the model, we determined which nourishment designs would lead to the formation of eddies. Because of its morphodynamic evolution, the Sand Motor changes shape continuously. This means that its effect on the tidal currents will also change over time. As the Sand Motor retreats and becomes more "streamlined", the tidal currents will eventually stop separating and eddies will no longer be formed. Our computer model predicts that this transition occurred in 2015, although a new measurement campaign would be needed to validate this.

At certain moments in the tide, these eddies can cause offshore-directed currents around the tip of the Sand Motor. These offshore currents may be hazardous to swimmers, as the currents can carry swimmers away

Figure 3. Morphological evolution of the Sand Motor lagoon and its entrance channel between March 2012 and March 2016. Due to ongoing alongshore spreading of the nourishment, the channel gradually became narrower and longer. Tidal currents in the channel were strongest in 2012.

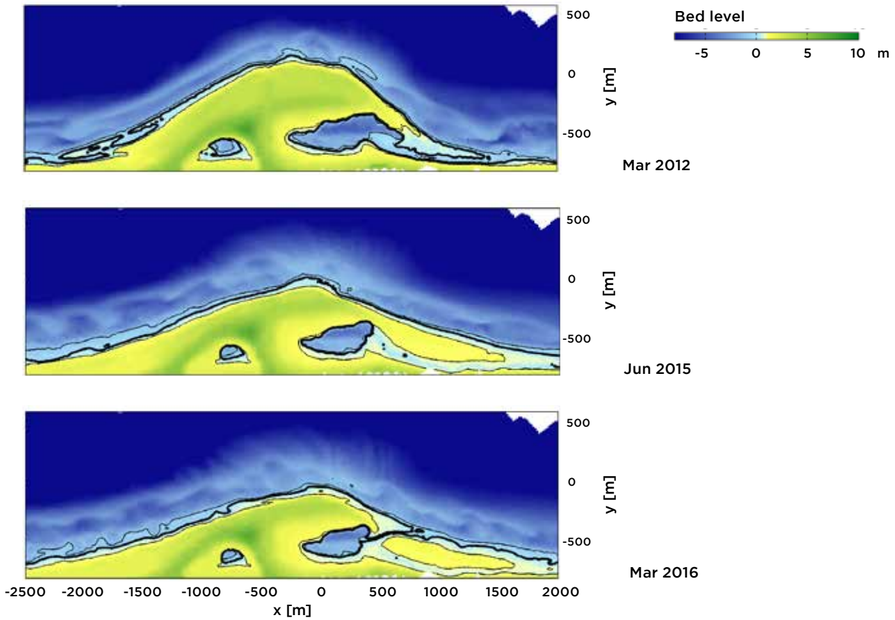


Figure 4. Distribution of beach facilities around the Sand Motor has an important influence on the spreading of beach users. Map shows locations of coastal towns of Ter Heijde (left) and Kijkduin (right).

from the beach. These eddies can also affect the morphodynamic evolution of the nourishment. In particular, they can influence the spatial distribution of sediment grain sizes, which is treated in more detail from Page 62.

Rip current generation
Rip currents are fast-flowing currents close to the beach that are directed offshore. These currents are generated when waves break on nearshore sandbars. The risk of rip currents is especially large when the sandbars are interrupted by small channels. Because they can carry swimmers away from the beach, rip currents are a serious hazard for coastal swimmers worldwide. Although sandbars and rip currents are a natural part of the coastal environment, the construction of a large-scale intervention can stimulate the formation of the formation of sandbars and rip channels along the coast.

At the Delfland coast, we found that the spatial variability of sandbars (and therefore the potential for rip currents) clearly increased between 2009 and 2012. Not only was the Sand Motor constructed during this period, but the entire Delfland coast was reinforced with several large beach nourishments. The new sand from the nourishment covered the relatively deep and straight sandbars that were there before. After the nourishments, new, shallow sandbars formed, which became highly variable over time. The evolution of sandbars and sandbar variability at the Sand Motor itself is treated in more detail from Page 58.

Tidal dynamics in the lagoon
While the artificial lagoon is largely sheltered from wave action, the water level inside the lagoon moves up and down with the tide in the North Sea. This leads to tidal currents in the channel connecting the lagoon to the open sea. Initially, the lagoon's entrance channel was very wide, leading to low tidal flow velocities. However, with the morphodynamic evolution of the nourishment, the channel became narrower (Figure 3). This squeezed the tidal current, leading to a strong and hazardous current in the channel about one year after the Sand Motor was constructed.

As the morphodynamic evolution continued, the channel became even narrower and longer, constricting the amount of water that could flow out of the lagoon at low tide. Therefore, the tidal range in the lagoon gradually became smaller and the average water level rose. This reduced the tidal currents in the entrance channel, significantly lowering the associated risk to swimmers.

Swimmer safety
The actual swimmer safety at a beach depends on more than the local nearshore hydrodynamics. The presence of beach users and their distribution over space and time are equally important. In order to determine the risk to swimmer safety at the Sand Motor, we have therefore assessed how hazardous hydrodynamic phenomena coincide with the presence of beach users.

At the Sand Motor, the spatial spreading of beach users is strongly linked to the availability of beach facilities (Figure 4). Most beach entrances, restaurants and parking facilities are clustered around the coastal towns of Kijkduin and Ter Heijde. Beach users therefore tend to cluster at the beaches in front of these two towns, around the outer edges of the Sand Motor. Beach use at the central part of the nourishment is very low. As a result, the risk posed by currents related to the tidal eddies is relatively small. These currents (directed offshore) occur around the tip of the Sand Motor, where hardly any beach users are present. In contrast, the other two hazardous phenomena (rip currents and tidal dynamics in the lagoon) occur in areas that receive significantly higher numbers of beach users.

The spreading of beach users over time is strongly linked to the weather. Suitable weather for a beach visit are days with high temperature, no clouds, no rain and weak wind. Since waves at the Dutch North Sea coast are typically generated by local winds, the wave height tends to be low on popular beach days. Most rip currents are formed by waves breaking on subtidal sandbars, which is not likely to occur during pleasant weather conditions. Hence, the risk of rip currents to swimmer safety is also relatively small.

This leaves tidal dynamics in the Sand Motor lagoon as the single largest risk for swimmers. Tidal currents in the entrance channel occur on a regular basis, determined by the tides, regardless of the weather conditions. In addition, beach users tend to cluster around the entrance channel near Kijkduin on crowded beach days. Nevertheless, it should be noted that the risks related to tidal currents in the entrance channel strongly depend on the channel's morphological evolution. At the Sand Motor, the risk was high in the first years after its construction, but has gradually diminished over the years.

Figure 1. (below top)
Ten-minute averaged top-view video images at the Sand Motor. The white line indicates the position of the sandbar (outer line) and the shoreline (inner line). Alongshore differences in patterning can be observed: a straight sandbar (western side, top panel; northern side, bottom panel) and a sandbar with a pronounced pattern (northern side, top panel; western side, bottom panel). Alongshore differences in geometry are also apparent, such as the alongshore wavelength of the patterns and the distance between the sandbar and the shoreline.

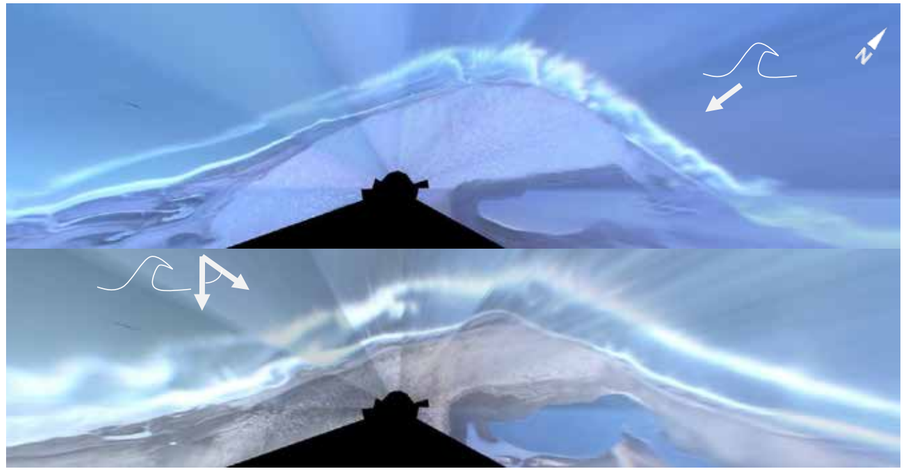


Figure 2.
X-band radar station (left) and Argus video tower (right) at the Sand Motor.

Jantien Rutten

THE IMPACT OF THE SAND MOTOR ON SANDBAR BEHAVIOR

Jantien Rutten obtained her PhD at the Department of Physical Geography, Faculty of Geosciences at Utrecht University, in 2018. She currenty works as a postdoc at Universidad Nacional Autónoma de Mexico (Instituto de Ingeniería).

Dissertation title:
"Sandbar behavior along a man-made curved coast."

PhD supervisors:
Gerben Ruessink (Utrecht University)
Timothy Price (Utrecht University)

Since the Sand Motor was completed in July 2011, the nourishment itself has been losing sand, whereas adjacent beaches have been gaining sand. This large-scale (O(1000 m)) evolution at decadal timescales was intended, and was predicted by numerical models (as will be discussed in detail on Page 145). How the morphology would change at meso-scales (O(100 m)) on daily and seasonal timescales was largely unknown at the moment of construction. Surveys of the seabed in the first months after construction showed morphologic features developing at these scales. A small subtidal sandbar formed, while the cross-shore profile of the nourishment changed from a convex shape with a steep slope towards a concave one with a milder slope.

Sandbars are ridges of sand nearly parallel to the shore, located below the sea surface for at least part of the tidal cycle. Sandbars are one of the most dynamic morphological features in the nearshore zone at daily to interannual time scales. In response to wave forcing, sandbars can migrate towards the shore as well as away. When migrating onshore, sandbars may develop a characteristic pattern, often with some rhythmicity (Figure 1, northern side). On the other hand, when migrating offshore, existing patterns are often destroyed, resulting in a straight sandbar (Figure 1, western side). Bars with a pronounced pattern are associated with strong flows moving offshore, which are potentially dangerous to swimmers (rip currents; Page 55). Therefore, understanding sandbar behavior is essential for swimmer safety.

Earlier studies showed that variations in the wave energy and the wave angle can explain sandbar behavior. These studies were mostly based on straight coasts or coasts with a slight curvature (embayed beaches). They barely addressed the spatial variability in sandbar behavior, which is expected to occur along curved coasts as they impose alongshore variations in wave energy and wave angle. The question how bar behavior is exactly affected by a curved coast became highly relevant with the construction of the Sand Motor. With similar concentrated, kilometer-scale nourishments expected elsewhere, we need to fully understand sandbar behavior along curved coasts.

To investigate how sandbars behave at the Sand Motor, frequent (hourly) measurements are needed with large spatial coverage (km^2), but at a limited cost. X-band radar and optical video are commonly used to collect such data (Figure 2). These techniques record the sea surface. The wave pattern in the resulting recordings tells us about the underlying morphology, such as seabed elevation and sandbar position. Subsequently, a morphodynamic model can show us the mechanisms underlying the observed sandbar behavior.

Morphological data
The elevation of the seabed can be deduced from the propagation speed of the waves via a smart algorithm. Several algorithms have been developed in recent decades, providing bed elevations with different accuracies. They mainly differ in the method for retrieving the propagation speed and the relationship between propagation speed, water depth and bed elevation. We derived bed elevations at the Sand Motor using two algorithms, which use the same relationship (linear dispersion relation) but differ in the method for retrieving the propagation speed: The FFT method was used with X-band radar data, and the cross-spectral

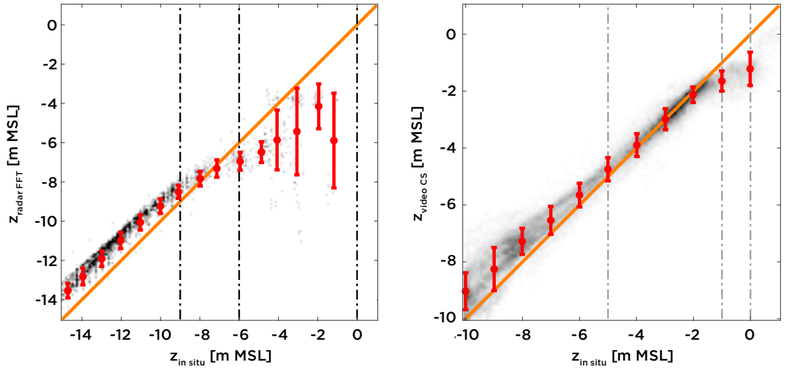


Figure 3. Bed elevations z_b derived from X-band radar (left) and optical video data (right) (vertical axes), against in situ (surveyed) elevations (horizontal axis). The gray shading indicates the number of data points, whereas the red error bars indicate the root-mean-square error.

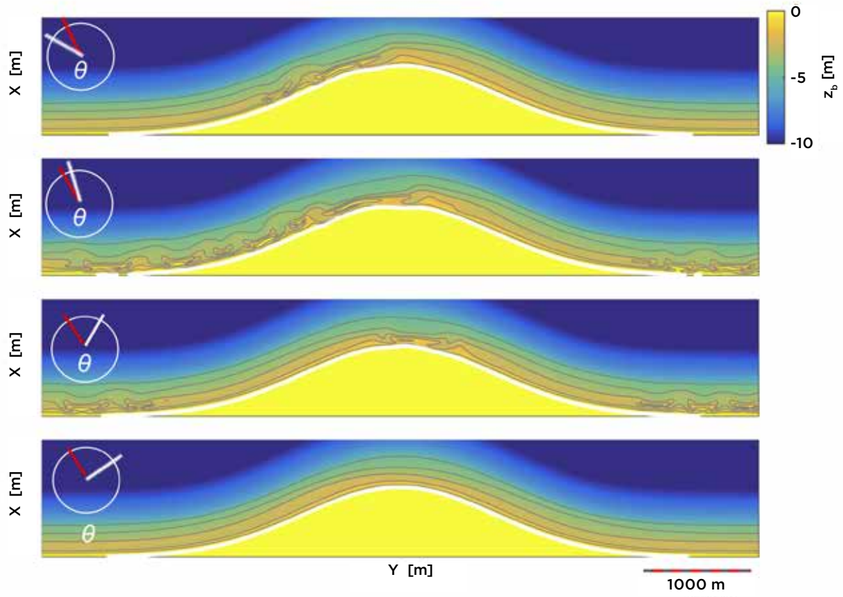


Figure 4. Predicted bed elevation z_b after 20 days for four different combinations of wave angles. The time-varying wave angle is indicated by the circles in the top left corner.

method with optical video data. An accuracy assessment reveals that both methods have a systematic bias: bed elevations being too shallow at large depths and too deep at shallow depths (Figure 3). This bias hampers us from accurately quantifying changes in sandbar position, geometry and shape at daily to seasonal timescales, and therefore we conclude that both methods seem still insufficient. However, as an alternative, breaker lines in time-averaged optical images can be used, as they approximate the position of the sandbar (Figure 1). At the Sand Motor, sandbar positions were identified with ~10 m accuracy using time-averaged low-tide video images, consistent with earlier studies.

Sandbar observations at the Sand Motor

Applying the latter method, breaker lines were extracted from a 2.4-year data set of time-averaged video images, providing data on the position and pattern of the sandbar on a daily basis. Bathymetric surveys provided data on the shape and depth of the sandbars on a bimonthly basis. The image data reveal that the sandbar migrated onshore in spring and summer and offshore in the winter months, at both the northerly and westerly exposed coast of the Sand Motor. This migration is associated with seasonally varying wave energy. Some differences were found between the northern and western side in the depth of the bar crest and its distance from the shoreline, as well as in the patterns that formed and were destroyed (Figure 1). At the northern side, the patterns had alongshore wavelengths of 200 m and formed in spring under low-energy waves that approached perpendicular to the coast (Figure 1, top panel). At the western side, patterns with wavelengths of 400-500 m formed in autumn under moderate to high-energy waves, associated with a series of storms (Figure 1, bottom panel). Given that storms pass through the North Sea basin from south to north, the direction of the waves gradually changed from southwest to northwest with every storm. Consequently, waves approached near-perpendicularly at the western side and highly obliquely at the northern side.

Patterns were destroyed when high waves approached the coast obliquely. This occurred three times at the northern side, but only once at the western side. To summarize, timing differences in pattern formation and destruction were observed along the curved coast of the Sand Motor, which seem to relate to alongshore differences in the local wave angle. The importance of the wave angle in the formation and destruction of patterns is consistent with earlier studies of straight coasts. The geometric differences between the sides (wavelength of patterns, bar crest depth, and distance to the shore) seem to relate to alongshore differences in the local wave height at breaking due to wave refraction.

Mechanism of pattern formation

A morphodynamic model was used to unravel the mechanism behind the formation of sandbar patterns along a curved coast. We systematically explored which conditions promoted pattern formation, using a setup loosely based on observations at the Sand Motor. The passage of storms was schematized by a wave forcing with a wave angle that shifted between two directions every day. Our simulations showed that the alongshore position of patterns, as well as their growth rate, vary with the local wave angle at breaking, i.e., the breaker angle (Figure 4). The local breaker angle depends on the offshore wave angle and the local orientation of the coastline. When the breaker angle increases, patterns form at a lower rate or not at all. Under such angles, a strong alongshore current is generated, which slows down or even inhibits pattern formation. Moreover, the local wave height reduces because of wave refraction over the curved depth contours. In addition, this slows down pattern formation. Simulations suggest that patterns along a curved coast may develop faster than along straight coasts in wave climates wherein the coastline curve decreases the local breaker angles.

The relatively high growth rate of patterns at a strongly curved coast under certain wave climates implies that the strength and occurrence of rip currents may increase when a concentrated, kilometer-scale nourishment is constructed. Since rip currents can be a serious hazard to swimmers, we recommend carefully considering the location and coastline curvature of large-scale nourishments at sites where beach recreation is important.

Figure 2.
Overview of sieve samples. (Photos by Laurens Bart)

Bas Huisman

DYNAMICS OF THE SAND PARTICLES

Bas Huisman will obtain his PhD at the Faculty of Civil Engineering and Geosciences at Delft University of Technology. His research fits in with the applied research at Deltares, which focuses on hydraulics, sediment dynamics and safety of rivers, deltas and seas.

(Tentative) dissertation title:
"On the redistribution and sorting of sand at nourishments."

Supervisors:
Marcel Stive (Delft University of Technology)
Gerben Ruessink (Utrecht University)
Matthieu de Schipper (Delft University of Technology)

Figure 1.
Sediment sampling at a small boat

Tide and waves redistribute sediment that is placed at the coast. This holds especially for a large-scale nourishment like the Sand Motor. However, not all of these sand grains are transported at the same pace. Fine grains typically move much faster than the coarse grains, but the dynamics of sand particles along exposed beaches are not well understood. Some studies have even argued that the coarser grains are more exposed to the flow and therefore more easily picked up than the fine grains. As most of these studies took place in a laboratory, it would be useful to see evidence of this behavior in the field. If the fine and coarse sand grains move differently, then areas with a coarser or finer bed composition will develop, as sand is removed from some regions and accumulates in others. In this sense, the Sand Motor can be seen as a big sand-sorting machine, which can provide us with fundamental understanding of the dynamics of sand grains. Such knowledge is essential if we are to protect and manage the coast in the future. This is particularly important to manage and protect fish populations, since changes in the composition of the sandy bed affect their habitat. For example, juvenile flatfish are known to favor the fine sand over coarser sand, since they can more easily hide from predators (Page 119).

To understand the actual situation at the seabed, we went to the Sand Motor and took samples of sand from the top-layer of the bed. These samples were collected with a grab sampler operated from a small boat (Figure 1). Accurate navigation and positioning using an RTK-GPS device was vital, and hundreds of samples were collected during the seven measurement campaigns conducted by Delft University and Wageningen Marine Research. The samples were later dried, pre-treated and sieved in the laboratory (Figure 2). This resulted in half-yearly maps of the typical grain size (i.e., median sediment diameter D_{50}) before, during and after construction of the Sand Motor.

The overview maps of the typical median grain size show that before construction of the Sand Motor, the sand was coarse in shallow water, gradually getting finer in deeper water (Figure 3). The post-construction surveys at the Sand Motor, however, show a much coarser bed in front of the nourishment (the D_{50} is twice as large in the red area in Figure 4 compared to the pre-construction situation). Interestingly, this coarser bed is especially present in intermediate to deep water where the influence of waves and wave-driven currents is smaller. This was not expected, since largest bed changes generally take place in the zone with the waves. At the same time, a region with fine sediment also developed just north and south of the Sand Motor. Finer sand was apparently moved from the Sand Motor to the adjacent coast. Waves are not likely to be responsible for this, because changes are strongest outside the zone with the most wave action, and a considerably finer bed was found after a storm event in October 2014, rather than a coarsening. We believe that the more energetic waves remove part of the coarser sand layer at the Sand Motor.

In practice it will be useful to be able to predict and evaluate the effects of large-scale nourishments before construction. This requires computer models with the right physical rules, which can compute waves, tide and sediment transport based on known relations. However, fine and coarse sand grains have not been treated separately in models to date. An in-depth

Figure 3.
Overview of surveys of median grain size (D_{50}).

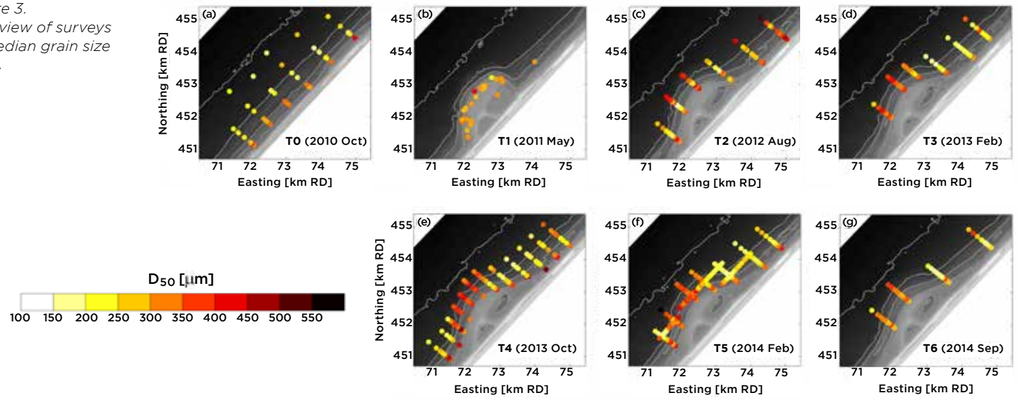
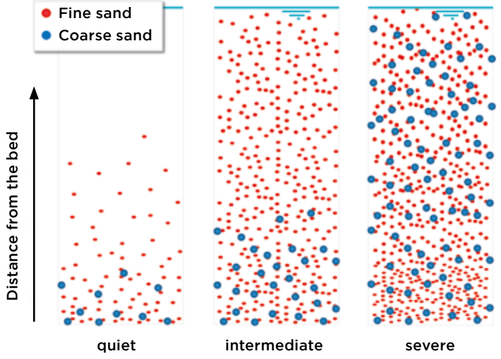
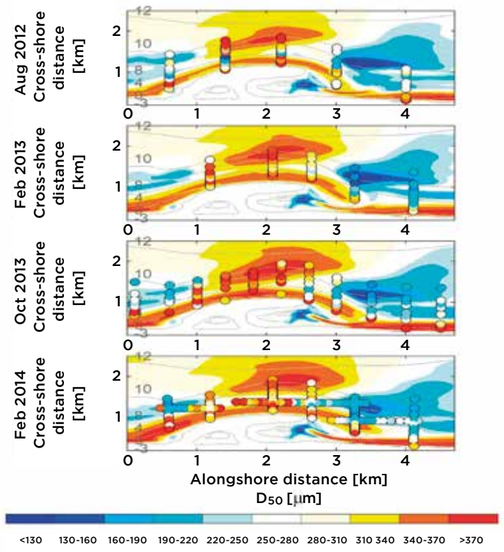


Figure 4. (right)
Comparison of modelled and observed grain sizes of the bed in February 2014 (i.e., 2.5 years after construction of the Sand Motor).

Figure 5. (below)
Illustration of the suspension of coarse and fine sand grains into the water column for quiet, intermediate and severe conditions.





reconstruction was therefore made of the development of the sandy bed of the Sand Motor over the first 2 years, which agreed well with the observed behavior. The model results are shown as the background color, while the measurements are shown as colored markers (Figure 4). Note that a clear coarsening is present at the Sand Motor (in red) and fining along the adjacent coast (in blue).

The model permits us to explore various alternative situations, which provides insight into the functioning of the coastal system. For example, the model shows that a situation with only tide can have a similar effect as the historic situation with both waves and tide. Decreasing the cross-shore width of the Sand Motor also considerably reduced the coarse sand patch in deeper water. More importantly, the modeling results can also help answer the underlying questions. The model clearly shows that the coarse sand grains are not fully lifted up into the water column in quiet to moderate conditions (Figure 5), which means they remain close to the bed. The fine grains, on the other hand, are easily lifted to the top of the water column in all conditions. Areas with a tendency towards erosion therefore lose more fine sand grains than coarser grains (which stay closer to the bed). This results in an armored top-layer with coarser grains (shown as a red layer on top of the bed of the central cross-section in Figure 6). The coarsest sediment also clearly accumulates in shallow water and finer sediment in deeper water.

So, what does this mean for the natural habitats? In essence, the coarse grained area is a more difficult habitat for juvenile flatfish (Page 119), as they will have more difficulty burying themselves in the sand, while the fine grained region at the adjacent coast provides a suitable habitat. This is just one example how this information can be applied in the design of future coastal interventions, by adjusting properties to minimize impact or even to obtain a desired change in habitat.

The implications of this study stretch beyond sandy coastal maintenance measures, since port breakwaters will presumably have very similar impacts on the sandy bed and marine habitat. In addition, our study showed that fine and coarse sand grains behave very differently in deeper water, which is seldom considered in studies of the seabed. Furthermore, evaluating long-term changes to the coastline due to sea-level rise will require a good understanding of the transport rates of the sand grains in deeper water, which improves substantially when the numerical models calculate the behavior of fine and coarse sand separately.

Figure 6.
Representative vertical cross-sections of the coast at the central, northern and southern part of the Sand Motor, showing the coarser or finer bed (respectively in red or blue colours). With landward side on the right.

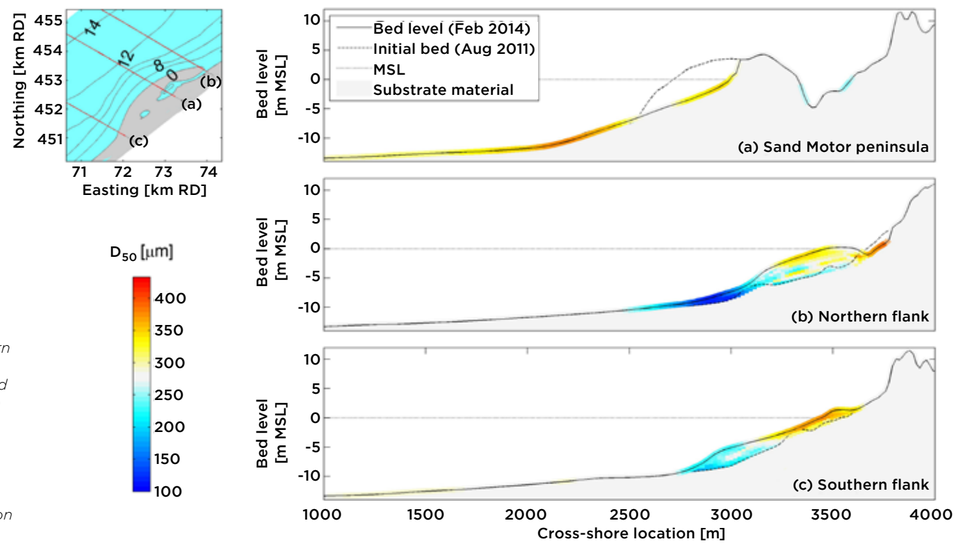
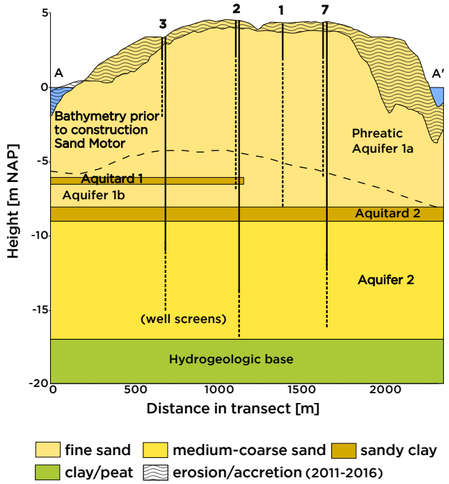
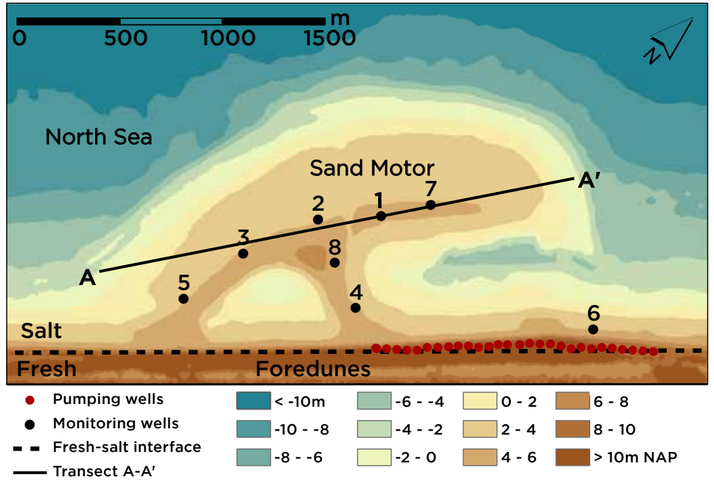


Figure 1.
(right) hydrogeological cross section (along black line, A–A'). The dashed line in the cross section marks the bathymetry prior to the construction of the Sand Motor. The wave-shading pattern marks the erosion or accretion of sand between 3 August 2011 and 3 June 2016,
and
(below) Contour map of topographic height (in meters with respect to the NAP datum) of the Sand Motor on 3 August 2011, with the location of monitoring wells (black points) and pumping wells (red points).





Sebastian Huizer

THE IMPACT OF LARGE-SCALE NOURISHMENTS ON FRESH GROUNDWATER RESOURCES

Sebastian Huizer will defend his PhD in 2019 at the Faculty of Physical Geography at University of Utrecht. He joined Arcadis in 2018 as a geohydrologist.

(Tentative) dissertation title:
"Fresh groundwater in large-scale beach nourishments - Growth of freshwater resources in coastal areas."

PhD supervisors:
Mark Bierkens (Utrecht University)
Gualbert Oude Essink (Utrecht University)

Most coastal regions around the world rely on groundwater as their primary source of freshwater. Excessive groundwater extraction, population growth, sea-level rise, and increases in storm surges threaten the availability of freshwater in many, often densely populated, coastal communities. Coastal lowlands and small islands are particularly at risk, because they are most susceptible to coastal flooding. To protect vulnerable coastal areas, an optimal management of the coast and coastal fresh groundwater should be adopted.

One way to protect groundwater is to implement coastal protection measures, with the aim to protect the coast against erosion and flooding. As discussed in Chapter 1, the Sand Motor is a prime example of this strategy and is one of the few adaptation approaches that might help to preserve or even increase the available volume of fresh groundwater. Since the Sand Motor is the first of its kind, little is known about the influence of mega-scale beach nourishment on fresh groundwater resources. To date, nothing was known about the dynamic nature of this coastal system (Page 53). This raises the question: what is the impact of the Sand Motor on fresh groundwater resources?

The Sand Motor can affect fresh groundwater resources in two ways:
1. directly, during the construction of the mega-scale beach nourishment, and
2. subsequently, throughout its lifespan.

The Sand Motor was constructed by depositing, pumping and spraying a mixture of sand and seawater taken from sand pits in the North Sea on the project site. Seawater accompanying the sand led to a salinization of the nourishment and its immediate vicinity (the shore and beach). However, the overall impact of the construction of the Sand Motor on fresh groundwater resources was likely limited. Effects would mainly take place during the last stages of the construction and in areas close to the shoreline with little fresh groundwater.

The subsequent effect occurs during the lifespan of the Sand Motor. The beach will expand seaward, thus displacing the direct influence of the North Sea towards the newly created shoreline. Combined with the likely growth of adjacent dunes (Chapter 4), the local extension of beaches and dunes will lead to an increased volume of fresh groundwater. This growth is driven by precipitation, groundwater flow from the dunes to the site, and a local shift in the impact of the sea.

While the direct impact of the construction of the Sand Motor on fresh groundwater was predictable and limited, the indirect impact of its creation is more complex. This is a result of the morphological evolution of the Sand Motor (Page 53) and the exposure to tides, waves, and storm surges (Figure 2, next page). In other words, the potential change to fresh groundwater resources is largely controlled by highly dynamic processes, which are hard to predict. To map the changes to fresh groundwater resources and to determine the impact of the various coastal processes in more detail, extensive field measurements and model simulations were conducted on the Sand Motor.

To better understand the impact of the Sand Motor on fresh groundwater resources we asked three questions:
1. What is the potential increase in fresh groundwater resources at the Sand Motor over a long period?
2. How do tides, waves and storms influence

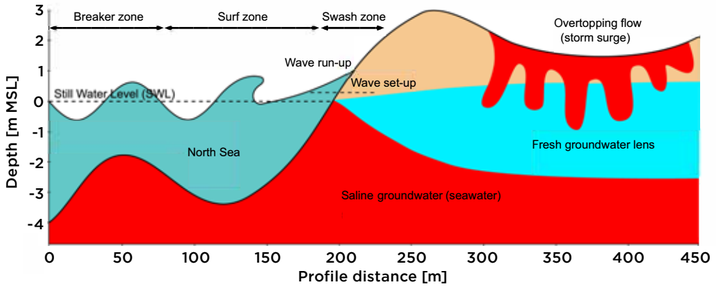


Figure 2.
Illustration of coastal hydrodynamic processes at the measurement site.

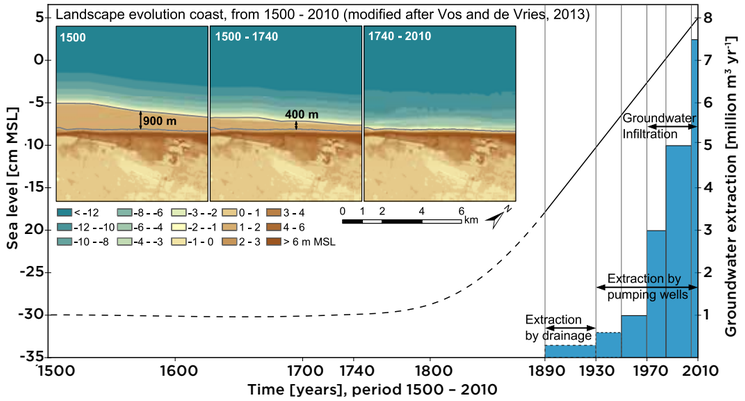


Figure 3.
Simulation of historical coastal erosion (based on paleogeographic maps), sea-level rise (black line) and groundwater extraction (blue) in the period 1890–2010; dashed lines indicate estimates, and vertical grey lines refer to stress periods.

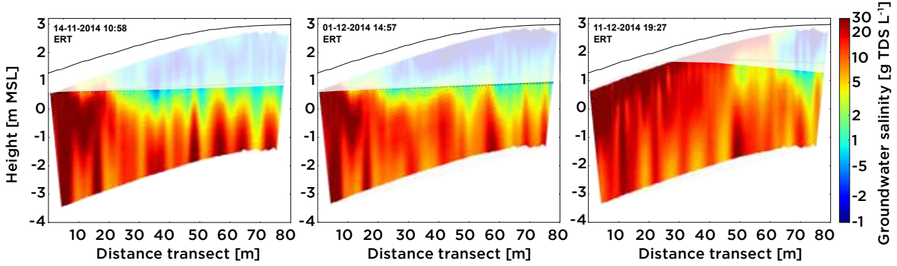


Figure 4.
2-D images of the measured groundwater salinity for three instances in 2014:
14 Nov. 11:00;
1 Dec. 15:00 (after a calm weather period); and
11 Dec. 19:30 (after substantial inundations).

the fresh groundwater lens in the Sand Motor?

3. What were the actual changes in the volume of fresh groundwater in the study area since the Sand Motor's construction, and which processes drove these changes?

To accurately assess the effects of the Sand Motor on fresh groundwater resources, the groundwater system was comprehensively analyzed (Figure 1). First, data was collected from local water authorities (e.g., boreholes, pumping rates, historical maps, groundwater levels, groundwater salinity), and groundwater levels and salinities were monitored at the Sand Motor. This data was used to reconstruct the spatial distribution of groundwater levels and salinities before and after the construction of the Sand Motor. This revealed interesting insights into the geological landscape evolution. Furthermore, insight was gained on the pumping rates in the Solleveld dune area, as shown in Figure 3.

A numerical three-dimensional groundwater model was used to reproduce and predict the growth in fresh groundwater resources in the study area. Model simulations predicting the morphological change of the Sand Motor up to 2050 confirmed that the Sand Motor could lead to an increase of fresh groundwater of between 0.3 and 0.5 million m³ per year. Reconstructions of the growth of the freshwater lens between 2011 and 2016 showed that this increase was primarily caused by groundwater recharge, highest land-surface inundations due to storm surges, groundwater in- and outflow, and to a lesser extent by morphological changes.

However, the growth in fresh groundwater resources from 2011 to 2016 was smaller than previously predicted, because of coastal flooding and because the initial geomorphological changes had been underestimated. Naturally, the accuracy of long-term morphological predictions of the Sand Motor will affect the reliability of the fresh groundwater predictions. These combined discrepancies will lead to larger errors when predicting the actual growth in fresh groundwater resources in the Sand Motor.

The impact of tides, waves and storm surges on fresh groundwater was successfully monitored with a technique called "electrical resistivity tomography." This technique uses differences in the electrical resistivity (or conductivity) of, for instance, sand and salt to produce two-dimensional images of the groundwater salinity in the subsoil (Figure 4). Measurements were taken near the shoreline on the outer perimeter of the Sand Motor. Over a period of several months, we were able to observe changes in the thickness of the fresh groundwater lens every 30 minutes, in both calm and turbulent weather conditions.

Most of the measured changes in groundwater levels and salinity could be imitated using a numerical groundwater model. This proved that with a thorough understanding of the local system, groundwater models can be used to make accurate predictions of the impact of tides and storm surges on fresh groundwater resources.

Thus, mega-scale beach nourishments such as the Sand Motor can lead to a substantial increase in fresh groundwater resources. This suggests that local mega nourishments might be an effective solution for low-lying coastal regions. In the Netherlands we generally have enough fresh groundwater for everyone. But many other countries suffer from droughts or salinization, which sometimes coincide with inundation of the coasts. Large-scale sand nourishments may become an interesting solution for some areas, to protect the hinterland and preserve and increase fresh groundwater resources.

However, the growth of fresh groundwater resources in a mega-scale beach nourishment are highly dependent on the shape and location of the nourishment, the precipitation, the evaporation, the frequency and the intensity of waves and storm surges, and local hydrogeological conditions. At the Sand Motor, observed changes in groundwater levels and salinity could largely be simulated by the groundwater model. This suggests that groundwater models can be used to predict the effects of tides and storm surges on fresh groundwater resources. In addition, detailed measurements and model simulations of tides and storms surges help us to improve our understanding of the mechanisms that affect coastal fresh groundwater. This might help water managers in the design of monitoring systems or to assess coastal groundwater availability.

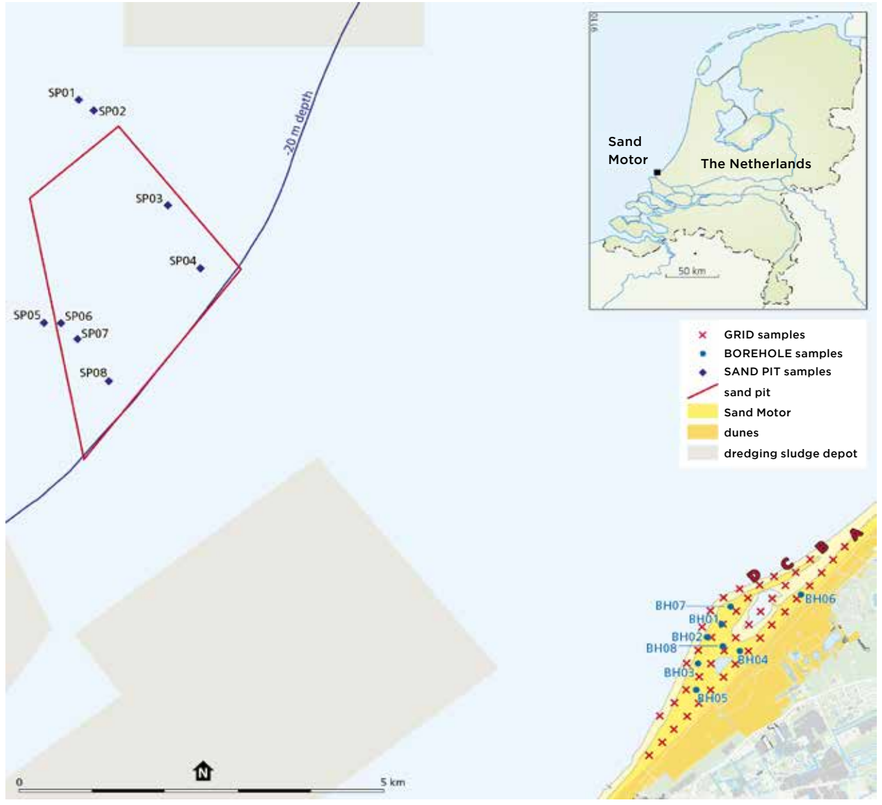
Figure 1.
The location of the Sand Motor and the sand pit, with sampling locations from GRID, BOREHOLE and SAND PIT.

Figure 2. (Page 72 top left)
A photo of the southwest part at the Sand Motor including bog iron ore fragments and shell fragments.

Figure 3. (Page 72 top right)
The sonic drill with obtained sediment from the Sand Motor presented by Bert Woertink (from Woertink Waterpompen) and observed by Iris Pit.

Figure 4. (Page 72 bottom left)
Two cores sampled along the water line at the lagoon (left) and the lake (right) of the Sand Motor with material from the surface till a maximum of 50 cm depth.

Figure 5. (Page 72 bottom right)
A photo of a sample taken at the Sand Motor placed under a microscope.



Iris Pit

ENVIRONMENTAL IMPACTS OF AN INNOVATIVE BEACH NOURISHMENT

Iris Pit will defend her PhD at the Copernicus Institute of Sustainable Development at Utrecht University in 2019, where she currently works as a lecturer.

(Tentative) dissertation title:
"The Sand Engine: Ecological and toxicological risks from geochemical processes."

PhD supervisors:
Stefan Dekker (Utrecht University)
Jasper Griffioen (Utrecht University)
Martin Wassen (Utrecht University)

The main question we studied was: Are there any environmental risks involved when applying a mega beach nourishment? Sand on a beach can form an environmental risk because of the biogeochemical processes involved. For example, we expect that the transfer of sea sediment from anoxic conditions (with limited dissolved oxygen) to oxic (atmospheric) conditions will lead to changes in biogeochemical processes: interactions with the atmosphere, freshwater and sea sediment may affect mineralogical composition, salinity, the availability of toxic trace elements, and the buffering capacity to maintain neutral pH conditions. As a result, environmental conditions may vary on a mega beach nourishment, increasing or decreasing the preferred environmental conditions for flora and fauna, but also for humans. In general, sand is considered "clean" and therefore few studies have investigated the chemical variation of sand, especially at sand nourishments. Hence, we explored the Sand Motor, compared it to different beach nourishments, and finally obtained an overview of possible risks that may or may not be present at a beach nourishment.

To study beach nourishments, one has to do fieldwork, and a lot of it. However, to do this, we first had to explore the best way of doing that fieldwork. Different carts were used to transport equipment and the samples we took from sand and water. The most productive (and relaxing) fieldwork was when Deltares was able to use their 4x4 to drive on the beach. This saved us a lot of time and gave us shelter when the wind was blowing sand in our nose and ears. Sampling surface sand was easy, but sampling groundwater at the top of the Sand Motor was a different story. When a colleague wanted to bore groundwater wells 10 to 20 m deep at the Sand Motor, we decided to work together and hire a sonic drill in order to collect sand samples, water samples, and finally create a hole for the well. A lot of time was also spent in the lab: sieving, dissolving sand in strong acid and diluting water samples because of the high chloride concentration. When possible and necessary, we measured the samples on different machines like a grain size distributor or a scanning electron microscope.

The 21.5 million m^3 of sand used to construct the Sand Motor was obtained from the sea bed 10 km offshore, from so-called sand pits, specific areas assigned by *Rijkswaterstaat* for sand mining. In general, sand is collected to a depth of 2 m from the surface of the bed, enough for a "traditional" beach nourishment. A larger amount of sand was needed for the Sand Motor, and therefore sand was retrieved to a maximum depth of 6 m. The sand was transported to the shore with large ships and released via the bottom of the ship or sprayed through the air in a process called rainbowing (Page 14).

The sand used for the Sand Motor originates from two different geological layers: a Holocene marine layer (up to twelve thousand years old) overlies Pleistocene fluvial sand (between twelve thousand and two million years old). Because the sand comes from different time periods with a varying sea level, the sand showed chemical variations, with the Holocene sands containing many more reactive minerals compared to the Pleistocene sands. As a result, the Sand Motor contains a mixture of Holocene and Pleistocene sand, which is also visible when you walk on the beach: some spots are very orange/yellow and

others show a greyish color. Furthermore, the Pleistocene layer had some surprises, like bog iron ore (5-20 cm large orange/brown rocks) and layers of shells. The amount of bog iron ore and shell material at the surface of the Sand Motor has increased over time, as the fine sand is transported more easiliy by the wind than the bog iron ore and shells.

The most interesting mineral we studied, and a very common one on the seabed, is pyrite. Pyrite (FeS_2), which is also known as fool's gold, forms on the seabed when oxygen is lacking. Besides iron (Fe) and sulfur (S), pyrite is known to have "contamination": when pyrite is formed, toxic trace elements are attracted, like arsenic, cadmium and copper. When the Sand Motor was created, a large amount of the sand was exposed to the atmosphere, and the oxygen could make the pyrite in the sand unstable. As a result, pyrite can dissolve in water, where iron likes to precipitate again. Sulfur will stay in the water and the toxic trace elements can either be attracted to minerals or stay mobile in the water. Arsenic turned out to be especially interesting, because it can have quite high concentrations locally in the pore water - water in the spaces between the sand. Although local arsenic concentrations can be much higher than allowed in drinking water, the presence of arsenic in pore water does not create a risk for humans. To be sure, we collaborated with the Dutch National Institute for Public Health and the Environment (RIVM) to rule out any human risk.

Calcium carbonate ($CaCO_3$) is a very important mineral, as it buffers water when the pH is low because of chemical reactions. For example, rain has a pH of around 5 and $CaCO_3$ will dissolve in water to make it pH neutral again. Seawater on the other hand, contains a high amount of dissolved $CaCO_3$ and therefore a pH of around 8.1. With the Sand Motor reaching a maximum height of 6 m above sea level, rainwater can infiltrate the sand. Fortunately, the Sand Motor contains a high amount of $CaCO_3$, and during the life span of this mega beach nourishment, enough $CaCO_3$ can dissolve to maintain a pH that is neutral or comparable to that of seawater. If the pH decreased to acid conditions, toxic trace elements would be more likely to dissolve in the water, which might cause a local problem for flora and fauna.

In general, contamination is mainly present in the finer soil fractions, like clay, because of their high diversity in minerals and an overall negative charge. As a result, dredging companies make sure that not too much fine material is present in the sand used for beach nourishment. In addition, coarse grain size distribution will not be transported as easily by wind and water. Compared to Schiermonnikoog, which has a natural beach, the Sand Motor, as well as the traditional nourishments at Julianadorp and at Zoutelande, have a much coarser grain size. In addition to grain size distribution, we compared the chemical composition of the Sand Motor, the two traditional nourishments, and the natural beach. The most interesting difference is in the unsaturated zone, the sand layer above sea level where rainwater infiltration and oxygen can play a large role. The unsaturated zone at the traditional nourishments is generally less thick than at the Sand Motor, and almost non-existent at the natural beach. This means that the intensity of rainwater influence and oxidation is largest at the Sand Motor, where the consequences of pyrite oxidation are most visible, and the highest risk that toxic trace elements may be mobilized. In contrast, at both the traditional beach nourishments and the natural beach, the influence of seawater is almost 100% and the buffering capacity stays intact, even though the $CaCO_3$ in the sediment can vary.

Another unique aspect of the Sand Motor is the time frame. Traditional nourishments are periodically replenished with fresh sand (every 2-5 years), whereas the Sand Motor can "develop" for 20-30 years. Because of the design of the Sand Motor, the inner side of the hook creates conditions where fine materials, like clay particles and organic material, can be deposited. This material attracts soil organisms related to a tidal flat, as occurs at the Wadden Sea, but it can also bring contamination. Even though the contamination is relatively low and harmless to humans, it might make it unattractive for soil organisms to create large populations. Besides that, the Sand Motor has developed relatively rapidly, creating such a dynamic environment that certain conditions like a tidal flat will not be present for long and therefore cannot stabilize for nature development.

Figures on this and next page: MEGAPEX2014 (Image courtesy: Top right: screenshot NPO2 Kennis van Nu; Bottom right: Esther Kokmeijer; Far right and below right: Marion Tissier; Below, left: Matthieu de Schipper; Far below, left and right: Timothy Price; Next page, left: Esther Kokmeijer; Next page, right: Marion Tissier.)

Timothy Price

MEGA PERTURBATION EXPERIMENT 2014 (MEGAPEX2014)

SPECIAL

Timothy Price was a postdoctoral researcher at the Vrije Universiteit Amsterdam for the NatureCoast research program in 2013 and 2014. He currently is an assistant professor of Coastal Morphodynamics at Utrecht University.

In addition to the ongoing monitoring of the Sand Motor by *Rijkswaterstaat* (morphology, wave height, salt spray and sand transport into the dunes), the NEMO project (bathymetry, sediment composition, offshore currents, turbidity) and the twelve NatureCoast researchers (surf zone morphology, dune vegetation, fish and bird counts, groundwater levels, geochemistry), the NatureCoast and NEMO postdocs organized a large six-week field campaign in September and October 2014 through a joint initiative.

This campaign, called Mega Perturbation Experiment, or MEGAPEX2014, aimed to perform multidisciplinary fieldwork and to stimulate interdisciplinary collaboration in the process. In contrast to the more common monodisciplinary approach to field data collection, this system-approach to coastal research fit the NatureCoast philosophy.

In total, MEGAPEX2014 involved more than 40 researchers from the NatureCoast consortium as well as other national and international organizations in the field of coastal research (from Sweden, UK, USA and South Africa). In addition to this, more than 10 BSc and MSc students participated as part of their thesis work.

Although each research group organized its own research, all participants could benefit from the centrally organized logistics and infrastructure, such as housing, a small field station, transport on the beach and permits. In preparation for the campaign, all NatureCoast and NEMO researchers met at the Netherlands Institute for Sea Research (NIOZ) in Yerseke to present their plans for the campaign, to fine-tune measurement locations, and to brainstorm on potentially overlapping research areas.

Overall, the campaign resulted in a unique, publically available data set of multidisciplinary measurements covering fourty-eight days, including one big storm. More importantly, the teamwork and cross-disciplinary interactions during the six weeks in the field sparked new collaborations and broadened the scientific perspectives of the participants. Besides its scientific achievement, MEGAPEX2014 gave rise to significant outreach, including a NatureCoast documentary, weblogs, excursions, radio interviews, and an item on national television.

Figure 1.
Beach use Sand Motor in summer.

Gerben Ruessink

COASTAL RESEARCH AND MANAGEMENT: WHAT IS NEXT?

REFLECTION

Gerben Ruessink is a professor of Wave-dominated Coastal Morphodynamics at the Faculty of Geosciences at Utrecht University.

The Sand Motor has been heralded as a boldly innovative solution to save our beaches from rising seas. Irrespective of whether one agrees that the Sand Motor is the best solution, let alone the only one, there is no denying that the 21.5 million m^3 of sand nourishment meant a massive upscaling with respect to more traditional beach and shoreface nourishments, and that implementing it was a truly daring achievement. The Sand Motor also resulted in a research effort worthy of its size, with a multidisciplinary approach unprecedented for the Dutch coastal community. This section provides a personal look back, and into the future. Should the Dutch implement another Sand Motor, especially now that scenarios for rising sea-levels that were considered almost absurd a decade ago are becoming thinkable?

The Sand Motor was constructed as a massive disturbance to a wave-dominated sandy coast. Under natural conditions such a coast is fairly smooth in the alongshore direction. True, natural sandy coasts also present alongshore variations, but the Sand Motor was unprecedented in its size. This was purposely done to ensure that nearby coastal stretches would be fed. Researchers argued that one could learn much more about coastal behavior from a heavily disturbed site, such as the Sand Motor, than from a natural, undisturbed coast.

While this idea makes perfect sense and the research that was conducted resulted in stunning new insights, the Sand Motor also resulted in processes that would not generally occur along a smoother wave-dominated coast. Examples include tidal-current separation and eddy formation (Page 54), unprecedented alongshore variability in sandbar dynamics and possible rip-current formation (Page 58), and sand-sorting processes seaward of the surf zone (Page 62). What made the research at the Sand Motor truly unique is that it included topics not commonly considered in coastal engineering projects, such as the effects of the nourished sand on the local and regional hydrology (Page 66) and the "cleanness" of the sand (Page 70).

What is next? By 2018 it has become clear that sea-level rise along the Dutch coast could be more extreme than was considered realistic during the design of the Sand Motor. Current high-end estimates for sea-level rise mean that by 2100 nourishment volumes would need to increase by a factor of 12 to 20. Does this mean we need more nourishments of the Sand Motor type? Is that the solution?

In my humble opinion, it is not, or, more precisely, not entirely. The current scenarios for sea-level rise demand for a truly innovative change in coastal management policy, a drastic change in the way we look at sediment management; we need to move away from the basic notion that safety just demands a sufficiently large static volume of sand. Evaluation of these predominantly shoreface nourishment projects teaches us that such nourishments can severely limit the dynamics of natural phenomena, such as sandbars. Another problem is that measures to increase the safety of the most seaward dune have reduced it to an artificial sand dike with suppressed dynamics and, unintentionally, a severely reduced number of plant and animal species. In other words, measures in one coastal subsystem can have far-reaching, often negative consequences elsewhere.

Let's do better: we should not just talk about saving "our beaches," but about saving "our coasts." There is an imminent need to re-connect different coastal sub-systems with each other, and to truly stimulate large-scale natural dynamics rather than imposing measures that limit natural processes. In coastal policy, this must mean a shift from evaluating whether the coast is safe to whether the coast is healthy: we need to ask whether it is sufficiently dynamic, whether it has sufficiently diverse habitats and, overall, whether it is truly climate resilient. Sand motors can surely play a role in this new policy, but it is critical that, where possible, the nourished sand benefits the entire coastal system, not just the nearshore. Though this was not the case here, it should be in the future. We should do more with less sand.

Physical geography, senior coastal specialist

JAN MULDER – RIJKSWATERSTAAT

INTERVIEW

In what way is the Sand Motor unique to you?
"The Sand Motor – as a large scale contribution to coastal maintenance – is unique because it was the first time something like this was carried out, anywhere. And also because I do not think the Sand Motor, in the shape and the way is has been designed and implemented, will ever be applied again. The Sand Motor was specifically designed for this location, with the aims that were in play at the time. A Sand Motor-like solution will always be tailored to the specific local situation, and it will always look different."

How do you see the role of scientific research at the Sand Motor, as end-user?
"As an end-user, this is very important because of its unique character. And not only because it was the first time this was done, but also because the project besides just a technical design, also implied consciously consideration of the social context. Scientific research helps to understand and explain why the Sand Motor works, not only technically but also socially. This can yield lessons that may help to improve the design of a next Sand Motor-like solution."

How relevant is multidisciplinary research on the Sand Motor?
"Very important, because for me, the Sand Motor is not a purely technical solution, but rather a multidisciplinary approach aimed to meet various societal objectives. A solution primarily addressing flood protection in the Dutch context, but at the same time, meeting with the demand for more natural areas in the densely populated part of the Netherlands, and stimulating recreation opportunities. In short, it is a multidisciplinary project, and if you want to learn from it, you will have to study it in a multidisciplinary way."

What are the main findings of the NatureCoast program for you as end-user?
"Perhaps the most striking (although not necessarily most important) that immediately comes to my mind concerns dune development. It was thought that the Sand Motor would contribute to dune growth in the entire dune area, from dune front up into the old dune area behind. Looking at the research results, this does not seem to be the case yet. Up to now, dune development appears to have been stimulated mainly at the dune front, resulting in wider, not in higher dunes. We had not expected that, and at this moment it is hard to attach a value judgment to it. However, it seems clear that for the long run it is an important issue."

How does the rest of the world view the Sand Motor in your experience?
"The Sand Motor was widely profiled in the media as a unique event and phenomenon; regularly spoken of in terms of "the Dutch show what they can do here." That pride, that sentiment of Dutch glory, I felt that a bit too. Yet I only partly agree with it: you are of course Dutch yourself and feel a certain pride when people say it. However, at conferences I have specifically asked foreign colleagues about it, and they confirm: "This is typical Dutch..." But they add: "... something like that can only be done in the Netherlands." The latter is very important and refers to the fact that the Sand Motor is more than a purely technical solution, but above all a solution that is embedded in Dutch society. The statement indicates that the Sand Motor as it is, may only be of limited value to the rest of the world. The specific context of the Netherlands made *this* Sand Motor possible. The main value to the rest of the world may be to consider a comparable long term and multidisciplinary approach that has been the basis of it."

Coordinator Beach Safety

MICHEL PUGLIA – LIFEGUARD & RESCUE TEAM, THE HAGUE

INTERVIEW

What makes the Sand Motor unique for you as end-user?
"It is unique that the beach of the Sand Motor is gradually becoming wider, and of course I look at the beach safety perspective. We have to constantly monitor the safety, and that has two aspects: the perceived safety and the actual safety. On the one hand, the Sand Motor has considerably helped to improve safety, but on the other hand we can never say that it is 100% safe. That sense of security is a bit of an equilibrium, something we have to keep in balance."

"For example, the groins, here officially called the *Delflandse Hoofden* (Delfland Heads), play a big part in safety. People often get into trouble because of the rip currents along those groins. Because of the Sand Motor, these groins have been gradually covered and as a result people feel safer. But that does not mean that there is no danger anymore. "

"The width of the beach also gives a feeling of safety. The beach can accommodate many more people, and it also provides more different recreational opportunities than before. The wider beach gives visitors a sense of security, but with so many activities and people we also need a lot more volunteers to monitor all of that. You can't take safety for granted, even if it is such a wide beach."

How do you see the role of scientific research at the Sand Motor, as end-user?
"Very interesting, because we are normally only concerned with beach surveillance and making sure the beach visitors are safe. But the NatureCoast program has shown us many aspects that we knew were there, but were not part of our daily job. You also see your work from a scientific point of view, because you look at all kinds of research results that are published. As a result, for example, we are also thinking about the ecological perspective now, the natural aspects that are also part of the beach."

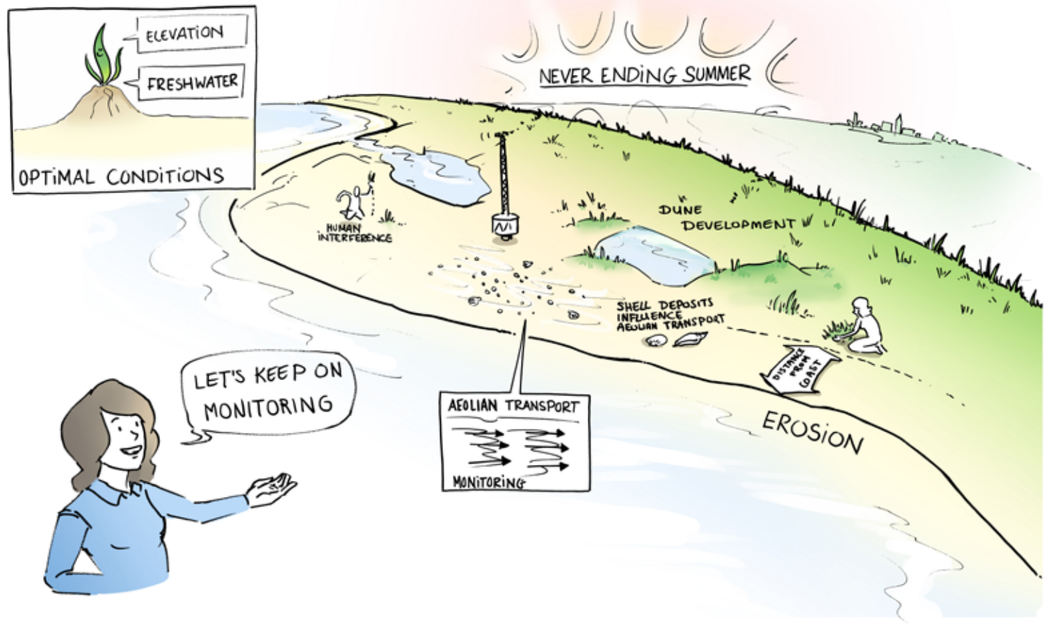
"For us the research has been an enrichment: it has generated new knowledge and broadened our insights and experiences beyond our day-to-day practice. Being part of such a scientific program has brought us into contact with researchers and shown us how they expand our knowledge. The program has also expanded our network; we can now find experts much more easily."

How relevant is multidisciplinary research on the Sand Motor for you as end-user?
"Multidisciplinary research is important. Of course, some things are just nice to know, interesting, whereas other things are crucial for us as end-users. The knowledge provided by the ecological research on the Sand Motor is very interesting for us. It has made us aware of the fact that we should not drive our vehicles through the young dunes, for example. But our main interest is knowing on how the sea moves, how a sandbox like the Sand Motor develops. Normally, we know a stretch of beach, we understand how it works, and we monitor it. But now we are facing new developments all the time, and the research program actually keeps us alert and up to date."

What are the main findings of the NatureCoast program for you as end-user?
"We conducted a risk inventory in relation to beach safety before the program to find out what we could expect, and what we should anticipate. So the most important thing, especially for beach safety, is the question: Is the Sand Motor on track and does it do what it needs to do? If that is not the case, then we have to adjust all kinds of risk assessments. But at the moment the researchers indicate that the developments are going according to plan. This is very nice to hear from a scientific research program, because it corresponds to what we have noticed in the field."

Which aspects of the Sand Motor system are important for swimming safety, and has scientific research made it sufficiently clear for you to be able to give advice on this?
"The most important aspects for us are water, currents, tides, topography, wind, wind erosion. The researchers have measured this extensively and converted the data into maps. The outcomes are certainly understandable, but can always be improved. Of course, the more detailed the maps are, the better for us. But the explanation also matters a lot. If a researcher comes to us with a map and explains the findings and what has been put into the map, that really helps us a lot. This also allows us to start a discussion with each other. Lifeguards are often very hands-on, and they prefer to talk to someone rather than reading about the research."

Figure 1.
Dune Formation
(Image by JAM Visual Thinking)



Arjen Luijendijk

THE JOURNEY OF A SAND GRAIN FROM BEACH TO DUNES

INTRODUCTION

In the Netherlands, dunes form our most important natural line of defence against rising sea levels and severe storms. As discussed in Chapter 3, the Sand Motor is an unprecedented large sandy nourishment with 128 hectares of new land. Sand is always on the move, and such a wide sandy beach provides large potential for wind-blown sand and hence dune formation. This wind transport (also known as aeolian transport) causes the foredunes to grow and makes them dynamic, but it may also cause early dune development, which has so far been largely ignored in coastal research.

In this chapter, we will introduce you to the interaction between aeolian transport, embryo dune formation, and dune vegetation as well as innovative monitoring and modeling techniques. We will follow a grain of sand as it travels from the wet beach to the dune. First, we need to know how dunes and vegetation have actually grown at the Sand Motor after its construction. We will show that the spreading caused by the natural forces of tides, waves and wind resulted in a fascinating formation of embryo dunes and vegetation (Page 86).

Next, we will discuss remote sensing monitoring techniques that help to identify key wind events at the Sand Motor. Isaac Wiliams (Page 88) explains how remote sensing techniques can efficiently reveal the conditions that are favorable for wind-driven transport (or that discourage it). Observations of large-scale transport events provide great insight into the meteorological, tidal and surface conditions that stimulate dune formation.

Early dunes can develop anywhere on the beach under specific conditions depending on the interaction of physical processes and weather. We will explain how and why embryo dunes develop, and how they can ultimately strengthen the foredunes. Marinka van Puijenbroek illustrates how important the height of the Sand Motor is for protecting the dune-building species against storms (Page 92).

Moving towards the main dune area, we will pay attention to the interaction between how vegetation takes hold and is covered by sand, which is essential for sustainable dune development. Corjan Nolet introduces the greatest dune-building champion and explains how important it is for protecting us against the sea (Page 96). We will show you the added value of applying advanced drone techniques to measure the dune dynamics (burial rates) and vegetation dynamics.

Bas Hoonhout introduces a newly developed numerical model that is able to reproduce the observed aeolian transports and changes at the dry beach (Page 100). We will explain why the intertidal area is much more important for dune development than the width of the Sand Motor. We will also demonstrate how important the sediment composition is for the long-term development of the Sand Motor and its dunes.

In the final section, principle investigator Kathelijne Wijnberg reflects on this chapter's findings and the implications for present and future coastal management (Page 104).

Arjen Luijendijk

OBSERVED DUNE DEVELOPMENT

This section looks at the development of dunes and vegetation at the Sand Motor in its first seven years after completion, but first we will start with some recent history.

The Delfland dunes
Early this century, the Delfland coast was designated as one of the "Weak Links" in the coastal defenses—not because the dunes had gotten weaker but because it was clear that storms could become more severe in the future. Therefore, the Delfland sea defense was upgraded by placing a large volume of sand at the beach and dunes. The operation, involving 17.6 million m^3 of sand, was completed in 2011 with the Delfland Coastal Reinforcement.

The beach and the dunes are important for nature and leisure activities along the entire Delfland coast, which includes various strictly protected Natura 2000 areas. This means that the dune area landward of the Sand Motor, called Solleveld, is protected from interventions in the area. Solleveld consists mostly of "old" dunes which were deposited by the sea starting in 3000 B.C.

There is a relatively narrow strip of young dunes at the seaward part of Solleveld. This hilly zone is a few hundred meters wide and has been affected by the coastal reinforcement operations in recent decades: a double foredune dating from the late 1980s (the result of a dune strengthening operation) and a row of dunes approximately 60 meters wide as a result from the Delfland Coastal Reinforcement.

For decades the Delfland dunes have been growing steadily, both in height and width, mainly due to coastline maintenance activities. This process has continued since the construction of the Sand Motor but not as quickly in the monitoring area as before its construction.

Dune development after the Sand Motor
The new dunes are primarily located on the eastern edge of the Sand Motor near the foot of the previously built coastal reinforcement. A few small primary dunes have also developed on the southwestern side of the Sand Motor. The new dune forms are highly dynamic and therefore extremely appealing in landscape terms.

The area of new dunes is increasing slightly. Just less than one hectare formed in the monitoring area in the first five years, which is surprisingly much smaller than predicted (23-27 hectares after 20 years). This can be partly explained by the fact that the dune lake and the lagoon capture large amounts of drifting sand and delay dune growth. The dunes are expected to continue to grow and this process should accelerate in the future, particularly once the lagoon and the dune lake have filled with sand.

Another reason for the limited growth of the dunes is the intensive shared use of the beach. The formation of a new row of dunes in front of the old one is slowed by traffic on the Sand Motor, particularly vehicles driven by supervisors, surveyors, and researchers. The cleaning of the beach performed by the city authority of The Hague also prevents dune formation.

Lidar measurements show that the average dune growth of 14 m^3 per meter longshore per year in the Sand Motor domain is slightly lower than the dune growth rates along the adjacent beach stretches, while this stretch has a much wider beach compared to the other stretches.

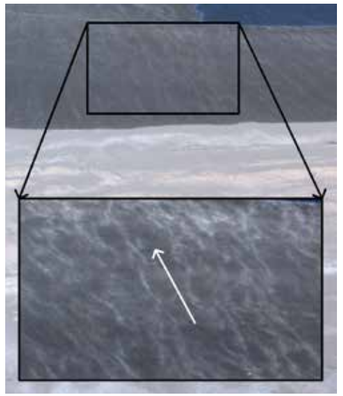
However, our measurements indicate that the aeolian deposits in the dune lake and lagoon are of the same order of magnitude, giving a total average sediment deposition of 27 $m^3/m/yr$ in the Sand Motor domain, which is on average 56% higher than along the adjacent coasts.

Impact of wind-blown sand on Solleveld
The construction of the Sand Motor resulted in a bare sandflat seaward of the existing Solleveld dune area. Prior to construction, concerns were raised about the possible negative effect this might have on the ecological values of the Solleveld. After construction, the amount of sand blowing into the outer Solleveld dunes would appear to have increased slightly. However, in absolute terms, the amount of sand being blown to Solleveld remains limited.

Vegetation and birds
The vegetation found on the Sand Motor consists of characteristic sand couch and marram. These habitats are subject to international protection under international agreements. Sea holly, a red-list variety, is growing in some locations.

Between 2011 and 2015, almost forty species of birds were observed regularly on and around the Sand Motor. The black-headed gull is by far the most common species (Page 200). Other species that have been regularly seen are the common gull, herring gull, grebe and great cormorant.

Figure 1. (right) Image from camera overlooking the lagoon area of the Sand Motor in which streamers can be observed within the intertidal area. Expanded area in the lower half of the image. White line illustrates direction in which the streamers propagate, which corresponds to the mean wind direction at the time the image was taken.



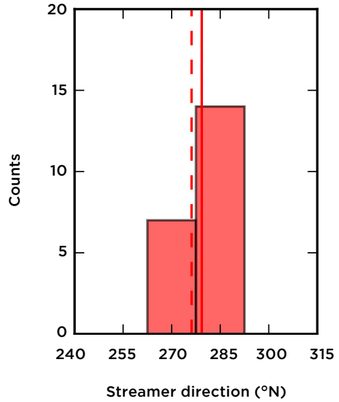
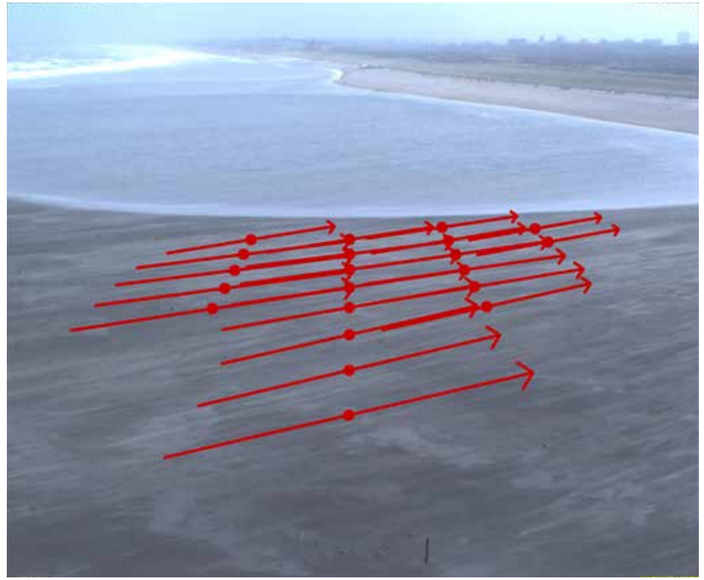


Figure 2. (bottom) Image examined for streamers using the developed method. Dots denote the center of areas of the image which were examined. The arrows point in the direction of the identified streamers.

Figure 3. (top right) Real-world orientation of the streamers as determined from Figure 2. The orientation is given about north (compass direction). Lines correspond to the mean wind direction at the time of the image (dashed) and the average direction of the streamers (solid).



Isaac Williams

OBSERVATIONS OF AEOLIAN TRANSPORT

Isaac Williams has worked as a PhD candidate at the Department of Water Engineering and Management, University of Twente since 2015.

(Tentative) dissertation title:
"The effect of mega-nourishment projects on sediment supply to the dunes "

PhD supervisors:
Kathelijne Wijnberg (University of Twente)
Suzanne Hulscher (University of Twente)

Dunes play an important role in protecting low-lying areas against coastal flooding. Their growth, and their recovery after storm erosion, requires the supply of sediment from the beach, which is driven by the wind. To be able to accurately assess the dune and its ability to protect against flooding, this supply needs to be understood and measured, both monthly and annually. At these larger timescales, the supply of sediment to the dunes is dominated by a few large-scale transport events.

To identify when large-scale wind-driven transport events occur, we need to know more than wind speed alone. In the ideal situation, sediment is transported by the wind once the wind exceeds a given critical speed. However, this threshold is affected by other weather and surface conditions, which reduce the wind's effectiveness in transporting sediment. The overall effect of these conditions on the transport system is still not understood, which makes it difficult to predict when transport events will occur. Since transport formulations are unable to account for these additional factors, estimates of sediment supply are both larger than observed values and inconsistent.

In order to understand what conditions encourage wind-driven transport, we need to link observations of large-scale transport events to meteorological, tidal and surface conditions. It is challenging to make in-situ measurements for this purpose that provide sufficient coverage in space and time. Remote sensing techniques offer a number of advantages. For example, a camera that observes a beach can document surface conditions over a wide area during daylight hours for however long the camera system is operational. This makes it possible to generate long-term datasets at a relatively low cost. In this case, images taken by the Argus video tower iso camera station at the Sand Motor were used to identify wind-driven transport events. The Argus video station has been collecting images every 30 minutes since 2013, across multiple cameras. At the same time, a meteorological station, mounted on the Argus tower at a height of 44 m, has been collecting data. This allows images to be related to the prevailing wind conditions at the time they were taken.

Large-scale transport events at the Sand Motor are often characterized by large, elongated regions with intense transport activity. Known as streamers, they rapidly snake across the surface of the beach, moving downwind. Streamers are frequently observed in areas where the underlying beach is moist. These areas offer strong contrast differences with the streamers, which are comprised of drier, and thus lighter, sediment. The presence of streamers at the Sand Motor is illustrated in Figure 1, which shows an image taken by a camera facing northeast overlooking the lagoon area. During the largest transport events, streamers are observed across the entire surface of the site. Identifying images in which streamers are observed allows us to identify individual large-scale transport events. To date, this has typically been done manually, making the generation of long-term datasets a slow, tedious process. An automated method has now been developed which identifies images containing streamers, allowing us to document large-scale aeolian transport events.

This new method searches for streamers around a series of points within a given image. To do this, pixels are extracted around each point and processed to form an aerial view of the surrounding area.

Figure 4.
Rose diagram illustrating the image averaged direction of streamers and corresponding wind speed, for all images in which streamers were detected by the developed method. Streamers are predominately observed from SSW, at wind speeds in excess of 10 m/s.

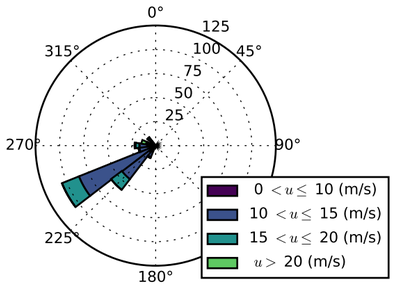


Figure 5.
Rose diagram illustrating the directional distribution of measured wind speeds greater than 10 m/s for all images considered over 3 month period.

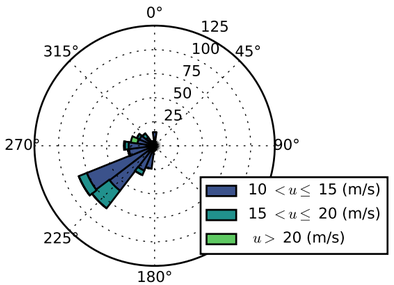


Figure 6.
The surface elevation across the lake area in August 2011 measured relative to the mean sea level. The dashed line corresponds to the +1.5 m contour which approximates the water level within the lake.

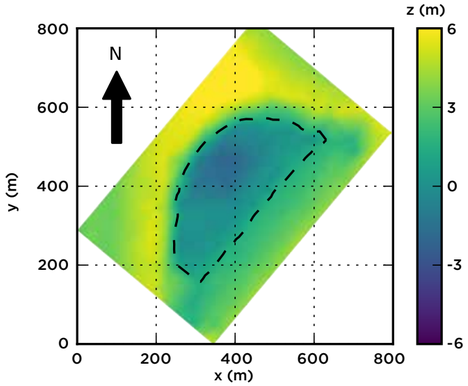
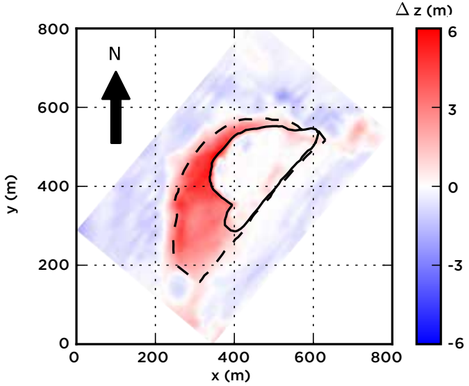


Figure 7.
The change in elevation within the lake between August 2011 and June 2015. There has been significant infilling as a consequence of wind-driven transport, particularly in the SW. Lines correspond to the spatial position of the + 1.5 m contour above sea level measured in 2011 (dashed) and 2015 (solid) highlighting the infilling.



When streamers are observed from this perspective, they typically appear as relatively linear features. Consequently, each area is examined for linear image features, which are then used to infer the presence of streamers. Figure 2 illustrates an image in which this method has been applied to detect streamers. The arrows, each of which represents 50 m, illustrate the orientation of the streamers around certain points in the image. The corresponding real world orientations are shown in Figure 3. As can be seen, the direction of streamers typically clusters around a mean value that is close to that of the mean wind direction at the time the image was taken.

The method was used to identify images showing large-scale transport events using a test dataset consisting of over 1800 images from a single camera, which represents three months' worth of images. The images were also manually examined for streamers. The new method compares favorably with the manual results, and is able to process the images in a fraction of the time. Streamers were only observed in ~10 % of the images, typically when the measured wind speed is greater than 10 m/s. In spite of this, they were only observed in ~60 % of the images where the measured wind speed was greater than 10 m/s. Figure 5 illustrates the direction of winds that exceeded this threshold across all image frames and Figure 4 shows the average direction of the streamers for all images in which streamers were identified. These figures illustrate that streamers occur over a narrower range of directions than the wind, and generally come from SSW.

This method will allow us to examine the entire image dataset from the Sand Motor, identifying large-scale transport events over multiple years. The derived dataset can then be compared to meteorological, tidal, and surface conditions, which will provide further insight into which conditions are favorable (or unfavorable) for wind-driven transport. In addition, this approach allows us to investigate how the surface of the site influences the direction in which streamers travel. This has important implications for the amount of sediment transported to the dunes.

Finally, we wanted to quantify how the observed transport events correspond to sediment supply. In this regard, the shape of the Sand Motor has some interesting consequences. The lake and the lagoon act as barriers for streamers. When the streamers meet these areas, the sediment that they carry is deposited. Regular measurements of the surface elevation across the site allow the change in volume of these areas to be evaluated. The high elevation of the Sand Motor has ensured that, to date, the lake area has been isolated from marine processes. Consequently, changes in its volume can be assumed to be almost entirely due to wind-driven transport processes. Figure 6 shows the elevation of the surface of the site in August 2011, and Figure 7 shows how it has changed over time. Consistent with the observations from the images, the lake has predominantly been infilling from the SSW. Figure 8 highlights that, after a relatively rapid initial period, the infill of the lake area has stabilized to a relatively linear rate of ~ 14,000 m^3/yr. The trapping of sediment by the lagoon and lake ultimately reduces the amount of sediment transported to the dunes.

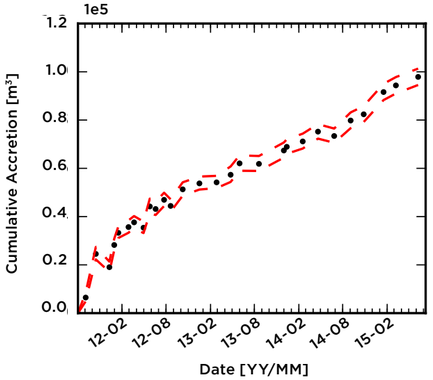


Figure 8.
The cumulative volume change across the lake area through time between August 2011 and June 2015. Dots represent the calculated volume changes. Lines denote error bands about the calculated volumes.

Figure 1.
The two main dune-building grasses in the Netherlands.
Figure 1a. Marram grass, Ammophila arenaria.
Figure 1b. Sand coach, Elytrigia juncea.

Figure 2a.
Overview of the Sand Motor. The presence of dune-building species on the Sand Motor and the location of the five transect in which we monitored the vegetation more extensively.

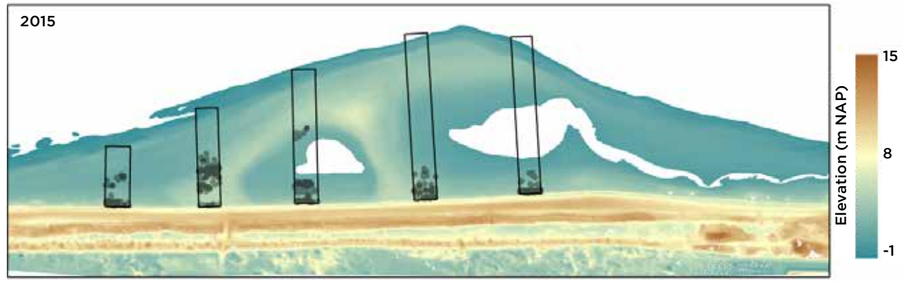
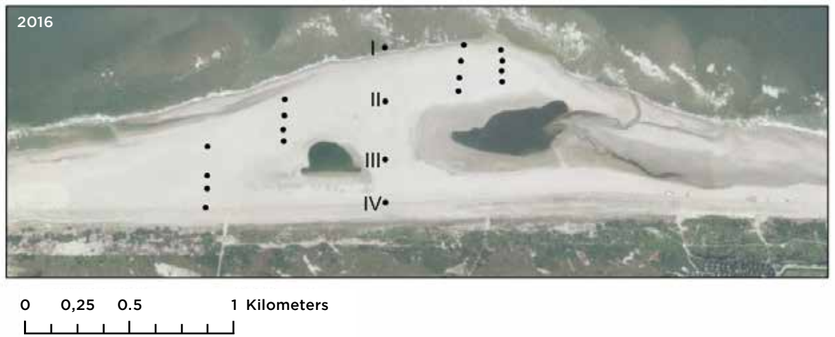


Figure 2b.
Aerial photograph of the Sand Motor, the points indicate the plots in our field experiment, the number indicate the locations number.



Marinka van Puijenbroek

EMBRYO DUNE DEVELOPMENT

Marinka van Puijenbroek obtained her PhD at the Plant Ecology and Nature Conservation group at Wageningen University in 2017. She currently works as a researcher on dunes and saltmarsh vegetation at Wageningen Marine Research.

Dissertation title:
"Dunes, above and beyond: The interaction between ecological and geomorphological processes during early dune development."

PhD supervisors:
Frank Berendse (Wageningen University)
Juul Limpens (Wageningen University)

The development of new dunes begins with the establishment of vegetation on the beach. The vegetation traps the sand, preventing it from blowing away, which results in a small embryo dune. Plant species that build dunes are specialized in catching the wind-blown sand and can grow with the trapped sand. In the Netherlands, there are two main dune-building grass species, marram grass (*Ammophila arenaria*) and sand couch grass (*Elytrigia juncea*) (Figure 1). Over time, when the vegetation grows and catches more sand, the embryo dune will transform into an established foredune. The process of a bare beach developing into a foredune depends on the establishment of plants, the growth of the dune, and the dunes surviving storms.

The establishment of plant species on the beach depends on various environmental factors. The beach can be a harsh environment with high soil salinity, low soil moisture, salt spray, sand burial and erosion. Soil salinity and salt spray are higher closer to the sea, whereas sand burial is higher close to the dunes. These abiotic factors do, however, depend on the beach morphology: on higher and steeper beaches, the soil salinity, salt spray, and soil moisture will be lower than on lower and gradual beaches. The Sand Motor has a distinctive morphology, since the beach is very wide (800 m) and several meters above sea level (4–6 m above mean sea level).

From studies of natural beaches, we know that more embryo dunes can develop on wider beaches. Large embryo dune complexes can develop on beaches wider than 300 m; this indicates the high potential for embryo dune development on the Sand Motor. The high elevation of the Sand Motor could, however, affect abiotic conditions, which could affect the establishment of plants. The high elevation also means that a large part of the Sand Motor is safe from storms, as waves cannot reach these areas. While this could be positive for dune development, note that the groundwater level is quite low (2 m below surface) at high areas of the Sand Motor, and this could lower soil moisture content, which could slow down the establishment of vegetation (Figure 2).

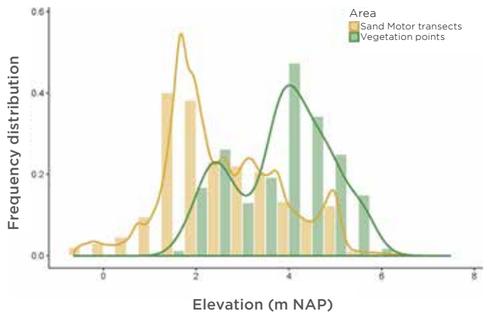
Dune-building species established spontaneously on the Sand Motor between 2011 and 2015. The most plants established in the southern part of the Sand Motor and around the lake, where quite large dunes have formed. We monitored the presence of the different dune-building species in five transects (Figure 2a). In 2015, dune-building species covered a total area of 1307 m^2 in all the transects: 76% of these dunes were covered by marram grass and 24% by sand couch grass. The high presence of marram grass corresponds to the low soil salinity on the Sand Motor, since marram grass cannot tolerate high soil salinity.

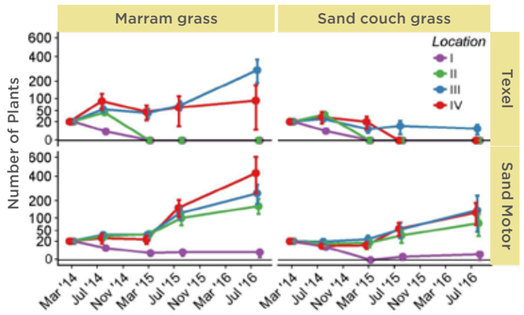
We expected that dune-building species would establish more on the lower parts on the Sand Motor, because of the low soil moisture at the higher elevations. Although the soil moisture was indeed quite low, the dune-building species mainly occurred on the higher elevations rather than the lower ones (Figure 3, next page). Furthermore, we did not find any correlation between the presence of dune-building species and groundwater depth. From this we can conclude that the low soil moisture on the Sand Motor does not limit embryo dune development; it is very likely that the dune-building species are dependent on precipitation for their plant growth.

Figure 3. (top left)
Frequency distribution of the elevation (m above sea level) for both the whole of the monitored transects and for points were natural vegetation actually established on the Sand Motor. Vegetation mainly occurred at higher elevations at the Sand Motor.

Figure 4. (top right)
Growth expressed as the number of plants per plot of dune building grasses Marram grass (left) and Sand couch grass (right) planted at different distances (locations) from the sea on a natural coast (Texel) and on the engineered coast at the Sand Motor. Location I is closest to the sea and location IV furthest from the sea. Although plant growth was initially lower on the Sand Motor, the high survival of vegetation during winter by the absence of storms resulted in an overall higher plant growth.

Figure 5. (bottom)
Images of vegetation growth over 2.5 years. A photograph of one of our field experiment locations in 2014 four months after planting, and a photograph 2.5 years later. This shows how fast embryo dunes can develop on the Sand Motor.





The distribution of the dune building grasses does not seem affected by the elevation; the absence of vegetation on some parts of the Sand Motor could be because the dune-building grasses cannot reach these areas. The dune-building species on the Sand Motor mainly occurred close to the foredune, where these species were already present. In fact, there is hardly any vegetation on the seaward ridge of the Sand Motor, which is much further away from any vegetation. Dune building species mainly disperse via rhizomes (root parts) and seeds. Rhizomes are mainly dispersed after a large storm, when the rhizome is broken off from the maternal plant. The rhizome can then establish on the location where it washes up, thus initiating the development of a new dune. Storms can therefore have a positive effect on the spread of dune-building species.

High waters as a result of storms do not reach most parts of the Sand Motor, which means that plant material of dune-building species cannot be deposited there. This could explain the absence of vegetation on higher elevations like the most seaward ridge. The seeds of marram grass and sand couch grass are relatively small, and it is unlikely that they could reach the whole of the Sand Motor by wind dispersal. In addition, the seeds might be trapped by the lake in the middle of the Sand Motor, which might reduce the availability of seeds. However, these seeds could drift to the edge of the lake and find suitable conditions due to the higher soil moisture there. This could explain the abundance of dunes in the area around the lake. The seaward ridge has been eroding since 2014, which could have a negative effect on the germination of seeds; seeds might be blown away from the seaward ridge, or seedlings might be unable to survive due to sand erosion.

Since the distribution of the dune-building grasses could be due to dispersal, we conducted a field transplant experiment, thus excluding the effect of dispersal and allowing us to compare the Sand Motor with a natural coast. For the field transplant experiment, we planted marram grass and sand couch grass in five transects at four locations from sea to dune. The locations were selected to represent the entire Sand Motor (Figure 2b). We established four plots of 50 x 50 cm at each of these locations, and planted 20 plants of either marram grass or sand couch grass in each. Over time, we measured the number of plants at each plot. The same experiment was conducted at a natural coast at the Hors, Texel to compare plant growth.

In the first summer, the growth of planted dune-building grasses was initially lower on the Sand Motor than on the natural coast of Texel (Figure 4), probably due to the lower soil moisture on the beach. This would make the dune-building grasses more dependent on the precipitation here than on a natural coast. In winter, average plant mortality was lower on the Sand Motor than on the natural coast, eventually resulting in higher vegetation growth on the Sand Motor. This clearly indicates the positive effect of the high elevation, where there is no storm erosion, the most limiting factor for dune development. The only field experiment locations which showed substantial plant mortality were those closest to the sea . Here, vegetation disappeared due to the structural erosion of the Sand Motor by the sea. Due to the rapid growth of the dune-building species in our field experiment, the planted dune-building species created quite impressive dunes at the Sand Motor within three and a half years (Figure 5).

Overall, the Sand Motor has a huge potential for dune development. The wide beach of the Sand Motor gives a lot of space for embryo dune development, and its high elevation protect dune-building species against storms. This potential is already visible at the Sand Motor, where new embryo dunes develop and become bigger every year.

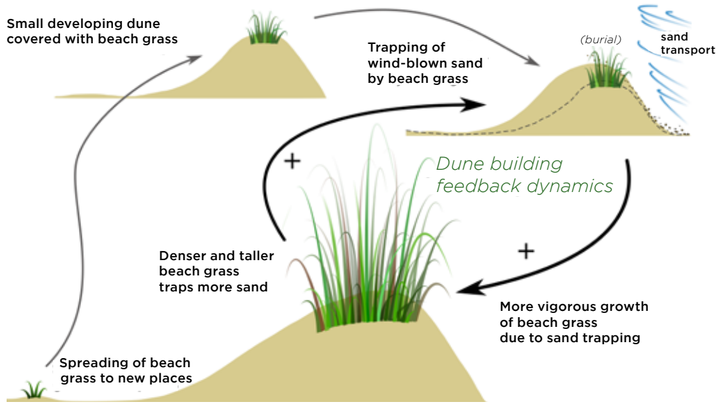


Figure 1. Overview of how plant-sand feedback dynamics drives coastal dune development.

Figure 2. The state of dune development on and along the Sand Motor in the summer of 2017. (Data derived from satellite imagery, photos courtesy of Rijkswaterstaat and Jurriaan Brobbel.)

Corjan Nolet

CONTRIBUTION OF VEGETATION TO DUNE DEVELOPMENT

Corjan Nolet is a PhD candidate at the Soil Physics and Land Management group of Wageningen University. He has extensively studied wind-driven coastal processes, using remote sensing techniques and geospatial analysis.

(Tentative) dissertation title:
"How biogeomorphic feedback drives dune development along nourished coastlines."

PhD supervisors:
Coen Ritsema (Wageningen University)
Michel Riksen (Wageningen University)

Marram beach grass (*Ammophila arenaria*) is perhaps the greatest coastal engineer that nobody has heard about. This rather unremarkable looking grass is a dune-building champion: without it growing along our shorelines, we would simply not have such tall and broad coastal dunes to protect us against the sea. Especially for a country below mean sea level like the Netherlands, marram grass provides a very important contribution to coastal safety.

What makes marram grass such an effective dune builder (Figure 1), is that it not only traps high amounts of wind-blown sand in its leaves and roots, but that it will in fact grow much more vigorously because of it. Sand is basically like a fertilizer for marram grass, causing it to grow taller and denser. This reinforcing interaction (positive feedback) is the driving force behind coastal dune development: trapping sand encourages marram grass to grow, which in turn enhances the capacity of marram grass to trap sand. To understand and predict dune development on and along the Sand Motor, it is therefore essential to focus on how much sand marram grass can trap and how its growth is affected by it (Figure 1).

Almost directly after construction, the conditions on the Sand Motor became quite favorable for dune development: there is a constant supply of fresh wind-blown sand towards the most seaward facing dune ridge (the foredunes), and the wide beach provides a lot of space and acts as an effective buffer against erosion by storms. So far, this has ensured that the existing dunes along the Sand Motor are actively growing and that small dunes (embryo dunes) are developing on the beach around clumps of newly established vegetation. Figure 2 gives an overview of the state of dune development on the Sand Motor in 2017. The dune cover density by marram grass has been mapped by satellite imagery. Together with the aerial photos, it is clear that the foredunes form an uninterrupted and densely covered dune ridge, while more sparsely covered embryo dunes have formed at the foot of the foredunes, as well as around the dune lake and on the southern part of the Sand Motor.

To start to understand how this development takes place, we compared the morphological changes of the Sand Motor against the changes in dune cover density. Using yearly digital elevation maps, Figure 3 shows how the average height of the Sand Motor changed between 2013 and 2017, and also how the dune cover density of marram grass differed in September 2017 compared to September 2016. The morphological map highlights the dynamic nature of the Sand Motor, showing how the sand has been redistributed along the coastline through wind and wave forces. The dune cover map highlights the overall positive effect of the Sand Motor on dune development, as the existing dunes have expanded or new embryo dunes have formed in most places.

Nevertheless, it must be noted that the dunes appear to have retreated slightly in some places. Increased pressure by recreational activities may have played a role in this retreat. For example, the placement of beach cabins along the foredunes in 2016 may have hindered dune development on the northern part of the Sand Motor. At the same time, mechanical cleaning of the beach during the summer may have negatively impacted newly developing embryo dunes. This illustrates how the fact that the Sand Motor has to fulfil different functions (coastal safety, recreation and

Figure 3. (right) Mapping changes in Sand Motor morphology and dune cover density of marram grass.

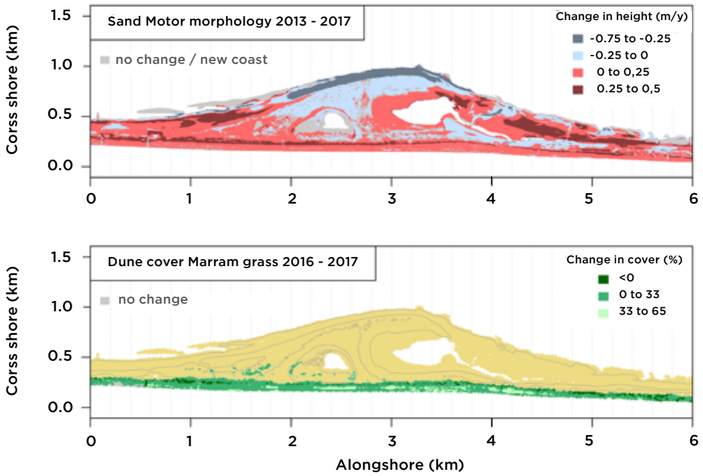
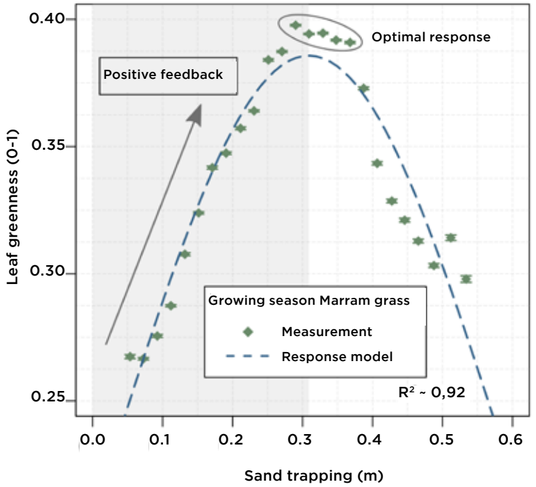


Figure 4. (left) Aerial mapping with a drone to make 3D models of the foredunes. The foredunes along the Sand Motor have been actively growing and a large number of embryo dunes have developed on the beach.

Figure 5. (right) Positive feedback relationship between sand trapping of wind-blown sand and growth response of marram grass. Marram grass grows better as it traps more sand, up to an optimal amount of sand per growing season.



leisure, ecology, drinking water supply) can sometimes make striking a good balance challenging.

Comparing the maps in Figure 3 made one thing clear: almost all the dunes on the Sand Motor, both the foredunes and embryo dunes, only developed in areas where considerable amounts of sand were deposited by wind. Although no clear relationship could be observed using the satellite data, this provided a first indication that reinforcing plant-sand feedbacks drives the development of coastal dunes. To truly measure this feedback, we had to study the dunes in much more detail. One way we did this was by aerial mapping with an octocoptor drone equipped with a high-resolution camera that, once in the air, would take a photo every second. With a special software technique (photogrammetry) all these photos could be stitched together to create an accurate 3D model of the dunes. Figure 4 shows two such models of the same dune, from a flight day in April 2015 and one in September 2016. The differences between these models clearly illustrates how much the foredunes have been growing, especially at the dune foot, and that quite a large number of embryo dunes have been developing on the beach.

Another striking finding is that the marram grass appears to be much greener on the parts of the dunes that have been actively growing. In other words, it seems that marram grass is much more vital in areas that receive the most wind-blown sand. We hypothesized that this was probably the result of more vigorous growth due to sand trapping, and set out to measure these differences in marram grass leaf greenness. Luckily, we were able to do this because the sensor of the camera that we used was modified to be sensitive in the near-infrared light spectrum. Because a plant absorbs visible light for photosynthesis but strongly reflects near-infrared light, there is a large contrast in reflectance which can be used to accurately determine a plant's vitality.

During one growing season (April – August 2016), we mapped the dunes every month with our drone and using the 3D models we identified changes in dune height and changes in marram grass greenness. Plotting the data (Figure 5) revealed an interesting pattern, which points towards feedback dynamics in dune building. In particular, the graph clearly shows that marram grass grows better when it traps more sand, albeit up to an optimal amount of sand per growing season. When too much sand is transported towards the dunes, the graph suggests that marram grass may get overwhelmed by sand, impeding its growth. At the same time, when marram grass traps less sand than the optimal amount, it may not grow as vigorously as it could potentially, meaning it also would not trap as much sand as it potentially could.

This pattern of optimal marram grass growth has an important implication for coastal management: optimizing the potential of marram grass to grow and develop dunes means we can maximize the potential of coastal dunes to provide coastal safety. Sand nourishment strategies such as the Sand Motor should therefore aim to ensure that supply of wind-blown sand towards the dunes occurs at optimal rates for marram grass to thrive. Luckily, the Sand Motor appears to do just that and in many places on and along the Sand Motor, the dunes are developing at optimal rates. Using high-resolution data obtained by a drone has proven to be invaluable for gaining insight into how marram grass contributes to dune development and coastal safety. The continuing application of such remote sensing techniques holds great promise to better understand the coastal terrestrial ecosystem with its interactions between the dry beach, dunes, vegetation and morphology.

Figure 1. (below) Visual impression of armor layer at three locations in the Sand Motor region. Covered surface is approximately 40 x 40 cm in each case:

Intertidal beach, no armoring.

Lower dry beach, minor armoring with shell fragments.

Upper dry beach, severe armoring with many shells and coarse sand.

Figure 2. (left) Measurement equipment with laser sensors deployed at the Sand Motor.

Bas Hoonhout

WHY MORE SAND NOT ALWAYS RESULTS IN LARGER DUNES

Bas Hoonhout obtained his PhD at the Coastal Engineering section at the Faculty of Civil Engineering and Geosciences at Delft University of Technology in 2017. Currently he has a dual position as morphologist and data engineer at Van Oord.

Dissertation title:
"Aeolian Sediment Availability and Transport."

PhD supervisors:
Marcel Stive (Delft University of Technology)
Sierd de Vries (Delft University of Technology)

Shortly after the Sand Motor was constructed, strong winds suspended large clouds of fine sediment in the air. These local sand clouds could reach up to 100 m high and travel several kilometers inland into the urban areas of Kijkduin. About half a year later, the nuisance disappeared as suddenly as it had appeared. What happened to this extreme aeolian activity, unprecedented along the Dutch coast?

The sand used to construct the Sand Motor was dredged from the bed of the North Sea and is far from homogeneous. It consists predominantly of sand (small mineral particles between 0.063 and 2 mm in diameter), fine silt and clay fractions (< 0.063 mm), and coarse elements, like shells, shell fractions, some pebbles and cobbles and an occasional fraction of a mammoth bone. These different constituents appear to largely determine the aeolian activity at the Sand Motor and the project's morphological development.

The different constituents of the Sand Motor's sand were reasonably well mixed shortly after construction. A large part of the Sand Motor is located well above storm surge level (> 3 m above MSL), and is therefore never inundated and only exposed to wind. The wind exerts a drag force on the exposed sandy material, which can lift particles up in the air and initiate aeolian transport of sand to the dunes (and beyond).

The wind drag is small, especially compared to the forces exerted by currents and waves. The size and mass of individual sand grains, shells and shell fragments determines the effectiveness of the wind to move the sandy material. In practice, only silt and fine sand grains are regularly lifted. Coarse sand and shells are only moved during very strong winds. Consequently, fine material disappears rapidly from the beach surface and only coarse material remains, sheltering the underlying fine material from the wind. Over time, the beach surface is covered by a thick layer of coarse elements: the armor layer (Figure 1).

The development of an armor layer explains why the sand clouds disappeared within a half year after the Sand Motor was constructed. On more regular beaches, storm surges frequently disturb the beach, breaking the armor layer, bringing fine material to the surface, and reactivating the aeolian activity. At the Sand Motor, there was no such counteracting force due to the fact that a large part of the Sand Motor surface is well above storm surge level (> 3 m above MSL). This restricts the aeolian activity at the Sand Motor more permanently.

Measurements
Bimonthly measurements of the Sand Motor's topography show that the dry beach (> 3 m above MSL) stopped eroding a half year after construction. Nevertheless, wind-blown sand continued to accumulate in the dunes, the dune lake and lagoon. In fact, even after the unusual aeolian activity stopped, three times more sand is deposited in the Sand Motor area every year than erodes from the dry beach. Where does this sand come from?

There are two possibilities: The sand can come from the low-lying beaches surrounding the Sand Motor (< 3 m above MSL), or from the adjacent coast.
The possibility that all this sediment originates from the adjacent coast is unlikely as the width of the beach connecting the Sand Motor to the adjacent coast is too narrow to transport such large amounts of sand. Therefore, the low-lying beaches, which are frequently flooded and up to 60% smaller than the dry beach area, appear to be the primary source of aeolian sediment in the Sand Motor area (Figure 3 on next page, green shading).

This hypothesis was tested during a six-week field campaign, during which we counted the number of airborne sand grains using lasers. Eight masts, each of them with three to six laser sensors stacked above each other, were deployed in one or more straight lines, aligned in the wind direction (Figure 2). The masts were deployed 24 hours a day, 7 days a week for almost the full six weeks. The masts were manually relocated according to the wind direction and the tide, which required an almost permanent presence at the Sand Motor.
If the number of particle counts increased from one mast to another in the direction

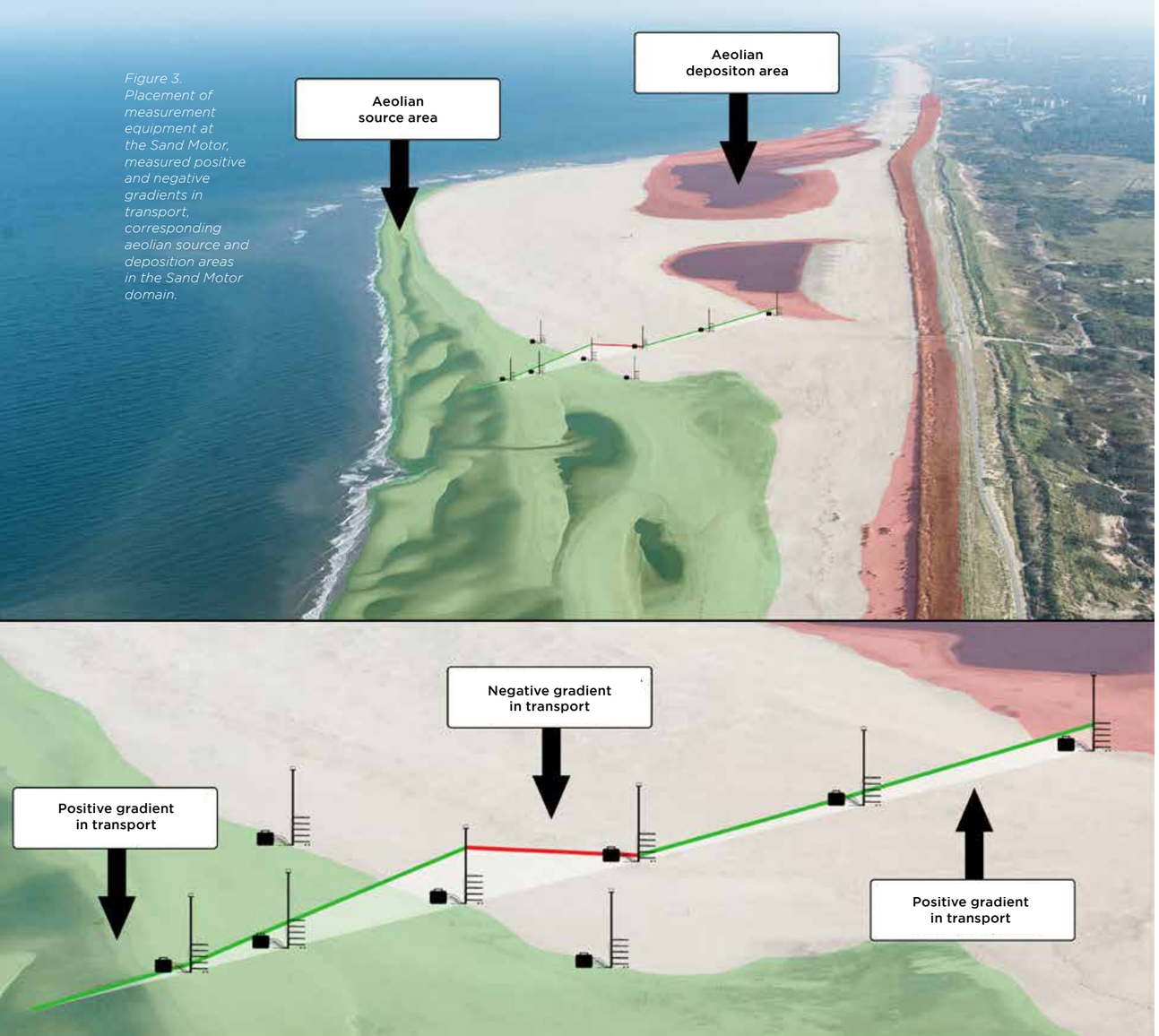


Figure 3. Placement of measurement equipment at the Sand Motor, measured positive and negative gradients in transport, corresponding aeolian source and deposition areas in the Sand Motor domain.

of the wind, sand was picked up from the area between the masts: we refer to this as a positive gradient in transport. Conversely, if the number of particle counts decreased from one mast to another in direction of the wind, sand was deposited between the masts: we refer to this as a negative gradient in transport. Analysis of the spatial variation in transport gradients thus reveals the areas of erosion and deposition of aeolian sediment (Figure 3, detail).

In addition, we conducted micro-topographic measurements in the low-lying beach area. We pressed about 100 small erosion pins (nails) in the beach during low tide, with their heads flush to the surface. If the low-lying beach eroded during low tide, the erosion pins would protrude from the beach. Just before high tide, we manually measured how much the erosion pins protruded to confirm and quantify the erosion.

If the low-lying beaches were indeed the primary source of aeolian sediment, we expect to find protruding erosion pins and positive transport gradients in this area. As the low-lying beaches are flooded during high tide, we also expect sediment supply near the dunes to modulate with the tidal cycle. The analysis of spatial variation in transport gradients did reveal a continuous strong positive gradient and erosion over the low-lying beaches during low tide. However, we also measured steady particle counts near the dunes. Also surprising was the strong negative transport gradient coinciding with the start of the beach armor layer. This negative transport gradient indicates rapid deposition of the sand that has just eroded from the low-lying beaches. In the long run, the deposition appeared to be temporary as the armor layer (i.e., shells) remained visible and was not buried under fresh deposits.

In order to explain what happened, we need to look at the mechanisms of aeolian sediment transport in more detail. Aeolian sediment transport occurs in three stages: suspension, saltation and creep. In coastal environments, saltation accounts for the majority (~70%) of all aeolian transport. Saltation is a form of transport where sand grains that are lifted from the bed are not suspended, but are deposited somewhat downwind. Upon impact, each sand grain ejects one or more grains from the bed. These ejected grains gain momentum from the wind, get lifted, and strike the bed again somewhat downwind. This cascade continues downwind and a thick layer of sand grains develops, jumping in the direction of the wind. The mechanism of saltation transport therefore implies a continuous interaction with the beach surface.

The continuous interaction with the beach surface causes saltating sand grains, originating from the low-lying beaches, to immediately "feel" the armor layer once they reach the dry beach. Significant amounts of sand from the low-lying beaches are trapped in the armor layer. During high tide, when no sand is supplied from the low-lying beaches, the wind can remobilize these fresh deposits and transport the sand further landward. Consequently, the strong variation in particle counts near the water line, associated with the tides, is not seen close to the dunes.

Model

An accurate description of the interaction between aeolian sediment transport and the formation of an armor layer is necessary to accurately predict aeolian sediment transport and dune growth in coastal environments. We developed a numerical model for this purpose: AeoLiS (Aeolian Sediment Transport with Limited Supply). AeoLiS is a model for aeolian sediment supply that includes the formation of armor layers and other supply-limiting processes. It predicts which sediment erodes and when: a spatiotemporal prediction of the erodibility of the beach. AeoLiS does so by simulating relevant supply-limiting processes, like sediment sorting, development of the armor layer, and flooding and drying of the beach.

AeoLiS was first applied to reproduce the accumulation of sand in the Sand Motor. We compared measured and simulated time series of sand accumulation in the dunes, dune lake and lagoon. AeoLiS explained 93% of the measured variance in the total accumulation volumes. The model captures the formation of the armor layer and the relative importance of the low-lying beaches. However, the distribution of the accumulated sand over the dunes, dune lake and lagoon is skewed a bit towards the dunes. Additional supply-limiting processes that are currently not included in the model, like groundwater seepage, vegetation growth, wind setup and wind steering, might explain these deviations.

AeoLiS provides a generic framework to implement formulations that describe additional supply-limiting processes and can be combined with existing sediment transport models to obtain a predictive coastal landscape model. Such a model can be used to explore the merits of different beach nourishment designs. For example, the armor layer and relatively limited aeolian activity at the Sand Motor is largely due to its height. A lower height and more frequent flooding of the dry beach might limit the development of the armor layer and stimulate aeolian activity. Similarly, the dune lake and lagoon intercept much of the sand transported from the low-lying beaches, limiting the possibilities for embryonic dunes to develop. If these water bodies were smaller or in different locations, local dune growth might be stimulated. The AeoLiS model can be used to explore the effectiveness of nourishment strategies (beach, foreshore or mega-nourishment), planting and grazing strategies, beach cleaning, raking, and prohibiting driving, among other things.

To design a nourishment or a maintenance strategy, proper goals of the intervention need to be formulated. The primary objectives of the Sand Motor were to supply the entire coast of Holland with sand for a period of over two decades and to stimulate recreation in the coastal zone. Intense aeolian activity and dune growth could very well conflict with these objectives. The AeoLiS model provides the tools to optimize coastal landscape design for tailored coastal interventions.

AeoLiS documentation and download:
http://aeolis.readthedocs.io

Kathelijne Wijnberg

IMPROVING THE ABOVE-WATER DESIGN OF LARGE SAND NOURISHMENTS

REFLECTION

Kathelijne Wijnberg is a professor of Coastal Systems and Nature-based Engineering at the University of Twente, Faculty of Engineering Technology. Within the NatureCoast program she was the principal investigator of scientific research project S2, which focused on dune formation.

The core ingredient for maintaining Dutch coastal flood defenses is sand. This is not surprising when realizing these mainly consist of dunes. Initially, sand was only used to repair storm damage to the dunes. At present, it is added once the volume of sand in an indicator zone drops below a reference value. This proactive approach was only developed because of increased scientific understanding of the coastal system and the processes involved in moving the sand.

With the Sand Motor pilot project, we are stepping up to the next level. Not only by scaling up the magnitude of sand nourishment and by raising the ambition that the nourishment should serve multiple purposes, but even more so by expecting natural processes to complete the job. In a few decades, the dunes in the region should have been strengthened to guarantee flood safety from rising sea levels. In the meantime, the Sand Motor area should provide space for recreation and allow additional beach-dune habitat to develop without jeopardizing the long-term goal of reinforcing the dunes.

To go from voicing the bold idea of the Sand Motor, to actually constructing it has posed many challenges, one of which was how to properly design it. Contrary to hard engineering measures, the Sand Motor is not a static intervention that needs to meet all its goals upon completion, when the contractors have finished their work. The Sand Motor is a dynamic intervention where nature is actually the master builder that should ensure that all goals are met over time.

Compared to our knowledge of below-water developments, little was known about how the above-water landscape would develop. Estimates of the magnitude of wind-blown sand supply necessary for dune growth as a flood defense were essentially based on past dune growth rates. Predicting how the above-water landscape at the Sand Motor would develop seemed largely left to artists, whose impressions often showed the Sand Motor covered with dunes and vegetation. Apparently, developments at the surface of the Sand Motor were not expected to have much impact on the rate of sand supply to the dunes. This was undoubtedly due to the lack of numerical models to predict above-water developments with computer simulations.

It turned out that considerable amounts of wind-blown sand were trapped in the lagoon and lake (Pages 86 and 88), which was not foreseen. This affected the initial dune growth rates observed at the foot of the dune reinforcement (Pages 96 and 100). The long-term effects of the trapping remain to be seen, because at some point these reservoirs of fine, wind-blown sand will become available, as the waves and currents continue eroding the Sand Motor. Additionally, the seaward expansion of vegetation was affected by activities such as raking the beaches, driving on them, and construction of beach huts; this slowed down the development of a new dune row (Pages 86 and 96).

With respect to new dune development away from the dune reinforcement, valuable insight was given by the research conducted by Van Puijenbroek (Page 92), who showed that the high, barren plain of dredged sea bed material was difficult for perennial plants to colonize, because root stalks transported by storms could not reach the higher elevations. Wind-blown seeds that could reach these elevations found conditions that were too dry to germinate, and the steadily lowering bed level due to wind erosion did not help either. Without perennial vegetation, it was hard for permanent dunes to form at the Sand Motor itself.

We are now finally starting to see a small incipient dune field forming on the south side of the Sand Motor. This dune field may actually become a new local sink for wind-blown sand, meaning that it will not reach the dune reinforcement, thus locally affecting the sand supply to the dune reinforcement zone.

So, will the long-term goal of strengthening the dunes be jeopardized by the shorter-term goals for recreation and development of natural habitat? We certainly see an influence, but to know the final effect we will have to keep following this dynamic project. We will only have the scientific basis for a definite answer towards the end of the Sand Motor's life span. NatureCoast research has offered advances in long-term monitoring approaches for wind-driven sand transport and predictive modeling. These consitute an important step towards improving the above-water design of large sand nourishments.

Ecologist and Advisor

KEES VERTEGAAL – ADVISEURS ECOLOGIE

INTERVIEW

In what way is the Sand Motor unique to you as end-user?
"It is unique as a coastal reinforcement experiment that also seeks to contribute to nature and recreation. And especially when it comes to nature. I am involved in the Sand Motor monitoring program through *Rijkswaterstaat*. From there I followed the NatureCoast studies, being interested in how they supplemented our work."

How do you see the role of scientific research at the Sand Motor, as end-user?
"Useful and necessary; much more research should be done. I think that long-term research in particular is very important for a project like the Sand Motor. This is because the processes actually occur relatively slowly, and with PhD research projects typically lasting four years, the time span is often too short. This applies to ecology, geomorphology, in fact, to almost all research topics."

How relevant is multidisciplinary research on the Sand Motor for you as end-user?
"I can be brief about that: as far as I'm concerned, it's almost pointless not to do this kind of research in a multidisciplinary way."

What are the main findings of the NatureCoast program for you as end-user?
"I mainly followed Marinka van Puijenbroek's research, which is focused on the first phase of dune development. Fortunately, this picture fits in well with what we have found in the monitoring for *Rijkswaterstaat*. Our work is related to that of Marinka, and her research has provided us more in-depth understanding. We mainly monitor, which involves limited scientific analysis, whereas Marinka has gone into more depth and shown, for example, the way in which the dunes formed and vegetation developed."

If you had to give advice about other dune areas, which lessons from the Sand Motor would you use?
"I think a very important lesson from the Sand Motor is that you have to do more than just deposit sand if you want to ensure the added value mainly for nature. At the Sand Motor, it was placing sand and nothing else. What I have learned, and this has already been applied in some of our advices, is that we need to build dunes earlier on or stimulate development of dunes more actively. If we leave it all to nature, it will become very beautiful; but that will take a lot of time.

However, the Sand Motor has a limited lifetime, given the principle that it is designed to last only twenty or thirty years. Now, the first ten to fifteen years it's just sand with a small dune here and there. If we want to enjoy it, especially in terms of nature, we would actually have to add some more to the design and construction: differences in elevation, planting or sowing of vegetation, and things like that. To a lesser extent, this is also relevant for recreation, as it helps to create a landscape in which people enjoy walking. If you initially invest more in the design, you will easily create a landscape structure that reinforces the added value of nature much sooner."

Senior advisor, Geologist

BERT VAN DER VALK – DELTARES

INTERVIEW

Why is the Sand Motor unique for you as end-user?
"The Sand Motor is unique to me because it is a one-to-one scale experiment. That is very unusual. I am a geologist, so I always think in somewhat longer terms, and the Dutch coast has always been as straight as a ruler for the past 5,000 years. Note that I'm talking about the Holland coast, not the entire Dutch coast! And then, with the Sand Motor, a large bump of sand suddenly appeared: 21.5 million cubic meters. Of course, the Dutch coastal system tries to smooth out the coastline immediately, because that is how it works. This resulted in a very exceptional situation, geologically speaking."

How do you see the role of scientific research at the Sand Motor, as end-user?
"Such a unique one-to-one scale experiment must be closely monitored and evaluated, which is exactly what the NatureCoast research program has done. I think it is also very important that scientific research continues after the NatureCoast program. Because the monitoring program that *Rijkswaterstaat* requires is actually not very elaborate. And I wonder about the usefulness and value of the next evaluation, from 2016-2020. It remains to be seen whether we will actually have sufficient arguments in 2020 to carry out a proper second evaluation of the Sand Motor."

"Continuing scientific research is not easy, because *Rijkswaterstaat* will of course remain the chief management authority, and they have limited funds for monitoring the Sand Motor. And this is where the shoe pinches, because nobody will do the monitoring by himself. Maybe NWO or another financer could jump in again, that would certainly be my advice."

How relevant is multidisciplinary research on the Sand Motor for you as end-user?
"Very relevant. The Sand Motor is a special construction; we have never seen anything like this on the Dutch coast in our time. That means you have to follow it well, and that requires more than one discipline. Not only morphology, but also ecology. For example, the lagoon and its development have remained largely unknown to ecologists. The lagoon also makes the Sand Motor a unique phenomenon, because it is not found anywhere else. The new lagoon at the *Hondsbossche Duinen* (Hondsbossche Dunes) cannot be characterized as a lagoon that is more like a swimming pool."

What are the main findings of the NatureCoast program for you as end-user?
"I think the morphological development is the most important one, dealing with the interaction of waves and flow-driven transports. We can use these results as end-users; they have provided insights into the working of this unusual and large amount of sand on the Dutch coast. This also provides eye openers for applying large amounts of sand nourishments on other parts of the coast. But again, the Sand Motor is a unique case. For example, the findings of the Sand Motor can certainly not be compared to those of the Hondsbossche Dunes, and also not to those of the major nourishment on the outer delta of Ameland."

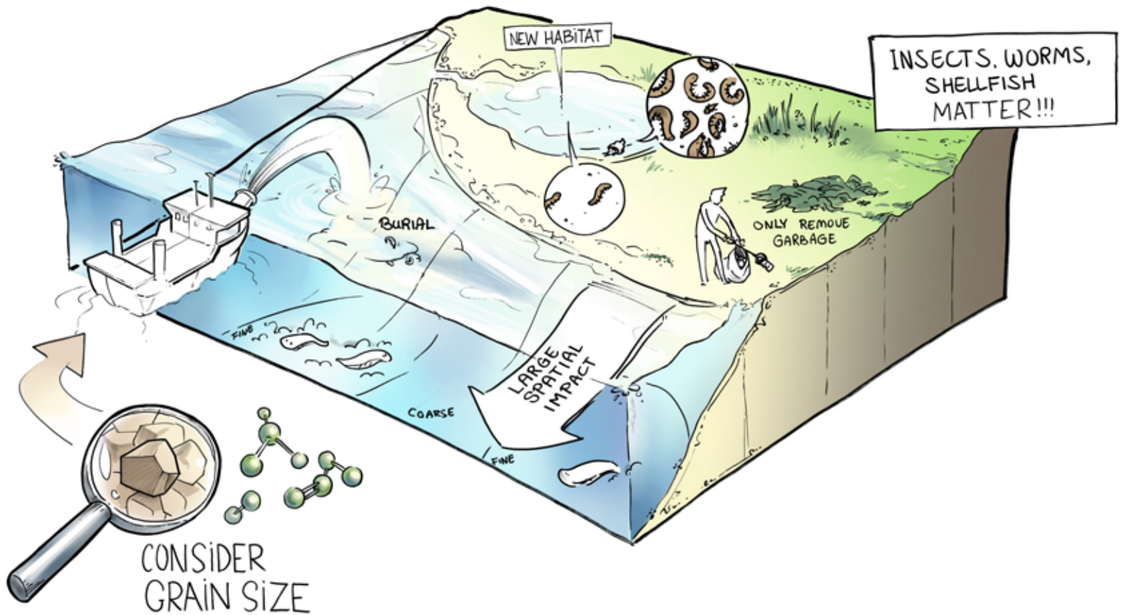
"I have been investigating the upper waterfront of the Sand Motor, *Spanjaards Duin* and the *Hondsbossche Duinen*, areas more than three meters above sea level, in order to understand this part of the coast better. That is comparative research: *Spanjaards Duin* is 10 years old, the Sand Motor 7 years, and the *Hondsbossche Duinen* are still very young at 3.5 years. And you have to deal with the seasonal changes, as we know them in our country, especially in how the supratidal area develops. After 10 years you start to understand it reasonably, but after 3.5 years it is clouded in quite a few uncertainties. So comparative research can be done, and I think that there is a lot of value to that."

Which research findings about the Sand Motor can be applied to other coastal zones in the Netherlands?
"The Sand Motor has shown that the design of the nourishment provides a very important starting position for future developments. This concerns the form: the Sand Motor has the dune lake and the lagoon. It was not foreseen that both the dune lake and the lagoon would absorb large amounts of aeolian sand. It will probably take another 20 years or more before more dune sand lands in the coastal dunes in substantial quantities."

"That is the big difference between the Sand Motor and the *Hondsbossche Duinen* for example. At the *Hondsbossche Duinen* much more sand ends up in the current dunes. And that is because there is direct contact between the beach and the dune, which is what happens when you apply this different design."

FIVE | **ANIMAL LIFE**

Figure 1.
Towards Nature Friendly Nourishment
(Image by JAM Visual Thinking)



Alexander van Oudenhoven

THE HIDDEN ANIMAL LIFE AT THE SAND MOTOR

INTRODUCTION

As we have shown, the Sand Motor differs from other Dutch sandy beach areas because of its size, shape, the low nourishment frequency and its lagoon. This has profound consequences for the ecology of the Sand Motor. Although many might regard sandy beaches as straightforward "sand flats" or "beach deserts," they are in fact highly dynamic and full of life. But this is just not always visible to the human eye.

The construction of the Sand Motor created a lot of potential for "new" nature. In addition, it has been suggested that the Sand Motor is a more nature-friendly solution than the more common smaller scale nourishments. But what kind of new nature has really been created, and is the Sand Motor truly more nature-friendly? In this chapter we will introduce you to four different zones, sub-systems that you might perhaps not associate with nature or biodiversity when walking along the shore. We will look at the sea floor, the shallow sea, the wet beach and the dry beach. Each zone is affected differently by the wind, waves, currents and many other factors. Naturally, the construction of the Sand Motor affected each zone differently too. Understanding these effects, both positive and negative, will help us to conclude on the net effects of the Sand Motor on nature and biodiversity.

The bottom of the sea is teeming with life, which also happens to be close to the bottom of the food chain. We will look at the fascinating animal life at the bottom of the sea, as deep as around 10 meters. The worms, shellfish and other animals living here are called macrozoobenthos, and they are preyed upon by animals higher up the food chain, such as fish, crustaceans and birds. Simeon Moons (Page 114) will show you how quickly the macrozoobenthos recovered from the construction of the Sand Motor, and which other factors contributed to a different composition of species.

Moving closer towards the beach, the shallow sea waters are crucial nursery habitats for flatfish such as sole and plaice. This is where we conducted research on the effect of the Sand Motor on the habitat conditions for juvenile sole and plaice, such as the availability of food (e.g., macrozoobenthos) and the size of the sand grains. These and other variables basically determine whether the shallow sea near the Sand Motor is good enough for flatfish to grow up in. Perhaps Marjolein Post (Page 118) will make you look differently at the fascinating life of flatfish in the shallow sea waters.

With our feet more firmly on the ground, we now reach the wet beach, which connects the sea to the dry beach. Also called the intertidal zone, this area is most directly shaped by incoming waves. We studied the many small invertebrate animals, such as worms and insects, that somehow manage to survive these harsh conditions. From Emily van Egmond (Page 122) you will learn more about their survival mechanisms, as well as why the Sand Motor attracts different species. Furthermore, we will show you the importance of nature-friendly maintenance of the dry beach, by leaving the organic material that has washed ashore where it is.

We will look at how different key animals of the four sub-systems have coped since the creation of the Sand Motor. In addition, we will identify the most important factors that have determined the success or demise of these species. By understanding the different sub-systems as well as the Sand Motor ecosystem as a whole, we will be able to tell more about how nature-friendly the Sand Motor truly is. The chapter concludes with two reflections on animal life at the Sand Motor, as well what these findings mean for current and future coastal management. The reflection by Peter Herman (Page 126) will zoom in on the fate of macrozoobenthos and underwater biodiversity, whereas the reflection by Rien Aerts (Page 128) will deal with the beach ecosystem.

Figure 1.
This sample (collected near Ameland, the Netherlands) illustrates how diverse the benthic community can be. The pink color was added for easy sorting. Diameter of the photo is 10 cm.

Simeon Moons

BURYING THE BOTTOM OF THE FOOD CHAIN

Simeon Moons conducted PhD research at the Royal Institute of Sea Research (NIOZ). He currently works at Royal Haskoning DHV, as a marine ecologist.

PhD supervisors:
Tom Ysebaert (NIOZ, Royal Institute of Sea Research)
Peter Herman (NIOZ, Royal Institute of Sea Research; and Delft University of Technology)

The seaside is loved by humans, but they are not the only animals attracted to it. Below the surface, the sea water and especially the seafloor are teeming with life. Often hidden from plain sight, hundreds of different worms, shellfish, crabs, shrimps and other rather odd-looking animals live at the seafloor. These animals are called macrozoobenthos, or just benthos (Figure 1). Although most of these animals are very small (millimeters rather than centimeters), together they make up an enormous biomass, which makes them an important part of the marine ecosystem.

Benthos fulfill many functions that contribute to a healthy ecosystem, and this in turn provides benefits to human society. Most importantly, benthos are a key trophic group in the food chain; many benthos species are preyed upon by fish, birds and even humans. Some species are commercially interesting too, such as mussels, clams, shrimps and crabs. More importantly, the fishing industry would collapse in the absence of benthos. Benthos themselves feed mostly on microscopic organisms like algae and bacteria, or on organic waste (detritus). Without them, the sea would probably be a murky green soup, and the seafloor would be an ecological garbage dump. However, benthos do a lot more than just eat and be eaten. Because benthic organisms live in between the sand grains, they have the potential to act as "eco-engineers": they shape the seafloor.

Eco-engineering can have a positive influence on other organisms, thereby increasing the biomass and the biodiversity in the ecosystem. Some "eco-engineers" can also benefit humans by contributing to natural flood protection. The best known example is above ground, where coastal vegetation helps in the formation and preservation of sand dunes (Pages 88 and 92). Something similar could be happening underwater, but not much is known about this yet. The underwater world is still full of mysteries and discoveries to be made.

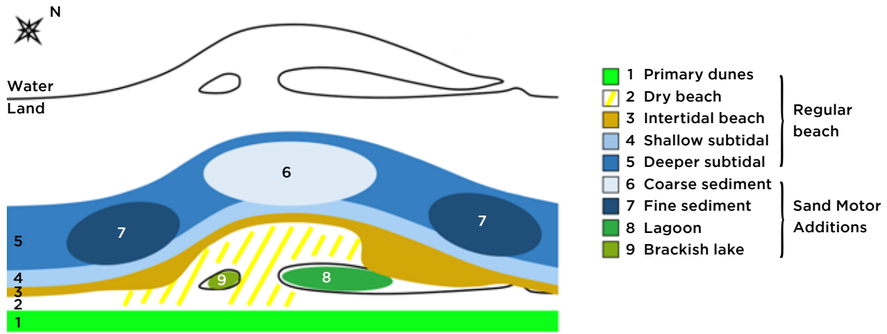
At the Sand Motor, we wanted to know how the coastal benthic community would respond when a large amount of sand is deposited on the seafloor. Because benthic organisms live in between the sand grains, they also risk being negatively affected by any coastal modifications, such as sand nourishments. Sand nourishments are known to bury and suffocate local benthic organisms.

Sand nourishments have frequently disturbed the Dutch coastal ecosystem in the last decades, and they are likely to become even more frequent or larger, as we find ways of coping with future sea-level rise. Although the benthic community tends to recover relatively quickly (generally 2 to 3 years), we would ideally like to avoid frequent disturbance. And this is where the Sand Motor and its "Building with Nature" philosophy comes in: to limit the ecological disturbance in time and space by applying a much larger volume of sand and using natural forces to distribute the sand to the adjacent shore. In theory, the Sand Motor would result in a longer period without disturbance, which should allow for natural succession and eco-engineering processes.

An extensive monitoring program provided us with yearly measurements of the benthic biodiversity, abundance and biomass in the area around the Sand Motor. For comparison, we also sampled the benthic community on the shore of Ameland, one of

Figure 2.
A sample is taken from the seafloor with a "Van Veen Grab Sampler" near the coast at Scheveningen, the Netherlands.

Figure 3.
Bird's eye view illustration of the ecological zones created by the Sand Motor.



the Dutch Wadden Sea islands (see Figure 2 for an impression of the sampling method). This island's shoreline has a similar hook shape as the Sand Motor and is similarly dynamic, but it has been formed by natural processes rather than human influence. We also had a closer look at the effects of regular nourishments, and especially shoreface nourishments (Pages 30 and 160), since they had not been widely studied.

To our surprise, we found that the benthic community can take several years to recover after a shoreface nourishment, rather than 2 to 3 years as is generally assumed—and in some cases, it did not recover at all. The difference in recovery time between beach and shoreface nourishments can be explained by the natural environmental conditions of the disturbed habitat. The deeper you move into the water, the less dynamic the seafloor will be, due to reduced influence from wave action, and the more biodiverse the benthic community will be. The benthos near the beach might be adapted to rapid sediment deposition, whereas the benthos at the shoreface might not. Fortunately, not every shoreface nourishment has a long-term negative effect. The most important factor influencing the recovery period seemed to be the sediment grain size; bigger is definitely not better in this case. Our findings underline the importance of designing nourishments with a longer lifespan, to allow recovery to take place, and this is exactly what the Sand Motor does.

But the Sand Motor does more; it creates diversity in the landscape and habitat of benthic organisms. At a regular beach, we can distinguish a number of zones with specific conditions, harboring specific groups of organisms (e.g. the intertidal zone, on Page 122). At the Sand Motor, however, we can distinguish a number of additional zones (Figure 3). Some are easy to spot, like the lagoon, but others only became apparent through research, like an area with coarse sediment at the tip of the Sand Motor and areas with fine sediment on the northern and southern side of the Sand Motor. The coastal hydrodynamics are altered by the size and shape of the Sand Motor, resulting in different sediment sorting. We think this diversification of the environment explains why we found more species overall after the construction of the Sand Motor than before. Moreover, we even found a higher benthic diversity surrounding the Sand Motor than at the naturally dynamic shore of Ameland, excluding the lagoons. Although the area has been successfully recolonized, that does not necessarily mean that the natural system has recovered. Rather, it can be argued that the Sand Motor has created new habitat, at the cost of the old. But was the original theory not that the Sand Motor would minimize disturbance to the habitat?

If we zoom out, we can see that the Sand Motor affects a much larger area than the original nourishment surface. We discovered that the effects on sediment sorting extend several kilometers along shore and to a depth of at least 12 meters. These changes were also reflected in the composition of the benthic community. The Sand Motor might not bury the benthos in the adjacent shore, but it does change the habitat. Over time, the Sand Motor will shrink in size and the effects on the hydrodynamics will lessen. Importantly, we only observed this extended effect in the deeper waters, beyond the outer breaker bar. In fact, only one year after construction of the Sand Motor, there were hardly any changes in benthic community composition in the shallow water. This can again be explained by the presence of waves, which apparently makes all the other factors redundant.

There is one exception to wave dominance: a shallow body of water without wave action, the lagoon (Figure 3, indicated by number 8). The lagoon is one of the Sand Motor's most remarkable design aspects. From an engineering point of view, it is easier to make a bell shape without a lagoon, and it may even hamper sediment transport to the dunes, but from an ecological point of view, it makes perfect sense. The lagoon makes the Sand Motor resemble the natural coastline of Ameland and other dynamic shores, and it is the lagoon that makes these areas so ecologically valuable. In the absence of strong wave action, the shallow water can change from a relatively poor environment to a rich environment, teeming with life.

Over time the lagoon can transform into a "green beach", with rare plant species and abundant birdlife. After additional research, we concluded that the Sand Motor lagoon harbors a very high benthic diversity up to 2 meters deep. The biodiversity is much higher than at the adjacent shore, and organisms are easily accessible for foraging birds. Unfortunately, the deeper parts of the lagoon have become oxygen depleted and are therefore unsuitable for almost all benthic organisms. While this highlights our ability to design and build an ecologically rich environment, it also shows that we still have much to learn and improve.

Overall, it can be argued that the Sand Motor design is a step in the right direction towards sustainable coastal protection. The lesson seems to be that if we incorporate ecosystem functioning into the nourishment design, the ecosystem will eventually pay us back. However, a simple copy-paste of the Sand Motor design elsewhere could have serious drawbacks. When considering the fate of macrozoobenthos in sandy solutions, our findings suggest that the most important factors are the grain size of the source sediment, the size and orientation of the nourishment, and, finally the shape of the nourishment and how this will evolve into an ecologically rich environment. Furthermore, it would be interesting to see whether benthic "eco-engineers" can eventually be utilized for coastal protection.

Of course, the Sand Motor has just started, and it will continue to evolve for several years. Whether the absence of frequent nourishment disturbance will truly result in a richer ecosystem remains to be seen. Many questions concerning the ecological development of the Sand Motor remain, and only time can tell.

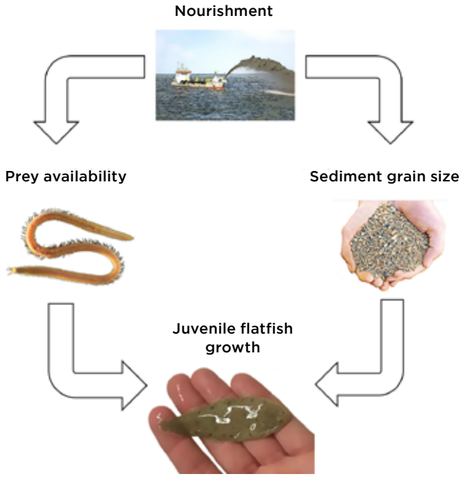


Figure 1. Schematic overview of the effects of sand nourishments. Implementing a nourishment will affect the abundance of prey species in combination with changes in sediment grain size. These changes in prey availability and sediment can have a large effect on the growth of juvenile flatfish such as plaice and sole.

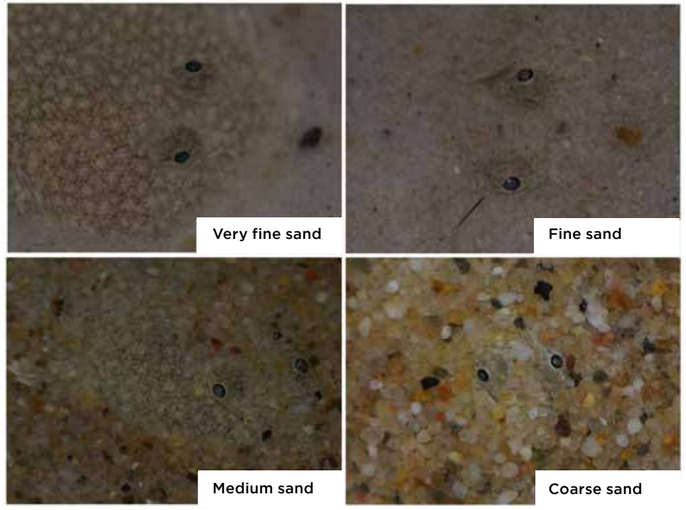


Figure 2. These four different sediment grain sizes can be found around the Sand Motor. The photos illustrate how juvenile sole (~4 cm) can bury themselves in very fine (63-125 µm), fine (125-250 µm), medium (250-500 µm) and coarse sands (500-1000 µm). They are more visible and less covered by the sand in medium and coarser grain sizes. (Photos by Marjolein Post)

Marjolein Post

FLATFISH GROWING UP IN A SANDPIT

Marjolein Post researches marine biology and ecology for her PhD project at Wageningen Marine Research, and is expecting to graduate in 2019.

(Tentative) dissertation title: "The effects of sand nourishments on juvenile fish."

PhD supervisors:
Han Lindeboom (Wageningen University)
Martin Baptist (Wageningen Marine Research)

The Sand Motor was established in the shallow coastal area, which provides an essential nursery habitat for many juvenile flatfish species, such as the commercially interesting sole and plaice. The fact that juveniles congregate in this habitat means that they are extremely vulnerable to a large disturbance, such as a sand nourishment. At present, we do not know much about the ecological impact of nourishments on juvenile flatfish and on the quality of their nursery habitat.

We do know that population renewal is directly linked to the size and quality of nursery areas. Juvenile growth and survival are promoted when nurseries offer suitable habitat conditions such as high food availability, shelter opportunities and appropriate sediment grain size. These conditions are likely to be affected by the addition of large amounts of sand, as was the case during the construction of the Sand Motor. We investigated the main impacts of the Sand Motor on important habitat conditions for juvenile sole and plaice. This includes the effects of nourishments on the availability of prey, sediment grain size, and the consequences of these changes on juvenile growth (Figure 1). We first investigated these impacts in an experimental setting, and then attempted to disentangle the different effects using a modeling approach.

Given that juvenile flatfish live on the bottom of the sea, the diameter of sand grains (grain size) is an important variable for their distribution. The ability of juveniles to bury in sediment with just the right size grains is a crucial factor for habitat selection. However, sand nourishment may lead to an overall coarsening of the sediment in the coastal zone. Coarser sediment can inhibit flatfish from burying themselves, or affect the availability of prey. In addition, prolonged digging can increase the energy requirements of juveniles, which could inhibit their growth and thereby make them more vulnerable to predators. Habitat degradation could thus lead to lower survival and fitness, as well as an overall negative effect on the number of juvenile flatfish that reach maturity. It is therefore important to understand how grain size affects flatfish in nursery areas.

As shown in our experiment, juvenile sole and plaice prefer very fine and fine sandy sediments over medium and coarse grain sizes (Figure 2). The question remains whether this preference also means that they are dependent on a specific habitat. Implementing the Sand Motor increased the grain size of the sediment, making the less favorable for juveniles. We found a high percentage of medium-sized sand with several large patches of coarse sand around the Sand Motor. This had a more prominent effect on the abundance of juvenile plaice than on juvenile sole. The grain size on the Dutch coast where the Sand Motor was implemented had already been shifting from fine to medium-sized sand as a result of earlier sand nourishments (Page 53). If this coarsening progresses, it could result in loss of the nursery function.

These effects could be amplified by the direct effect of the nourishment on the abundance of prey. Adding a thick layer of sand results in the large-scale burial of benthic fauna, with few surviving (Page 114). To facilitate rapid re-colonization of the foreshore by benthic fauna, the characteristics of the nourished area have to match their habitat demands. When a large amount of sand is added,

Figure 3.
The Sand Motor lagoon is a shallow artificial area that was created to serve as a nursery for juvenile fish, offering shelter and increased temperatures. Over time the entrance channel to the lagoon has reduced in depth and width.(Photo by Rijkswaterstaat/ Jurriaan Brobbel)

Figure 4.
Coastal survey in 2016, fish sampling in shallow near-shore at Sand Motor. (Photo by Marjolein Post)

the new substratum may be unsuitable for re-colonization by the species that previously inhabited the area. When these environmental changes are permanent, long-term changes in the benthic community may also occur.

Opportunistic species usually become more successful and their biomass increases shortly after a nourishment event, as they take advantage of the initial death of the benthic community. In the case of the Sand Motor, this translated into high availability of prey, and as a result, high numbers of juvenile sole and plaice. This suggests that both species are able to optimize their foraging behavior and adapt to the situation. For instance, the fish could migrate towards areas with more prey if the food were limited. Our findings also suggest that the timing of a nourishment could affect the abundance and recovery of the species on which sole and plaice prey. The availability of this prey will have consequences for the caloric intake of juveniles and their growth.

We developed a model to directly relate changes in the availability of benthic species following a nourishment to fish growth. Fish growth can be optimized by increasing temperatures and the quantity of food. Thus, in our model we let temperature and the availability of food determine the individual growth of juvenile plaice. The model was applied for different nourishment scenarios that differed in the time of the year the nourishment was implemented. We compared the differences in growth at the end of the summer for each scenario. This enabled us to capture the most extreme effects of nourishments and to showed the importance of seasonal timing of nourishments on juvenile flatfish growth.

We found that the nourishment has the highest impact when the water temperature increases. Juveniles already require an increasing amount of energy to reach a larger body size and this is amplified when the water becomes warmer. The impact of a sand nourishment on juvenile fish growth, as well as on the environment as a whole, could be minimized if seasonal timing were considered. The length that juveniles reach during their first growing season is most affected when a nourishment coincides with high summer temperatures and the period the benthic population normally increases. The final length of juvenile plaice could drop from 8.5 cm to 6.6 cm in this scenario. However, if this scenario coincided with a period of low benthic productivity, the juveniles would only reach a length of 2.8 cm by the end of summer. These represent extreme situations, and the reality will lie somewhere in between. Nonetheless, if the juvenile's growth is inhibited, they will be more prone to predation, and fewer will survive. This highlights not only the importance of seasonal timing but also that the conditions for benthic productivity and recovery must be considered.

From the perspective of a fish, nourishments should ideally take place between October and December, to avoid the season that the population of their benthic prey grows most. Sand nourishments in this period will have a lower impact on benthic organisms and will allow the benthic community sufficient time to recover before the start of the juvenile flatfish growing season. Nourishments in the spring or summer will damage the benthic population, and juvenile fish that have just entered their nursery grounds could be buried. If the sand nourishment continues until the reproductive season, recovery of fish populations could be postponed for a year. These results provide useful insights on how to design sand nourishment schemes and when to implement them, in order to protect the nursery function of sandy coasts for juvenile flatfish.

The development of the Sand Motor provided us with an opportunity to study how sand nourishments can improve habitat diversity and ecosystem functioning. The Sand Motor has created a more diverse system and also temporarily provided an enhanced nursery area for juvenile plaice in the lagoon (Figure 3), due to its higher water temperatures and the shelter it provides. At the start of the season, we observed substantially higher numbers of juvenile plaice in the lagoon than in the adjacent shallow coastal area. However, growth conditions in the lagoon did not exceed those in outer areas, possibly due to food limitations.

It was originally thought that the lagoon would also benefit other flatfish species such as sole, turbot and dab. However, it was mostly used by juvenile plaice, indicating species-specific habitat preferences. However, changes in the lagoon dynamics and morphology resulted in the loss of this nursery potential in the second year. In particular, the narrowing of the entrance channel (both in depth and width; Figure 3) could have prevented fish larvae entering the lagoon. These results suggest that mega-nourishments can be applied to enhance existing nursery habitats in order to improve growth. However, the current design appears to be inappropriate for long-term nursery creation. For the lagoon to be successful, it needs to increase in size and persist for several years.

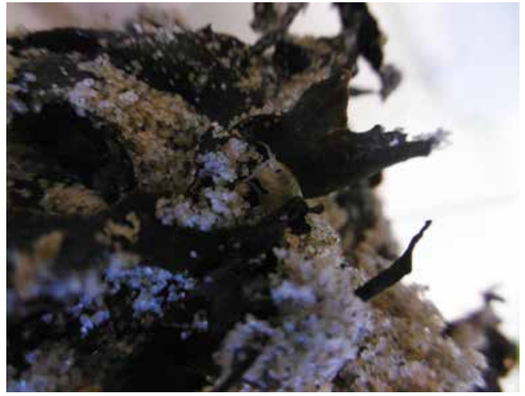
We mostly focused on the effects of the Sand Motor on the suitability and quality of the nursery habitat for juvenile fish, specifically looking at sediment type and the availability of food. Ensuring optimal habitat suitability does not necessarily mean that juvenile fish will magically appear. Nevertheless, it is important to carefully consider the impacts of mega-nourishment to safeguard suitable nursery habitats for juvenile flatfish and also, if possible, to enhance these areas.

Figure 1. (top left) The polychaete worm Scolelepis squamata, which lives in the intertidal zone.

Figure 2. (top right) The amphipod Talitrus saltator in a patch of wrack.

Figure 3. (bottom left) Field work at the beach in autumn.

Figure 4. (bottom right) Mesh bags containing wrack were placed in drift lines on the beach, to perform our "litter bag" experiment.



Emily van Egmond

WASHED ASHORE

Emily van Egmond obtained her PhD at the Systems Ecology section of the Factulty of Science of the Vrije Universiteit Amsterdam in 2018.

Dissertation title:
"Living on the edge: resource availability and macroinvertebrate community dynamics in relation to sand nourishment."

PhD supervisors:
Peter van Bodegom (Leiden University)
Matty Berg (Vrije Universiteit Amsterdam)
Rien Aerts (Vrije Universiteit Amsterdam)

At first sight, few organisms or animals seem to inhabit the wet and dry parts of sandy beaches. The opposite is true, however: they are just difficult to find. Many organisms either live a few centimeters in the sand or in piles of beach-cast sea weed, where they can be found in high densities. These organisms are mainly small invertebrate animals, such as bristle worms, amphipods, isopods and insects (Figures 1 and 2). These invertebrates are important for the sandy beach ecosystem, as they connect the marine and terrestrial food webs. They link marine organic matter that is deposited on the beach (e.g., sea weed) with higher trophic levels (e.g., fish and birds).

When looking at the beach, we can observe a clear separation between the wet beach, or intertidal zone, and the dry beach, or supratidal zone. Twice a day, the intertidal zone alternates between being dry or saturated by sea water. Invertebrates living in the intertidal zone are well adapted to this dynamic environment. During low tide, invertebrates dig themselves into the sand to avoid drying out. As the tide rises, they emerge from their burrows. Most species are filter or deposit feeders and catch organic particles floating in the water column or lying on the bottom. With incoming tide, juvenile flatfish (Page 118), but also shrimp and crabs, can prey on the intertidal invertebrates.

When we move further away from the sea, we are at the supratidal zone, which ranges from the high water mark to the foot of the dune. In contrast to the intertidal zone, this zone is not submerged by the sea during the tidal cycle, and the sand remains dry for most of the time. As food is scarce on sandy beaches, beach-cast sea weed, also called "wrack", is an important food source for supratidal invertebrates. In addition, it protects them against drying out and predation by birds, and it provides space for them to reproduce. The invertebrate community contributes to a unique biodiversity exclusively associated with sandy beaches, but also supports nutrient cycling and provides food for predators. It is therefore crucial to understand the impact of the Sand Motor on the composition and assembly of the macroinvertebrate community. In other words, does the Sand Motor have an effect on what macroinvertebrate species are found where, and if so, why?

We evaluated the development of the intertidal macroinvertebrate community at the Sand Motor for four years after its completion. We also compared the macroinvertebrates living in wave-exposed locations at the Sand Motor with communities found on sandy beaches subject to regular beach nourishment or without nourishment. To do this, we analyzed field data from three different data sets (see Figures 3 and 4 for an impression of the field work). For the Sand Motor, we had data for several years (before and after completion) at four locations. From the other two data sets, we obtained data for eight nourished and six unnourished beaches to compare with the Sand Motor.

Within a year of the Sand Motor's completion, we already found intertidal macroinvertebrate species that are common for wave-exposed sandy beaches. These common species included the polychaete worm *Scolelepis squamata*, the amphipods *Haustorius arenarius* and *Bathyporeia pilosa*, and the isopod *Eurydice pulchra*. This rapid colonization was especially noticeable for *Scolelepis squamata*, the most abundant

Figure 5. Collecting animals after sieving sand in summer.

of all species encountered at the Sand Motor. When comparing different years after completion of the Sand Motor, macroinvertebrate abundance was lower in 2014 than in other post-nourishment years, while the number of species was lower in both 2010 and 2014. The macroinvertebrate community had the least variety in 2010, and it became more varied after completion of the Sand Motor.

It is common to find large differences in the community composition between individual years at the beach. This variation may be due to the changing environmental factors on a sandy beach (e.g., average temperature, grain size distribution, food availability) or between-year differences in macroinvertebrate reproduction and survival. When comparing locations within the Sand Motor, the beach south of the sand hook had both the highest macroinvertebrate abundance and highest number of species. This may be due to the sea currents that move from south to north along this part of the Dutch coast and, hence, influence migration of intertidal species. Many intertidal macroinvertebrate species depend on currents and other hydrodynamic forces for their dispersal. As a result, the southern beach might act as a sink for migrating intertidal species, which could lead to an accumulation of macroinvertebrates. Moreover, environmental conditions may differ from other Sand Motor locations, with different sediment characteristics and more variation in dry and wet beach.

Our most striking finding on the macroinvertebrate community composition was that a distinct intertidal community was present in the lagoon. This community included the amphipod *Corophium volutator* and the polychaete worms *Heteromastus filiformis*, *Capitella capitata* and *Pygospio elegans*, which are species commonly encountered on intertidal mudflats. In contrast to the other wave-exposed locations, the lagoon is a sheltered beach where organic matter has accumulated over the years. This kind of intertidal macroinvertebrate community is uncommon along the coast in the Netherlands. However, these conditions are present in the upper north of the Netherlands (the Wadden Sea) and the lower south (the Zeeland Delta). Thus, the Sand Motor has locally given rise to a habitat that attracts a different intertidal macroinvertebrate community.

We compared the Sand Motor beach (excluding the lagoon) with beaches subject to regular beach nourishment, to evaluate how wave-exposed intertidal macroinvertebrate communities differed across nourishment types. The number of species was higher at both the Sand Motor and regular beach nourishment than at unnourished beaches. However, abundance was lower at the Sand Motor compared to other nourishment types. This suggests that intertidal species can establish at the Sand Motor, but only in limited numbers. This could be due to non-optimal habitat characteristics or competition for food. Furthermore, the Sand Motor produced a slightly different intertidal macroinvertebrate community than beaches subject to regular beach nourishment or unnourished beaches. The Sand Motor differs from regular beach nourishments in shape, size and frequency of application. This may result in a range of environmental changes (i.e., different hydrodynamic forces, beach slope, grain size), which influence the presence of certain intertidal species and result in an altered composition of the macroinvertebrate community.

Supratidal macroinvertebrates can be found in freshly deposited wrack close to the high water line and also in older, partly decayed wrack in drift lines closer to the dunes. It is not known whether these macroinvertebrate communities differ in structure, and seasonal variation of the supratidal macroinvertebrate community has rarely been studied. To explore whether young or old wrack and season affect the supratidal macroinvertebrate community composition differently, we performed a "litter bag" experiment at the Sand Motor (Figure 5). We placed mesh bags containing wrack on the beach in young and old drift lines in the spring, summer and autumn. We collected the bags after two weeks, and determined both the number of individuals and species of macroinvertebrates present. We found large differences in the supratidal macroinvertebrate community between seasons.

Macroinvertebrates were more abundant in autumn than in spring and summer, mainly due to large numbers of fly larvae. The number of species, however, was higher in summer than in spring and autumn. Macroinvertebrate diversity varied during the seasons, with the highest diversity in summer and the lowest in autumn. The most distinct supratidal macroinvertebrate community was found in summer, while communities in spring and autumn were more similar. Young and old drift lines showed the greatest differences in diversity in spring, with more diversity in young drift lines than in old ones. Young wrack is normally swiftly colonized and consumed by the amphipod *Talitrus saltator* and other species, whereas old wrack may be less palatable or of lower nutritional quality, and the species may leave in search of other food sources. We conclude that there is both seasonal and spatial variation in the supratidal macroinvertebrate community at the Sand Motor. In particular, this field experiment stresses the importance of leaving wrack undisturbed on nourished beaches and elsewhere to support a diverse supratidal macroinvertebrate community, especially in summer.

Compared to other forms of sand nourishment, local disturbance to the macroinvertebrate community was lower at the Sand Motor, and it also provided a new, temporary habitat for other macroinvertebrates. In conclusion, the Sand Motor created a new habitat for intertidal species by increasing the spatial heterogeneity of the sandy beach. While coastal protection is the primary goal of most Dutch sandy shores, well-designed mega-nourishments also seem promising ways to support the macroinvertebrate community of the sandy beach.

Peter Herman

THE BALANCE SHEET OF NATURE UNDER WATER

REFLECTION

Peter Herman is a professor of Ecological Hydraulic Engineering at Delft University of Technology, and senior researcher at Deltares. Within the NatureCoast program he was the principal investigator for scientific research project S3, which focused on the marine ecology of the Sand Motor.

The Sand Motor is a miracle of governance flexibility. Despite the strict, legal constraints for coastal defence in the Netherlands, a group of visionary people succeeded in convincing all stakeholders that this pilot was worth pursuing (Chapter 2). Value for nature was a prominent argument. It was even stated that the Sand Motor would "create nature" over vast areas, which makes one wonder what was there before.

In reality, the Sand Motor was constructed in an area that was already full of life, as one could read in the sections on benthos (Page 114) and flatfish (Page 118). Although the area had already been regularly disturbed by sand nourishments, these did not have the same impact, as they were not nearly as large-scale and artificial as the Sand Motor. One could say that the Sand Motor was designed to be in disequilibrium with the prevailing natural forces, and to be large enough to resist nature's efforts to clean it away for decades. The largest part of its surface was constructed as a very dry beach that has remained almost devoid of life for the entire period. Hence, the Sand Motor started its natural balance sheet very much in the red.

But what if we focus on underwater life? Does this help to balance the record? First of all, as described in Simeon Moons' contribution (Page 114), the Sand Motor has diversified habitats. A temporary increase in species numbers shortly after construction could have been due to colonization, but even after this phase we observed a sustained increase in diversity. The Sand Motor has created habitats that normally do not occur along sandy beaches, such as the deep waters dominated by tidal currents at the tip of the Sand Motor, or coarse sands kilometers away from the tip. These zones are now occupied by species that are not normally found along the sandy beach coasts of Holland, although they are not uncommon further north and south.

At first, the lagoon promised to be a biodiversity hotspot, as it accumulated mud and organic material and became productive for benthos and young fish. However, high oxygen loss and low water exchange soon resulted in anoxia and loss of life in parts of the lagoon deeper than two meters. Lack of water renewal in a deep lagoon was an unavoidable consequence of the large sand movement along the sides of the Sand Motor. It is an interesting design question whether a much shallower lagoon could have evolved faster into a green beach. This would have avoided water quality problems, but would also have created a much rarer habitat type than the one that has now developed.

The existing practice of foreshore nourishment regularly disturbs the fauna in the dumping areas. Simeon Moons observed that rapid recovery from this disturbance is possible (within a few years), on locations where the grainsize composition of the sediment has not changed. However, since the nourishment sand tends to be coarser, long-lasting changes occur if the coarse fraction remains in place. The elegant carousel experiment conducted by Marjolein Post illustrates how juvenile flatfish dislike this coarse sand, if given the choice (Page 118). It is not expected that the Sand Motor will have less effect on sediment sorting and coarsening, as it used river sand with a considerable coarse fraction (Page 66). Thus, the Sand Motor avoids disturbances but has similar or larger long-lasting effects on the composition of foreshore fauna.

So, what will the natural balance sheet be in 20 years? After a negative start, the increase in biodiversity gave a positive element. Compared with regular nourishments, the Sand Motor decreased the short-term disturbance to the ecology. However, assuming that sediment sorting remains the same, the long-lasting effects through change of sediment may be similar or larger. In the end, the best result we can hope for is a more or less neutral balance. Design options to improve the natural balance are limited. The lagoon could have been designed to become a green beach in a shorter time span, but reducing changes in sediment grain composition is difficult. All in all, from the point of view of a worm, a Sand Motor is something one has to endure. In the end it will disappear anyway.

Rien Aerts

SIZE MATTERS

REFLECTION

Rien Aerts is a professor of Systems Ecology and head of the Section Systems Ecology at the Vrije Universiteit Amsterdam,. Within the NatureCoast program he was the principal investigator for scientific research project S4, which focused on the terrestrial ecology of the Sand Motor.

The Sand Motor is unique, not only because of its size but also because of the time span during which the project should be functional. The rationale behind this approach is that applying an enormous volume of sand and using natural forces ("Building with Nature") would reduce the disturbance to the subtidal and intertidal zones, compared to the usual nourishment strategies, resulting in more natural succession and biogeomorphological processes. How does this work out for the macro-invertebrate community of the intertidal zone?

The intertidal zone, with its highly variable and often very harsh conditions for natural organisms, is at first sight almost devoid of life, but a closer inspection shows that there can be abundant invertebrate life just a few centimeters in the sand or in piles of sea weed that is cast ashore (Page 122). These organisms are very important for the ecological functioning of sandy beaches. Study of the intertidal zone after the creation of the Sand Motor indicated that, despite the initial major disturbance, colonization of the new beach by macro-invertebrates started within a year and continued during the rest of the study period. This shows that colonization is an ongoing process, which is good news!

Another striking discovery was that different invertebrate communities occur at different locations within the Sand Motor. This is due to the sea currents that move from north to south along the coast of Holland, but also to the design of the Sand Motor, where the lagoon plays a very important role. This strongly suggests that future designs of the Sand Motor should try to create more diverse "beachscapes," as this would increase the diversity of the beach communities.

Comparing the effects of different sand nourishment strategies on the intertidal beach community showed that the Sand Motor had higher species diversity but lower numbers of individuals than beaches subject to regular nourishments or unnourished beaches. At this moment, it is not clear if this is due to specific characteristics of the Sand Motor or if not enough time has elapsed to reach a fully developed community. Longer term monitoring is clearly needed here.

Also interesting was that macro-invertebrate communities were found higher up on the beach, living in freshly deposited wrack close to the high water line and also in older drift lines close to the dunes. These supratidal communities contribute strongly to biodiversity at the higher parts of the beach, but may also help to initiate dune formation due to the release of nutrients from the wrack (Chapter 4). Therefore, beach management in general (and not only at the Sand Motor) should be directed towards preserving these drift lines.

NatureCoast was unable to consider the effect of climate change on the ecological communities of the intertidal zone (and other zones). Storm frequencies and water temperatures are expected to increase during the coming decades. Both factors will undoubtedly affect the composition and functioning of the beach communities. Clearly, further studies are needed here.

Based on the study of macro-invertebrates in the Sand Motor, we can conclude several things: First, a large-scale sand nourishment such as the Sand Motor is an ecologically friendly nourishment strategy. Second, future designs of the Sand Motor should emphasize diverse "beachscapes," such as the lagoon. This will increase ecological diversity and make the nourishment function more robustly. Third, given the highly dynamic nature of the Sand Motor and the climate, long-term monitoring is needed to see whether the relatively short-term observations obtained so far are maintained in the future. Finally, the effects of climate change (more storms, higher sea water temperatures) on the intertidal communities should be included in future studies.

Senior scientist Marine Ecology

MARTIN BAPTIST – WAGENINGEN MARINE RESEARCH

INTERVIEW

What makes the Sand Motor unique for you as an end-user?
"For me the location is unique: a wide beach with lagoons and mudflats is a unique environment for the otherwise closed Dutch coastline. I emphasize the environment because we see similar ecological phenomena along all the Wadden islands, the barrier islands in the north of the Netherlands! All the outer deltas of the Netherlands are dynamic, where especially the islands form a kind of Sand Motor. This applies to the Wadden islands, and also to the delta in the southwest of the Netherlands. The design of the artificial Sand Motor at Delfland is therefore based on the natural Sand Motor of the *Bornrif* near the island of Ameland. But also in the southwestern delta, for example in an area like *Kwade Hoek*, we have sand banks that behave similarly."

How do you see the role of scientific research at the Sand Motor, as end-user?
"A great added value is that the NatureCoast researchers have used the systems of the Wadden islands and the southwestern delta as reference sites. They have also conducted research there, which has enabled us to make comparisons. For example, research on the aeolian process along the coast, dune formation, and sediment displacement. In terms of ecological research, NatureCoast researchers have investigated the benthic animals and fish in this environment. The unique experiment that is the Sand Motor has had great added value also because it has generated enormous attention for scientific research into these phenomena. This is certainly due to the location of the Sand Motor: close to densely inhabited and urbanized areas, easily accessible, and with Delft University of Technology close by."

How relevant is multidisciplinary research on the Sand Motor for you as an end-user?
"Extremely relevant, beyond any doubt! However, we have to remain cautious on what we call "multidisciplinary." The average Dutch citizen will often associate our ecological research with "research on nature." Us scientists already consider multidisciplinary to be, for example, one morphologist and one ecologist that together look at how dunes develop; the influence of vegetation, sand transport, waves and so on. The NatureCoast program considers many more disciplines such as hydrology, hydraulics, ecology and swimming safety: these different perspectives not only increase knowledge, but also help to look beyond conventional boundaries, and thus help to understand systems as a whole."

"Translating multidisciplinary findings into scientific outcomes remains extremely difficult. As is evident in NatureCoast, a research program with a collection of PhD students who have a very independent assignment: to write a dissertation. For such a researcher it is complicated enough to really make one subject your own, let alone some other ones as well. I don't quite know a solution for this, it remains a huge challenge."

What are the main findings of the NatureCoast program for you?
"The Sand Motor has created several new environments at the coastline. The lagoon is an example. It has worked very well for a short time as a nursery habitat for young fish. You normally do not have such a nursery area along the Dutch coastline, which is significant because it increases the biodiversity of the coast. In the meantime you have to realize that it is temporary. For example, the lagoon is currently already too shallow so that it no longer functions as a nursery."

"New environments have also been created on the exterior of the Sand Motor: with coarser sand, steeper gradients, higher flow rates and erosive conditions. That results in a different species community than was there before. I am not immediately saying that it is better or worse, because that is a value judgment, but it is certainly different than it was. It is still difficult for us to estimate whether this is richer and more diverse or not."

"Dune growth went more slowly than anticipated, and we had also thought that seals would rest on the Sand Motor. I have looked at 50,000 photos and I have only seen one seal on the Sand Motor. I am not a pessimist, but on the topic of "ecology and nature-friendly" a lot of things spring to mind that start with "we had hoped that," which ended up not coming true. But there are always two sides to the story. Maybe we would have liked to keep the lagoon open for longer, for instance. But on the other hand it is also interesting to see what is going to happen now. If the lagoon starts to fill up, I expect a green beach to arise there, because it is already a muddy environment. Then, for example, many salt-loving plants will grow, very fascinating and instructive."

How do you see the role of ecological research in iplinary research projects?
"Ecology is important in many ways in multidisciplinary research projects, because it by definition already looks at other disciplines such as geology, physical geography and morphology. Ecology is also important for the public opinion, because many people are concerned with nature, biodiversity and which plants, animals, birds and fish develop. You should therefore at least study these phenomena to meet demands from society."

Senior Ecologist and Advisor

LEO LINNARTZ – ARK NATURE DEVELOPMENT FOUNDATION

INTERVIEW

In what respect is the Sand Motor unique for you as end-user?
"Very unique. For a very long time, we have maintained a fully straightened, artificial coast in the Netherlands, while that coast would naturally have had a less uniform shape. The Sand Motor is effectively a bulge, an irregularity, and thus we see processes reappearing that are associated with such natural coasts. So the Sand Motor is enjoyed very much by anyone who loves geology and natural processes."

How do you see the role of scientific research at the Sand Motor, as end-user?
"For nature conservation organizations the key question is: Is the Sand Motor more environmentally friendly than other coastal reinforcement alternatives? Scientific research is essential in gaining better understanding of processes that take place and the time frame in which they take place. The research also helps us to look at the overall effects on nature. One can imagine that if the Sand Motor washed away in a few years, the gains for nature would be questionable and other alternatives would have been better. But if it does its job for twenty or thirty years, the scale will soon tip in the direction of those gains, when compared to other coastal reinforcements. This knowledge is essential and can be derived in part from scientific research."

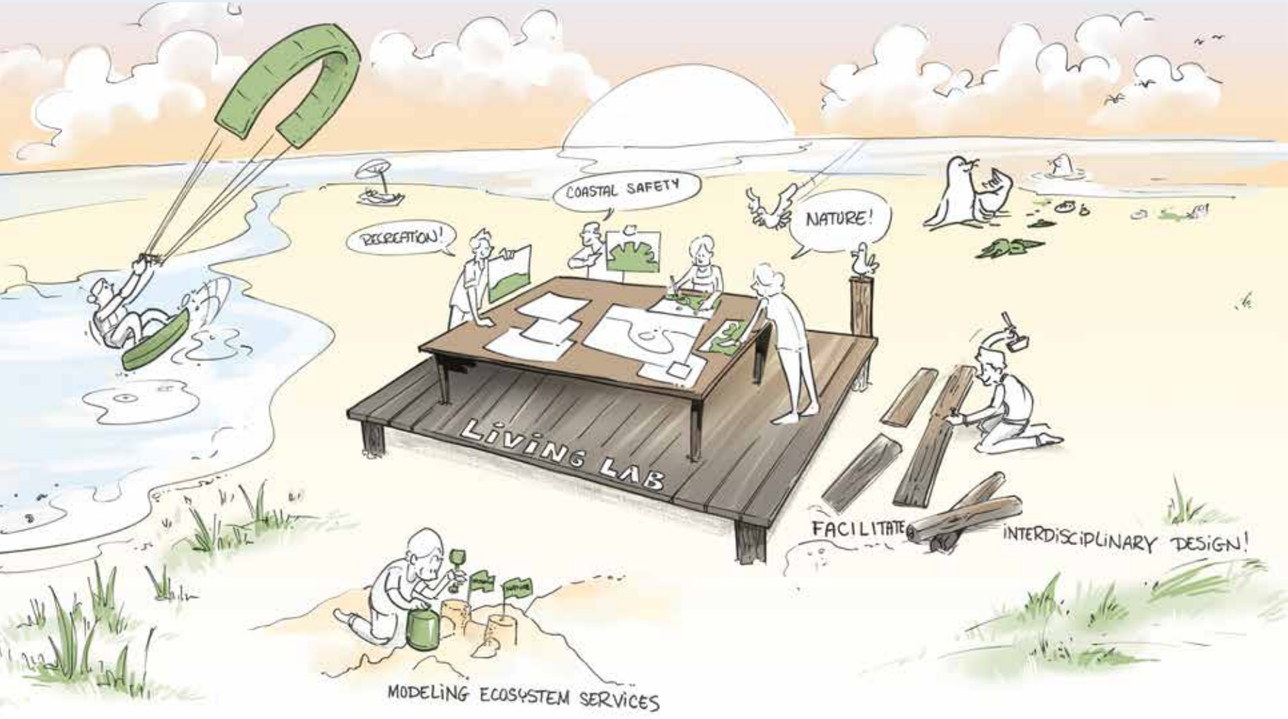
How relevant is iplinary research on the Sand Motor for you as end-user?
"This is also very important, because if we only looked at plants, or birds, or fish, we would only see part of the picture. There are many examples, but let me highlight the inclusion of the hydrodynamic and biophysical processes driving the ecology. The changes in salt content in the dune lake, for instance, enable us to understand more about the changes in flora and fauna."

What are the main findings of the NatureCoast program for you as end-user?
"An important result for me is that having vegetation, seaweed and driftwood washed ashore and buried is an essential catalyst for biodiversity on the beach. A large part of the beach on the Sand Motor is not cleaned mechanically, which creates a much better starting point for nature development than on all the other neatly cleaned beaches in the Netherlands. In order to please beach users, we often compromise and throw away some of the natural quality, usually without being aware of it. Many people think that that there are fewer birds on the beach because the mechanical cleaning disturbs them, but it might actually be because the cleaning removes the very elements that form the base of the food chain. The NatureCoast type of research makes those processes more visible."

Which ecological zone of the Sand Motor is the most interesting for you to communicate with "laymen"?
"The most interesting and relevant aspects of the Sand Motor, both to observe and to explain to visitors, were the constant and often spectacular changes happening to the system. The Sand Motor was built against the Delfland coast reinforcement, which had a horrendous sand dike with marram grass planted in neat rows, which was slowly fading away. After the Sand Motor was put in place, considerable amounts of sand accumulated against the foot of the dike, and a more or less natural dune started to develop. And then the marram grass suddenly started to flourish in those lower parts. It was almost like it said: "Hey, this is what I know, I belong here." For a long time this showed a nice contrast between the artificial plantings at the top and the natural growth at the dike toe. The spontaneously grown dune area caused the marram grass to thrive, and soon this grass at the toe was supplemented with numerous other plants that naturally belong in a young dynamic dune. It was incredibly interesting to experience this happening and to tell visitors about it, to inform them about this process of young dune formation and embryonic dunes, why it works in some places and not in others."

SIX | INTEGRATION OF RESEARCH

Figure 1.
When designing sandy solutions, ecosystem services offer a useful framework to integrate the different interests of stakeholders. (Image by JAM Visual Thinking)



Alexander van Oudenhoven

INTEGRATING RESEARCH THROUGH THE ECOSYSTEM SERVICES LENS

INTRODUCTION

The versatility of the Sand Motor has been repeatedly mentioned in this book. Most stakeholders actually went on board with the project because of the multiple benefits that the Sand Motor offered (Chapter 2). As a result, in addition to "just" strengthening the dunes for coastal safety, supplying the adjacent coastline with sand addressed different aims and created different expectations. These included an attractive area for nature and leisure, as well as the creation of knowledge and innovation. In other words, the Sand Motor was developed as an innovative, nature-inclusive approach to coastal protection that could also promote both recreation and biodiversity.

Now, almost six years down the line, these expectations are being appraised by integrating the multidisciplinary research that has been done by NatureCoast researchers and others. The previous chapters highlighted important advances in different scientific disciplines. But it is only by combining and integrating these findings, by looking for themes that cut across disciplines and considering the societal implications of the research, that we can make the NatureCoast program truly interdisciplinary and meaningful. Therefore, we bring together findings from NatureCoast research here, some of which were highlighted in the previous chapters, some of them new. We evaluate the ecosystem services of the Sand Motor from a wider societal perspective, relate the findings to the original expectations of the Sand Motor, and consider implications for the design of future sandy solutions.

The framework or "lens" we take for this integration is that of "ecosystem services". The ecosystem services framework will be further explained in the next section.

Ecosystem services are the contributions that ecosystems provide to human wellbeing, such as food, recreation, climate regulation and coastal protection. Thinking in terms of ecosystem services leads to the notion that changes in an ecosystem lead to changes in the benefits that people obtain from nature, be they positive or negative. For instance, reduced beach width can increase the risk of coastal flooding and decrease recreational opportunities. Also, in the next section, we will summarize what the first six years of Building with Nature have brought for each ecosystem service of the Sand Motor.

Next, we will take an in-depth look at how to design and engineer ecosystem services for sandy solutions like the Sand Motor (Page 142). We will identify the key factors that drive ecosystem services that need to be considered when designing solutions such as this. These could be likened to the "buttons and switches" on a dashboard; when creating a sandy solution, the designers and engineers need to know which to push when. Think of the shape and elevation of the nourishment, or the grain size and chemical properties of the sand.

With this understanding of the factors that drive ecosystem services, the next section explores how these can be used to shape the sandy solutions of the future. Will more Sand Motors be useful, or do we need to rethink their shape, size and frequency? The behavior of the Sand Motor has been monitored extensively in an interdisciplinary way, feeding into NatureCoast's integrated models. These forecasts can teach us how the Sand Motor and other sandy solutions will develop over time. In this section (Page 146), we have applied the model for three alternative designs with similar sand volumes at the location of the Sand Motor.

Finally, we will reflect on the usefulness of the ecosystem services framework, integrated and interdisciplinary research, and the consequences of our findings for future designs and policies dealing with sandy solutions like the Sand Motor. This fits directly with the final section, where we will describe the data management system used to compile all the research data gathered by the NatureCoast team and more.

Figure 1.
The Sand Motor provides many ecosystem services, such as recreation opportunities, coastal defense and new habitats for species of conservation interest.

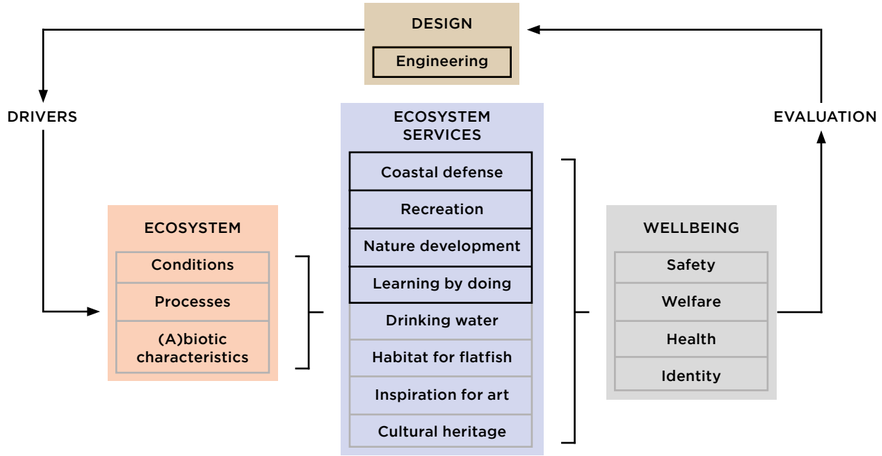


Figure 2.
The ecosystem services framework of NatureCoast. The framework connects what happens in the ecosystem to consequences for human wellbeing and how this can be incorporated into future designs of sandy solutions. Note that the first four ecosystem services, in thicker boxes, correspond to the original aims of the pilot Sand Motor.

Alexander van Oudenhoven and Arjen Luijendijk

THE ECOSYSTEM SERVICES OF THE SAND MOTOR

A unique natural landscape. A beach to strengthen the dunes. A great place to walk the dog. The Sand Motor is all of those and more (Figure 1). It provides different benefits to people, and people perceive those benefits differently as well. Collectively, we refer to the contributions that the environment provides to people as "ecosystem services". Ecosystem services are the link between nature and society, between ecosystems and our wellbeing. For instance, dune ecosystems are beautiful to hike in, but also protect millions of people against rising sea levels, while at the same time filtering and storing large amounts of drinking water. A change in the condition of dunes would therefore result in considerable changes to human wellbeing.

If we look at the Sand Motor from the point of view of ecosystem services, we can assess the "success" of the Sand Motor in terms relevant to society. It also allows us to identify which ecosystem services would change, if certain features of the Sand Motor were to change. In this chapter, we integrate the research findings of NatureCoast under the "umbrella" of ecosystem services. To measure the success of the Sand Motor, we will look at the ecosystem services it offers and will put them in context by relating them to the original aims of the pilot Sand Motor.

The ecosystem services framework
Figure 2 gives a schematic overview of the interdisciplinary ecosystem services framework, which can be applied to designing and engineering sandy solutions. We will go through it step by step, starting with the ecosystem. In the previous chapters, we explained that the Sand Motor can be seen as an ecosystem, albeit manmade and managed. Most of the NatureCoast research focused on what has happened in and around the Sand Motor ecosystem and what has driven these changes. On a larger scale, conditions and processes, such as soil and water quality, sediment transport and dune formation were studied. On a smaller scale, specific biotic and abiotic characteristics of the Sand Motor were studied, such as sediment size and chemistry, and specific plant and animal species.

The Sand Motor is highly dynamic, so the previously-mentioned conditions, processes and characteristics are constantly changing. This is a result of drivers, such as the tide, waves, wind and current, the natural forces that shape the Sand Motor, and which are central to Building with Nature.

The ecosystem services are central to the framework, as they link the ecosystem to society and its wellbeing. The latter can be expressed and measured in terms of safety, health, employment, welfare and sense of place. While these might appear vague and imprecise to the natural scientist, we must not forget that many political and personal decisions are based on such measures. This evaluation step is of course a lot more complex than illustrated in the figure, as was clearly shown in Chapter 2. Moreover, it can involve many different stakeholders and can thus go beyond political decision making.

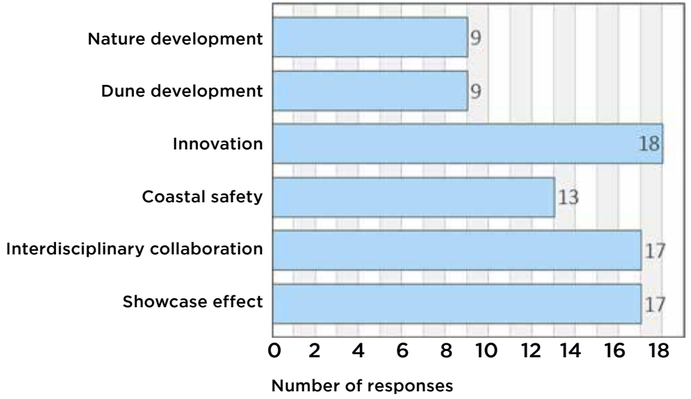
The strengths and weaknesses of the solution or system at hand, be they economic, societal, physical or cultural, usually have consequences that can be considered for future designs and engineering solutions. The design can be altered, for instance, if more recreation potential is desired, or if there are safety concerns. Note that most hard engineering solutions tend to be monofunctional, mostly focusing on coastal protection. However, as we have seen throughout the book, Building with Nature as a design philosophy considers multiple functions and ecosystem services. It considers, just like in our framework, the drivers of ecosystems, as thus closes the circle, as we see in Figure 2.

We have adopted this framework because ecosystem services are widely discussed in relation to Building with Nature or nature-based solutions in general. However, few studies and projects truly evaluate the designs of sandy solutions in terms of ecosystem services. In the remainder of this chapter, we will look in detail at the ecosystem services that the Sand Motor provides.

Key ecosystem services for policy actors
It is important to remember that ecosystem services go beyond scientific assessment. Scientists should not decide which ecosystem services are important, but they can help to understand how society ultimately views these services, which it considers important, and why. This inspired us to go back to the interviews that Ewert Aukes and Lotte Bontje (Chapter 2) conducted with key policy actors who were involved in the startup of the pilot Sand Motor. In these interviews, the actors shared how they experienced the governance process but also expressed what motivated them to go on board with the pilot project. These motivations were mostly in line with the original aims of the Sand Motor, but we also discovered important additional motivations. All of them could, however, be expressed in terms of ecosystem services. We also found that policy actors used broad and ambiguous terms, which have to be clarified and defined if we are to assess them scientifically.

Figure 3. (below)
Opportunities for recreation constitute one of the main success factors of the Sand Motor, with up to 5,000 people visiting on a busy summer day.

Figure 4. (far below)
The main success points of the Sand Motor: responses from people attending the final NatureCoast symposium. Note that the highest scores go beyond physical aspects.



Of the twenty categories of ecosystem services that are commonly used, only four were regularly referred to by the policy actors: coastal defense, recreation, nature development and "learning by doing", or knowledge development. Let us first summarize how these four have fared over the last years.

Policy actors referred to coastal defense in quite general terms, but note that the Sand Motor has contributed on two different, albeit interrelated fronts. First, it was designed to spread sand in both northern and southern directions, and thereby widen the beaches and prevent erosion. Wider beaches absorb the energy of incoming waves, especially during storms, which makes sandy beaches the first line of defense against coastal flooding. Sand transport by the Sand Motor has been close to optimal, with around 4 million m^3 of sand having been transported in the first five years. Second, the Sand Motor contributed to coastal defense by strengthening the dunes. Both the height and volume of the dunes have gradually increased, after a delay of several years. In addition, the formation and dynamics of embryo dunes across the Sand Motor are a clear indication that natural dune formation has been possible, though not without challenges.

The Sand Motor offers a unique variety of opportunities for recreation. However, just as with coastal safety, we need to distinguish specific categories in order to truly understand the Sand Motor's contribution. Research conducted for the province of South Holland found that a third of the people who visit the Sand Motor come to walk, whereas a fourth come to swim, and most of the others come to visit one of the beach restaurants and cafes. Other activities include, in decreasing levels of popularity, kite surfing, jogging, flying kites, biking and sailing. On a busy summer day, up to 5,000 people visit the Sand Motor. According to interviews, visitors especially enjoy the quietness and the vast space, as well as the opportunity to unwind. Interestingly, many people also visit the Sand Motor out of curiosity; they want to see it for themselves and often travel quite far to see it, with up to 40% of the visitors coming from outside the province of South Holland. All in all, it is fair to say that recreation is definitely one of the main success factors of the Sand Motor, although the diversity of recreation opportunities is challenging to manage, and the kite surfing opportunities are dwindling as the lagoon shrinks.

Nature development was often referred to in combination with recreation. The two were even combined as one of the original aims of the Sand Motor. However, the Sand Motor shows that nature and recreation only go together in moderation. Dune vegetation has suffered from recreation pressure and, conversely beachgoers do not appreciate the muddy lagoon and its smell. If we were only to evaluate the Sand Motor based on nature development, it is clear that the project could have done better, although it is still a young project from an ecological point of view. There is no doubt that a large area of new nature has indeed been developed, and with it a great diversity of habitats and species, including many with conservation value. The fact that the lagoon currently still harbors a higher variety of benthic species than the Wadden Islands has gone practically unnoticed. Put together, this should make it a considerable success from the point of view of policy actors. However, Chapter 5 showed that ecologists have divided opinions, depending on which aspect and sub-system they are evaluating. Clearly, "nature" encompasses many different aspects, ranging from a nice landscape to the diversity of benthic species to the one seal, photographed once, that continues to appear on official communication channels. From an ecological point of view, the Sand Motor could have clearly done better.

One of the unique features of the Sand Motor has always been the learning by doing aspect, which is something that was embraced by all who were involved. The consortium behind the project has always had the explicit aim of innovating and learning from the unknown. This might not sound like an ecosystem service, but if you think about it, we are learning a lot from the Sand Motor, its behavior regarding morphology, ecology and other aspects. NatureCoast itself is a prime example of how the project has contributed, as we have shared knowledge at over 30 different scientific events, by engaging with the general public, and through around 40 scientific publications (Page 200). Due to its shape, size, multifunctionality and its aim to contribute to knowledge, the Sand Motor has become an icon of coastal management. This is perhaps best exemplified by the sheer number of excursions that were hosted by NatureCoast, *Rijkswaterstaat*, the province of South Holland and many other involved partners - between 50 and 100 excursions per year. These were requested and attended by delegations from all over the world, which means that the knowledge gained here has been shared all over the world too. Taken together, the showcase effect of the Sand Motor, the fact that it had never been done before and that we can learn from it account for a major part of its success (Figure 4). This cannot always be replicated in the future; five more Sand Motors would not be especially innovative. However, explicitly combining innovation and developing knowledge seems a feasible and worthwhile approach, both from the point of view of scientists, practitioners and policy makers.

Surprise! Unexpected ecosystem services
Based on NatureCoast research and our overall experience, we can identify at least four other ecosystem services that were not explicitly targeted or mentioned during the design or initial phase of the Sand Motor. Applying the ecosystem services framework can help to identify aims that could be included in future sandy solutions. A great example is kite surfing, which is currently hailed as one of the greatest success of the Sand Motor, even though it was not referred to by a single policy actor at the start of the project.

The freshwater lens under the Sand Motor has continued to increase, potentially providing drinking water for over 8,000 households per year. Research by Sebastian Huizer (Page 66) clearly indicates that providing freshwater can be considered an added benefit of mega nourishments like the Sand Motor. The same could be said about habitat provision for flatfish and other species, even though this was not a prime consideration in the design of the Sand Motor. Sandy solutions could play a significant role in providing a nursery habitat for juvenile fish, with many species having high commercial and conservation value.

Perhaps surprisingly, we end with two cultural ecosystem services that have been experienced but were not actually studied by NatureCoast. The Sand Motor is a cultural phenomenon as well as a physical and natural one. It has served as an inspiration for art and design, as well as contributing to cultural heritage. First, as the Satellietgroep showed (Page 156), the Sand Motor has sparked an ongoing dialogue between art, science and the general public. On top of that, the Sand Motor has been hailed as quintessentially Dutch, a leading example of innovative coastal management, as well as just a beautiful place to be. Policy makers, scientists and beachgoers seem to share a strong sense of pride about both the Sand Motor itself and the process that led to it. A few quotes from the final NatureCoast symposium illustrate this: "It can be seen from space!" "We should be proud of what we have achieved." "This could only work in the Netherlands." "It has put us back on the world map of coastal management."

Pride, innovation, knowledge development and cultural heritage (Figure 4). These are not the usual terms that end up in a cost-benefit analysis evaluating coastal infrastructure. However, it would be foolish to discount these non-tangible outcomes, and without them the Sand Motor might not even have been built. Even so, the next Sand Motor or sandy solution will not be a pilot anymore; it will have to be designed based on solid insights on what will happen, and which ecosystem services will be promoted or affected by the design. Therefore, the next chapter will focus on the characteristics on which the ecosystem services of the Sand Motor depend.

Arjen Luijendijk and Alexander van Oudenhoven

ENGINEERING THE ECOSYSTEM SERVICES OF THE SAND MOTOR

To actually design for sandy solutions, designers need to know the key factors that drive ecosystem services. This section will look at the key factors that drive the three main ecosystem services of coastal defense, recreation and nature development, followed by a description of how to evaluate these. Finally, an example of arguable the most important design factor is discussed.

Drivers of the main ecosystem services

Coastal defense

The dunes landward of the Sand Motor need to grow to increase coastal safety from flooding. Sediment composition will determine how effective this process is; this involves the mean sediment diameter, the sediment grading, and the presence of shells (Figure 1). Simulations suggest that if shells had not been present in the nourished sand, much more sand would have been transported from the crest of the Sand Motor. In addition, the Sand Motor developed an armor layer which resulted in relatively limited wind-blown transport activity. This was largely due to its height. If the Motor had been lower and the dry beach had experienced more frequent flooding, the development of the armor layer might have been limited, thus stimulating aeolian activity. Similarly, the dune lake and lagoon intercepted much of the sand transported from the low-lying beaches, limiting the possibilities for embryonic dunes to form. If these water bodies had been smaller or in different locations, local dune growth might have been stimulated. The long-term effects of the trapping remain to be seen, because at some point these reservoirs of fine, wind-blown sand will become available, as the waves and currents continue to erode the Sand Motor.

Figure 1. (left) Photo of the variation in grain size diameter of the nourished sand taken at the cliff (Photo by Iris Pit)

Recreation

The Sand Motor has become a hot spot for kite surfers, due to relatively flat waters in the lagoon combined with an undisturbed sea wind; in addition, the neighboring open waters provide more challenging conditions. A design without a lagoon would not have attracted kite surfers, although other beachgoers seemed complained about the smells generated by the lagoon.

Swimmer safety can be increased by minimizing tidal eddies and rip-currents. This can typically be achieved by reducing bathymetry gradients as well as preventing alongshore variability in sandbar dynamics. To some extent, this can be engineered by changing the size and shape of the nourishment, the bathymetry and grain diameter of the nourished sand. Of course, catering for such various recreational activities requires many physical and social factors to be considered, and this leads to tradeoffs. The sheer size and uniqueness of the Sand Motor seem to be the main factors driving recreation; however, in future nature development and suitability for recreation need to be explicitly considered when designing sandy solutions.

Nature Development

The Sand Motor has created habitats that do not normally occur along the linear sandy beaches of the Dutch coast. At first, the lagoon promised to be a biodiversity hotspot, as it accumulated mud and organic material and became a productive habitat for benthos and young fish. However, after some years, high oxygen loss and low seawater exchange soon resulted in anoxia and loss of life in parts of the lagoon deeper than two meters. A shallower lagoon could have evolved faster into a green beach, which would have created a much rarer habitat type than the one that has now developed. Furthermore, the lagoon side of the Sand Motor has created a location where fine materials, like clay particles and organic material, can be deposited. This material attracts soil organisms related to a tidal flat, but it can also bring contamination. Even though the contamination is relatively low and harmless to humans, it might hinder soil organisms from creating large populations.

Research into benthic species has shown that they can recover rapidly from such a large disturbance (within a few years) as long as the grain size composition of the sediment has not changed. However, since the nourished sand in the Sand Motor is coarser, long-lasting changes will occur if the coarse fraction remains in place. As the Sand Motor is expected to continue to act as a "sediment sorter", this could have long-lasting effects on the composition of foreshore fauna. Selecting an appropriate sediment size and composition for a beach nourishment are key factors for the development of the marine ecology.

Study of the intertidal zone after the creation of the Sand Motor indicated that macro-invertebrates started to colonize the new beach within a year and continued throughout the study period. Another striking discovery was that different

Figure 2. Predicted bathymetric evolution between 2011 and 2040 of the present Sand Motor.

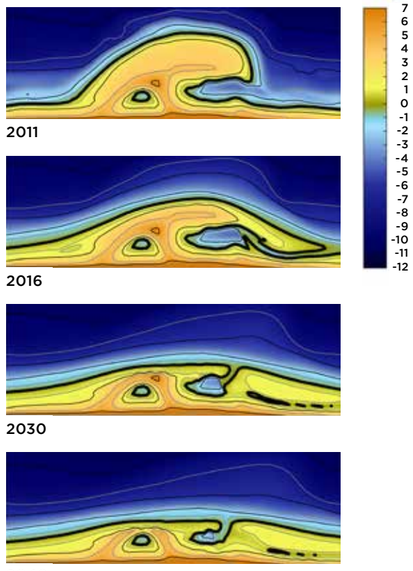


Figure 3. Time series of the predicted development of the surface area of the sheltered subtidal ecotope (lagoon area).

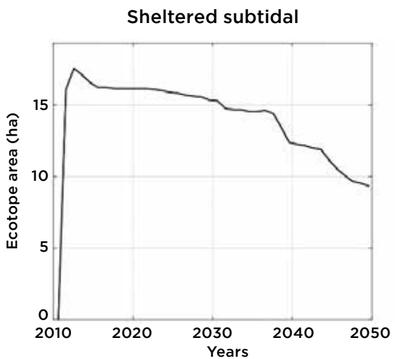
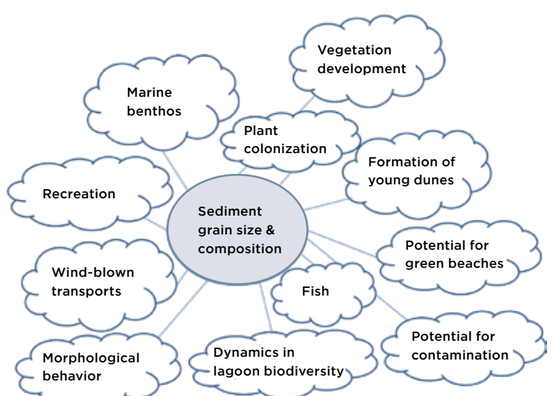


Figure 4. (far below) The many relations of the sediment grain size and composition to other processes and aspects at the Sand Motor.



invertebrate communities occur at different locations within the Sand Motor. This is due to the currents, but also to the design of the Sand Motor, with the lagoon playing a very important role. To increase the diversity of the beach communities, future designs should try to create more diverse "beachscapes".

Research on new dune development away from the existing dunes showed that the high, barren plain of dredged sea bed material hampered perennial plants from colonizing, because root stalks transported by storms could not reach the higher elevations. Wind-blown seeds that could reach these elevations found conditions that were too dry to germinate, and the steadily lowering bed level due to wind erosion did not help either. Without perennial vegetation, it was hard for permanent dunes to form on the dry beach. Thus, the sediment composition and crest height are two important factors that affected the development of vegetation at the Sand Motor. Another surprising factor is the effect of human behavior. The seaward expansion of vegetation was affected by activities such as raking the beaches, driving on them for supervision and research, and construction of beach huts; this slowed the development of vegetation and new dunes.

All in all, "nature development" covers many different facets of the vast and complex Sand Motor ecosystem, and there are many factors behind these developments. Although using a broad term like "nature" will get many stakeholders on board, designs for sandy solutions should have specific ecological aims that can be readily monitored. All these factors need to be incorporated when designing and evaluating Building with Nature solutions with specific emphasis on nature development.

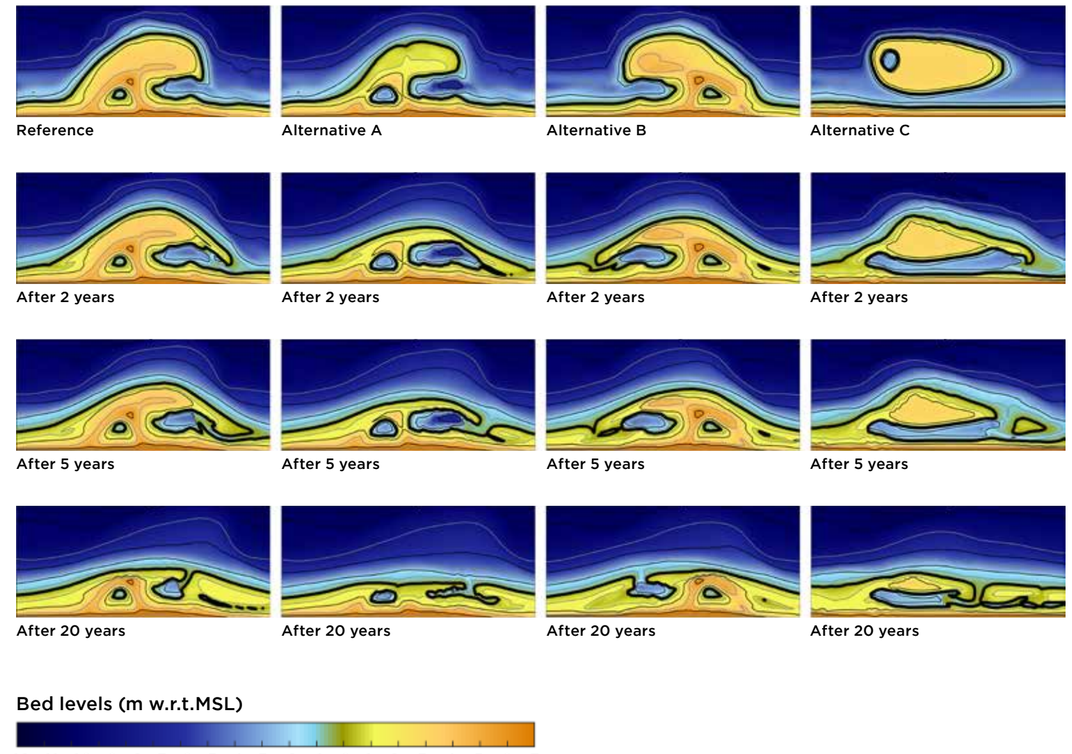
Evaluating ecosystem services over time
To truly achieve solutions that offer ecosystem services along our coasts, we would need to integrate coastal defense, recreation and nature development more comprehensively. Only then can an optimal sandy solution be designed and implemented - the one that provides the best combination of desired ecosystem services.

We found that most ecosystem services are driven by factors that can be captured in hydro- and morphodynamic models. Hence, to quantify and evaluate the ecosystem services we applied numerical models to predict the morphological changes over time. Field-verified predictions still show clear remainders of the Sand Motor along the coast in 2050 (Figure 2). As sandy solutions will change over time, it is important to realize that the different ecosystem services will also change. For example, the predicted ecotope (a landscape feature), representing the sheltered subtidal lagoon area, shows that the surface area of the lagoon will diminish over time reducing the kite surfing opportunities (Figure 3). In addition, the beaches towards Scheveningen harbor will become significantly wider. This will be disadvantageous for beachgoers as the walking distance to the water line will become much longer.

When comparing alternatives for sandy solutions, the focus should not only be on the initial impact on the most important ecosystem services, but also consider how these are affected at various time points in the project's lifetime. Adding the time dimension into the design phase provides even more opportunities to truly integrate and (potentially) optimize the ecosystem services. This, however, demands a sound understanding of how these services behave over time and what drives them.

The influence of sediment size and composition
The NatureCoast research has clearly illustrated the complexity of the Sand Motor's behavior in space and time. Many interrelations were found that could only have been identified by combining knowledge across various disciplines. The most telling example is how sediment size and composition has influenced the Sand Motor's morphology and ecology and thus the ecosystem services. The driving mechanisms of the tides, waves and wind cause sediment sorting processes to act upon the nourished sand. The sediment size and composition were found to influence everything from the communities of marine benthos, fish, plant colonization, wind-blown transports, the formation of embryo dunes, development of vegetation, the dynamics in biodiversity in the lagoon, the potential for green beaches in the lagoon, the potential for contamination, morphological behavior, and even recreation.

Figure 1.
Predicted bathymetries for the reference case (the Sand Motor as constructed in 2011) and three alternative designs;
Alternative A - the lowered Sand Motor,
Alternative B - the mirror-image version of the Sand Motor, and
Alternative C - the wing-shaped island.



Arjen Luijendijk and Alexander van Oudenhoven

SHAPING FUTURE SANDY SOLUTIONS

The behavior of the Sand Motor has been monitored extensively in an interdisciplinary way, feeding into NatureCoast's integrated numerical models. Applying these models enables us to forecast the future changes of such sandy solutions. This section demonstrates the impact of three design parameters on the predicted evolution over a period of 20 years.

Understanding the factors that drive ecosystem services (as discussed in the previous sections) allows us to better shape new sandy solutions. We can change the shape, size, and elevation, and add features like a dune lake, lagoon, or small inlets. After this, we can apply the numerical models to forecast the morphological behavior of the sandy solution, both under and above water. In this way, the design tools can be developed, tested and made available for application. But when considering such a multifunctional coastal intervention, the starting point for the design will always be a main goal, or more often a combination of goals.

The province of South Holland played a crucial role in the development of the design of the Sand Motor. From the point of view of coastal safety, there was no need to place sand above water, but these offered opportunities for recreation and nature development. As the province promoted these goals, a design that included above water elements was preferred and implemented.

Many design parameters can be varied when designing a sandy solution, for example, the volume, size, shape, orientation, elevation, slopes, grain size, sediment composition, chemistry of the sand, groundwater table, and features like the dune lake, lagoon, and intertidal flats. To demonstrate the impact of a few of these design parameters, we predicted the 20-year evolution of different alternative designs (Figure 1) by applying a Delft3D model. The main message that we wish to convey here is that the hook shape is just one of the possible shapes and designs. A Sand Motor is not per se a hook-shaped beach nourishment, but a concentrated nourishment that feeds the adjacent beaches at a rate that is in pace with the natural dynamics.

For alternative A the present Sand Motor has been lowered by 2.5 m. The hypothesis was that the crest would then be flooded during storms, thereby showing more dynamics. The second column (of Figure 1) confirms this and shows that the lagoon area would be larger for the first 5 years compared to the reference case. Alternative B illustrates what would happen with a mirror image of the hook-shaped peninsula (third column in Figure 1). Surprisingly, the model prediction shows that a lagoon with comparable size would develop as that in the reference design. Alternative C starts with a different design: a wing-shaped island. Such an island could promote recreation (boats could visit the island) and would create a large lagoon over time, which is clearly visible in the predictions up to 5 years.

After 20 years, the predicted shapes of all four designs are generally not that different. The natural forces tend to smoothen the coast back to its original orientation and spread the sand along this stretch of coastline. This tells us that if we think in terms of decades, the initial design becomes less important, although differences still occur at a more detailed level; for example, the lagoon area after 20 years differs among the designs. Based on the decadal predictions, the lifetime of the Sand Motor will easily exceed twenty years and could be as much as 40 - 50 years. This means that it is worth putting time and effort into the design of such a prolonged sandy solution.

For other sites in the world where a sandy solution is being considered, it is important to realize that the ratio between the nourishment volume and the sediment transport capacity (determined by the natural forces of tide, waves and wind) will differ. The latter determines the dispersion of the sandy solution over time, its final footprint, and its lifetime, all of which need to be considered when the goals of the nourishment are being determined.

Peter van Bodegom

ECOSYSTEM SERVICES: AN UMBRELLA CONCEPT TO ESTABLISH INTERDISCIPLINARY LINKS

REFLECTION

Peter van Bodegom is a professor of Environmental Biology at the Institute of Environmental Sciences at Leiden University. Within the NatureCoast program, he was the principal investigator for scientific research project I1, which focused on integrating the program's research findings.

When the development of the Sand Motor started, the concept of ecosystem services (Page 138) had not yet been explicitly mentioned in the various policy documents. Instead, the Sand Motor was introduced primarily as a new way to protect our coasts against soil erosion, by using the forces of nature. Based on this concept, nature would be used to do what it is good at: changing the landscape. In fact, this aspect of building "soft" solutions based on ecological processes has been strongly emphasized to advocate nature-based solutions for coastal defense. However, coastal protection is just one ecosystem service.

Soon enough, it became clear to policy makers that the concept of nature-based solutions could be broadened to more than coastal protection alone, and that a whole suite of functions or services could be achieved through nature-based solutions, which might in turn increase the acceptance of the proposed solutions. When interviewing policy makers about what they considered the policy objectives of the Sand Motor, many mentioned coastal protection, next to nature and landscape (which fits in the concept just presented), but they also indicated the importance of recreation and knowledge development. The research described in the beginning of this chapter (Page 138) showed that policy makers had various aspects of ecosystem services in mind when considering coastal solutions. Indeed, the concept of ecosystem services (defined here as the benefits people obtain from ecosystems) may be seen as a framework that unites and integrates the various functions that have been studied in the NatureCoast program.

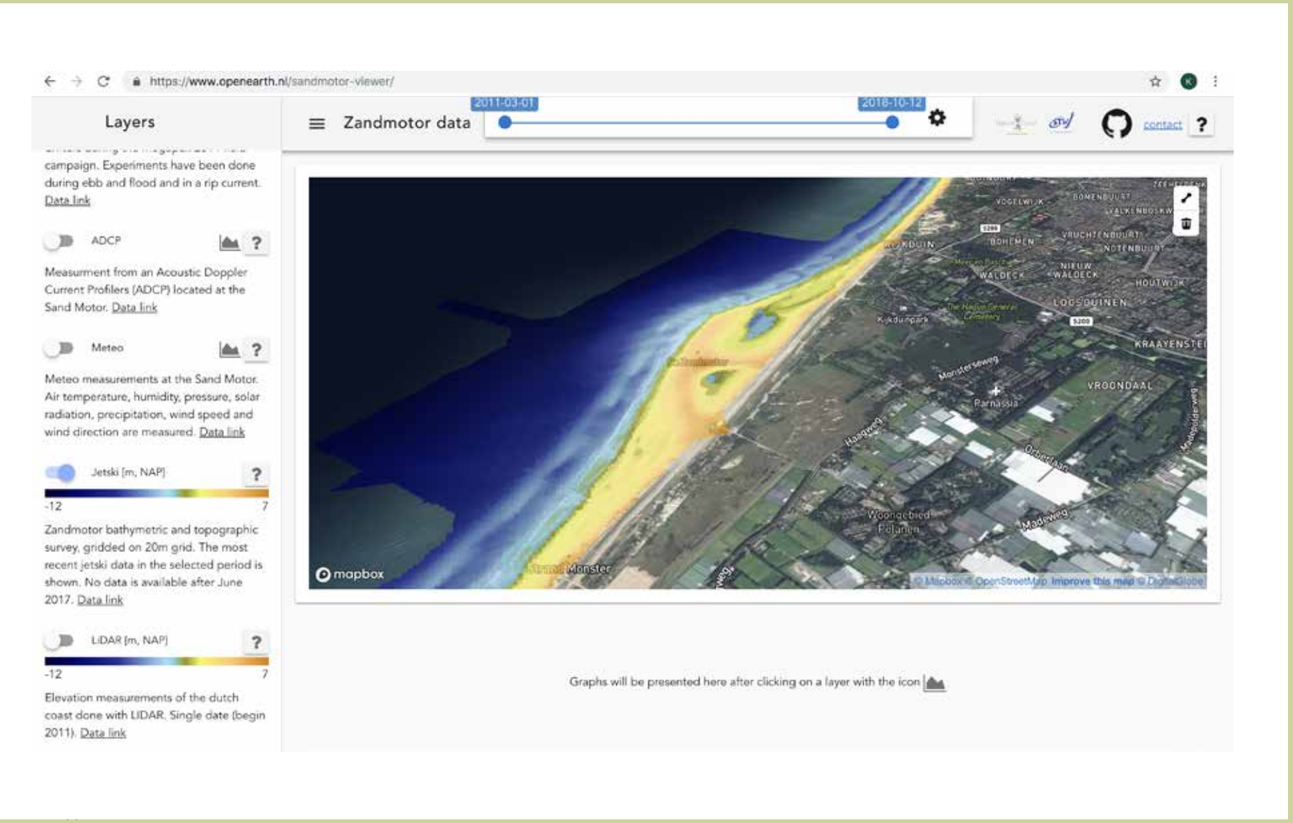
The combination of sand deposition below the water surface and dune formation ensures sustained coastal protection. The Sand Motor has also become a national hot spot for kite surfers, and attracts recreational visitors in every season. It impacts on local hydrology (Page 66) to provide water regulating services, and it serves as a fish nursery, as investigations on fish stocks showed (Page 118). Many ecosystem services of sandy beaches demand the support of well-functioning food webs in the subtidal and intertidal zones to provide food for fish, sequester carbon, and to regulate the nutrient cycle. Each of these aspects reflects a (potential) ecosystem service. Ecosystem services can thus act as an umbrella concept to understand the interdisciplinary links between all these aspects relevant to nature-based solutions, as was studied in the NatureCoast project.

To truly achieve ecosystem services-based solutions along our coasts, however, we would need to integrate these aspects more comprehensively. For each coastal challenge, stakeholders, whether governmental organizations or companies and NGOs, will have different demands regarding the necessary ecosystem services, since societal and physical conditions differ in each location. Those demands represent one way to express the value of the ecosystem services, and may be preferable, as monetary valuation is complicated at best. Based on those demands, an optimal solution - namely, the one that provides the best combination of desired ecosystem services - can be designed and implemented.

This optimal solution could be very different from the nature-based solutions we have seen so far. The actual difference will be hard to predict beforehand, as all solutions currently assume that coastal defense is the prime ecosystem service being demanded. This assumption also complicates evaluating the physical properties of the Sand Motor, which are almost by default considered to be more important than properties and benefits associated with other services. Thinking of new ecosystem services-based solutions, which consider a multitude of demands and are potentially based even on a transdisciplinary approach, can be exciting. However, such solutions should always be based on an understanding of how the system functions from a physical, ecological and societal point of view. And this is exactly where NatureCoast has provided a solid base.

Figure 1. (right page)
The data stages as defined by the OpenEarth philosophy.

Figure 2. (below)
Screenshot of the interactive viewer of Sand Motor data.



Kees den Heijer

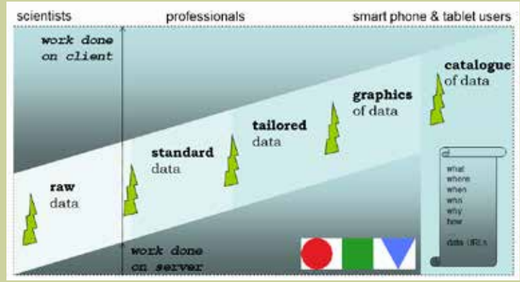
SAND MOTOR DATA MANAGEMENT SYSTEM

SPECIAL

Kees den Heijer is a senior researcher at Deltares and Data Steward at Delft University of Technology. Within the NatureCoast program, he was responsible for the Data Management system designed to be compatible with OpenEarth.

The Sand Motor is the first project of its kind in the whole world and has thus attracted both national and international attention from researchers, policy makers and the general public. Valuable data has been collected by Rijkswaterstaat through the Monitoring and Evaluation Plan, and by researchers of NatureCoast and other projects. All data is publicly available via https://zandmotordata.nl.

The preparation, design, and construction of the Sand Motor, as well as its development over time, has been the subject of research by multiple disciplines, ranging from technical to environmental and social sciences. Integrated research is especially important to the NatureCoast program, and this requires proper sharing of data across all involved disciplines. Terminology, measurement methods, or abbreviations that might seem obvious within one discipline are not automatically clear to people from other fields. Hence, sharing data across disciplines sets additional requirements to the level of standardization and documentation. The project was able to stimulate cooperation and integrated research by making the data publicly available and by paying special attention to the terminology used across the different disciplines.

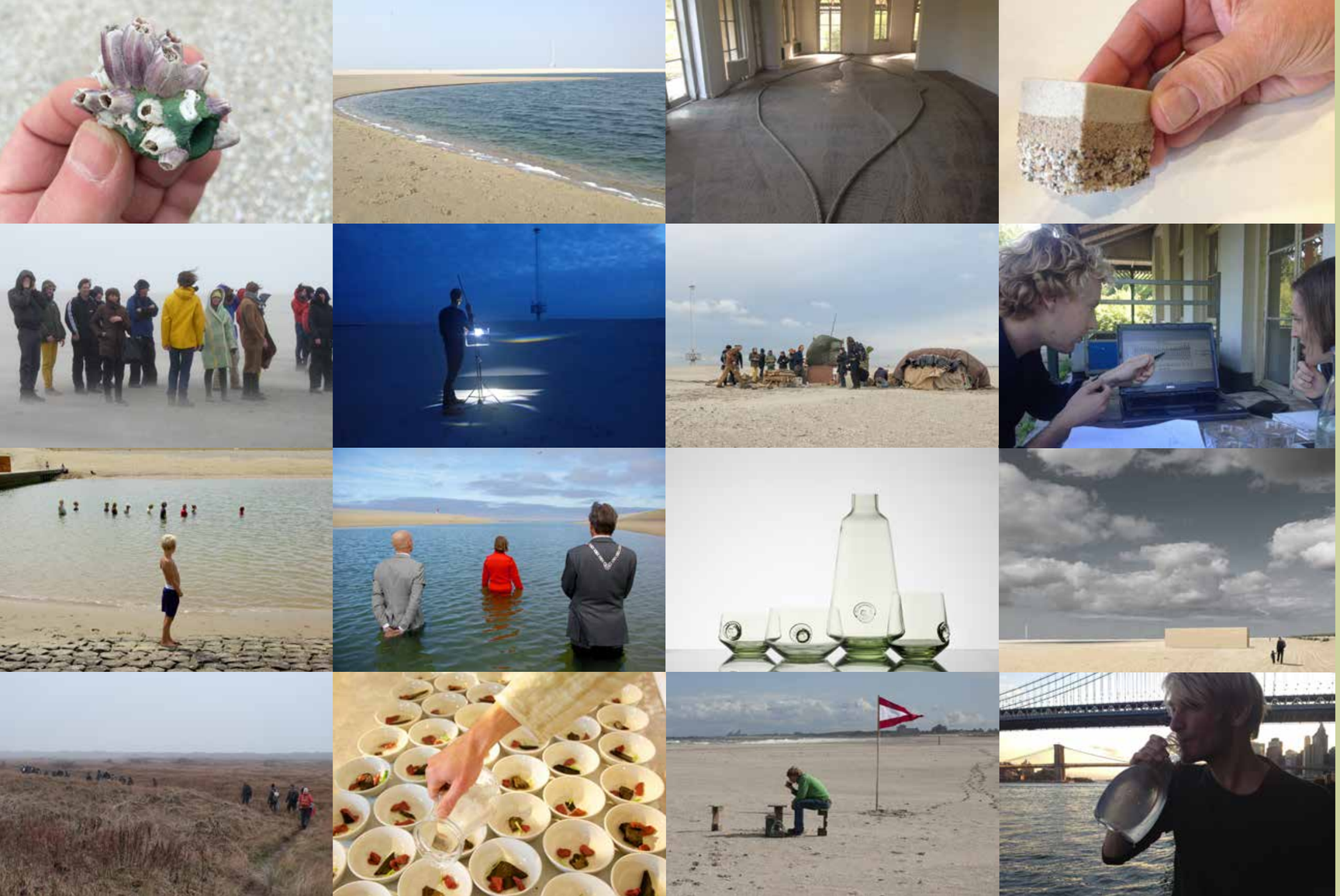


The 4TU.Centre for Research Data, Delft University of Technology and Deltares collaborated to create a data management system to store and share the Sand Motor data. The data management approach was based on the OpenEarth philosophy, with transparency, version control, international data standards, and sharing as key principles.

Figure 1 shows the data stages defined in the OpenEarth philosophy. All raw data is stored in a version-control system, which keeps track of the history of all files, including what was added and modified by which user and when. The scripts are also stored together with the raw data, to process it to standard data and higher stages. The catalog gives insight into the availability of the data at all stages. All data is publically available, from standardized data and upwards. Access to raw data can be granted upon request.

Generating standardized data not only stimulates reuse across disciplines, but also simplifies its presentation to a variety of audiences, for instance using an interactive viewer, as shown in Figure 2.

Finally, in the Sand Motor data management, we paid attention to the FAIR principles:
- Findable, via a catalog
- Accessible, by sharing the raw data and making the standard data publicly available
- Interoperable, by adopting international data standards
- Reusable, by adopting data standards and providing interactive viewer functionality



Satellietgroep

SAND MOTOR: A CULTURAL PHENOMENON

SPECIAL

Photos: left to right, top to bottom:
1. Artistic research Sand Motor: The Culture of Nature. Photo Jacqueline Heerema.
2. Sand Motor, quote Satellietgroep: "The Dutch are masters in disguising a cultural landscape as a natural one. We tend to design, construct, reconstruct and deconstruct nature to fit our needs." Photo Jacqueline Heerema.
3. Public Expedition Zandmotor #1: Sand Drift, artist Zoro Feigl: Untangling the Tides. Photo Thijs Molenaar.
4. Building with sand, Beach Rock TU Delft.
5. Public Expedition Sand Motor #2: Cultural Geology.
6. Public Expedition Sand Motor #3: artist Berndnaut Smilde: Breaking Light. Photo Annegret Kellner.
7. Climate Experiment Sand Motor #6: artist Esther Kokmeijer: Climate Proof. How climate adaptive is mankind? Photo Esther Kokmeijer.
8., 9. & 10. artist Sarah Cameron Sunde (USA): 36.5/A durational performance with the sea (8) Art meets science: 1. Photo Jacqueline Heerema.
(9) Art engages audiences: 2. Photo Florian Braakman.
(10) Art engages policymakers: 3. Photo Florian Braakman.
11. Zandmotor ZandGlas by Atelier NL. Photo Teun van Beers.
12. Design ZandGast, public information center Sand Motor by RAAAF, Atelier de Lyon icm TU Delft, 2016.
13. Public Expedition Zandmotor #10: Walking a timeline of 10.000 years coastal history, Solleveld & Zandmotor. Photo Theo Mahieu.
14. Cultural Geology, artist Theun Karelse: Fossils Soup. Photo: Florian Braakman.
15. Public Expedition Zandmotor #16: artist Maurice Meewisse: Eight Working Hours
16. Satellietgroep, A Taste of the Anthropocene, international exchange Sand Motor - New York City.

Satellietgroep redefines and explores the Sand Motor as cultural phenomenon, reflecting on the impact of the Sand Motor in the context of artistic research in polders, Wadden Sea and islands and international exchange projects. The artists collective hosts artists in residence for artistic fieldwork and creates conditions to collaborate with local experts and scientists. Together they develop new concepts and works that explore the sea, coastal transitions and climate change in past, present and future. In collaboration with artists, designers, students, pupils, local experts and scientists, Satellietgroep creates a growing Sand Motor Collection. During Public Expeditions on the Sand Motor audiences are engaged with these visual narratives. The works and insights gained are presented at international art exhibitions and coastal conferences. Society needs engaged artists and passionate scientists to jointly test our perceptions to raise public and professional awareness.

The Sand Motor can be regarded as the largest cultural statement regarding the shifting relationship between people and water of this time. All issues related to climate variations, perceptions of time and place, culture and nature come together. An in-depth reflection on the Satellietgroep line of thought is developed in the essay "Who is nature?" The artists explore and explain how visual narratives in art and design can overturn prevailing understandings of environment. They draw from their own experiences and projects on the Sand Motor to illustrate the statement and to explain how they came to the question "Who is nature?"

Now that people all around the world are slowly starting to rethink how people and planet are interrelated, new questions arise around the understanding of time and the perception of place. It is not merely a technical or political challenge that we are facing. It is a cultural one.

Policy officer Asset Management Technology

PATRICK BACON – DUNEA

INTERVIEW

In what way is the Sand Motor unique for you as end-user?
"The Sand Motor has put a profound and far-reaching external pressure on our drinking water production. At the location, we have dunes that actually contain polluted debris, which were dumped after the Second World War. Our water extractions had ensured a constant downward flow towards the sea with the watershed. After the Sand Motor was built, the watershed shifted towards the sea, but part of the groundwater suddenly moved in the other direction. This meant that the pollution present in that dune suddenly came our way. And we had to take quick action to prevent our water sources from being contaminated. At the time, we put a management and control measure in place to pump up water, and we still have to maintain this measure today."

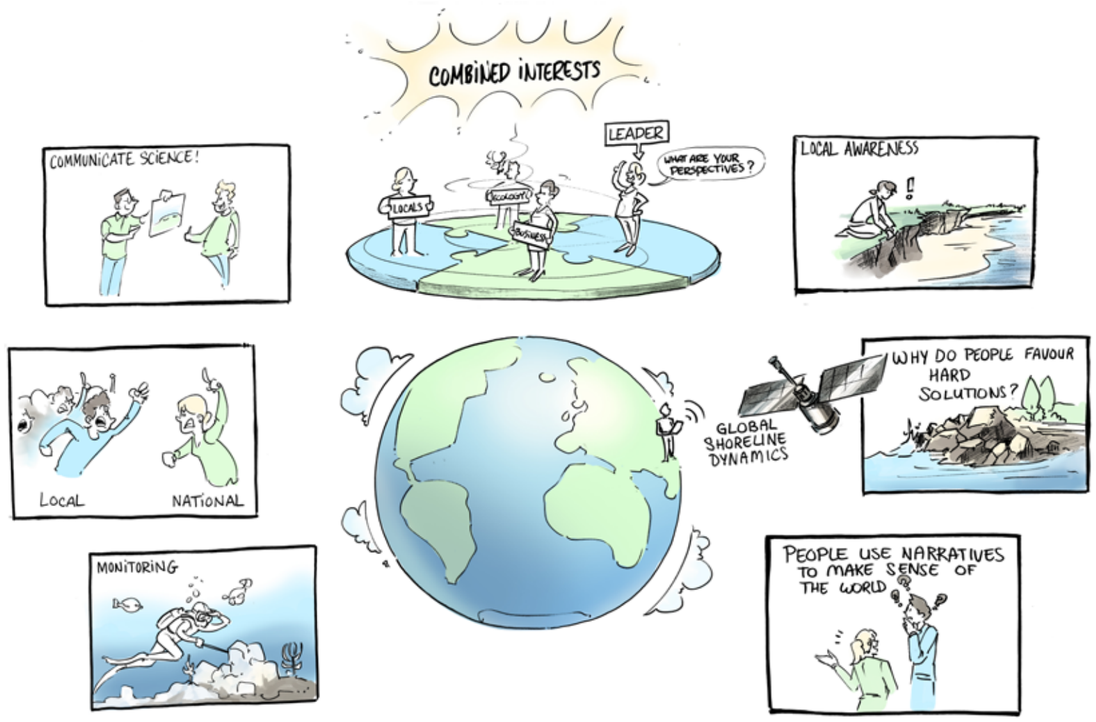
How do you see the role of scientific research at the Sand Motor?
"After its construction, of course, there was a lot of research into the effects of the Sand Motor. Twelve PhDs conducted all kinds of research into the effects on nature, ecology, hydrology, geochemistry and more. However, I wonder how much research had actually been done on these effects before the Sand Motor was built. If these effects had been known ahead of time, I doubt that the project would have been executed in the same way. Of course this is inherent to a pilot project. The scientific research has given us more insight into the effects of large sand nourishments and this knowledge can be used in future large sand nourishments along the coast."

How relevant is multidisciplinary research on the Sand Motor for you as end-user?
"For Dunea, multidisciplinary research is important, because our assets can be affected on various scales, and by multiple causes simultaneously. Whether the effects are on the ecology, hydrology or bring on changes in the geochemistry of the groundwater, all these aspects need to be considered for us to maintain the production of clean drinking water of high quality to serve the public."

What are the main findings of the NatureCoast program for you as end-user?
"I think it has created a large sense of awareness on the subject and an understanding of the effects it has on its surroundings. The program also produced a groundwater model created by Sebastian Huizer, which we were able to use on several occasions."

SEVEN | OPPORTUNITIES FOR SANDY STRATEGIES

Figure 1.
Global Opportunities
(Image by JAM Visual Thinking)



Arjen Luijendijk

EXPLORING THE POTENTIAL

INTRODUCTION

This chapter looks at the international potential of sandy solutions to mitigate coastal erosion and maintain or develop various functions of the coastal ecosystem. First, we discuss the evolution of nourishment strategies in the Netherlands since the 1980s. We pay special attention to how adapting to climate change will affect future nourishment needs. Next, we will outline the sandy solutions that have been implemented along the Dutch coast in the past and recently. We will illustrate the most recent trends in sandy solutions that have adopted the Building with Nature concept along the Dutch coast and lakes: *Hondsbossche Duinen*, *Prins Hendrik Zanddijk* and the *Houtribdijk*.

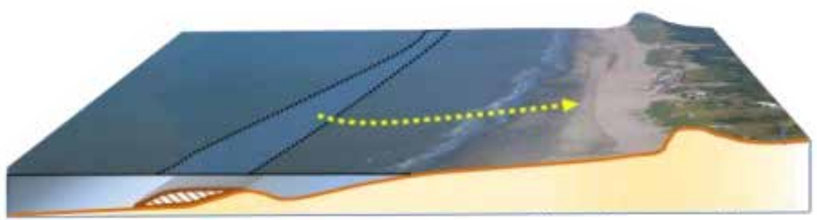
During the NatureCoast project many delegations from across the world visited the Sand Motor. A common question that many visitors asked the NatureCoast researchers was: "Could this also be built at our coast?" This was often followed by extensive discussions to understand the reasoning behind the question. In several cases that led to the active involvement of NatureCoast postdocs in the planning and design of a project. In this chapter we will highlight our experiences and findings from four cases: Bacton, United Kingdom (Page 166), Scania, Sweden (Page 168), Negril, Jamaica (Page 170), and Lima, Peru (Page 172).

In addition to responding to these queries, we have developed methods that can follow all the beaches in the world and their shoreline behavior over the last 33 years. We used satellite imagery to detect the locations of sandy beaches and identify their shoreline position for every year since 1984. This resulted in a database of all (erosive) sandy beaches across the globe.

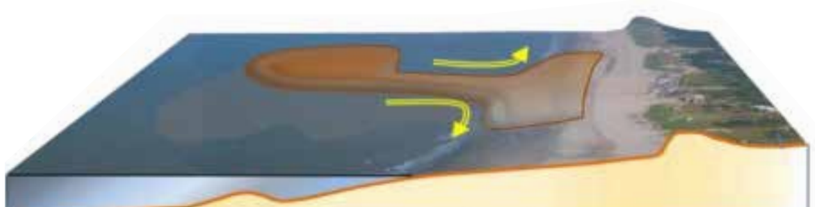
To conclude the chapter, the principle investigator will reflect on the global potential for large-scale sandy solutions to perform additional functions beyond coastal safety (Page 176).

Figure 1.
Alternative nourishment designs:
a Traditional beach and dune nourishments, frequently used from the 1970s onward, place sand directly on the beach and dunes.
b Shoreface nourishments, initiated in the 1990s, use natural marine processes to redistribute the sand that is placed under water in the cross-shore direction and gradually create a wider coastal defense over time.
c Concentrated mega-nourishments exploit both marine and aeolian processes to redistribute the sand both crossshore and alongshore.

a Traditional beach and dune nourishment



b Shoreface nourishment



c Localized mega nourishment

Arjen Luijendijk and Jaap van Thiel de Vries

SANDY STRATEGIES

Working with sand
31% of the world's coastline is composed of sandy beaches with dunes. These dunes form a natural defense protecting the hinterland from flooding, while at the same time providing valuable space for recreational activities and nature development. Due to alongshore variation in hydraulic loads, sandy shorelines can experience structural sand losses, which results in a receding coastline over the longer term. This can negatively influence the functions in the surrounding areas. To mitigate these effects, coastal managers implement various measures, either hard constructions (i.e., a sea wall or revetment) or soft (sandy) sediment strategies involving periodic sand nourishments.

Sandy strategies are usually achieved through sand nourishments, whose design (shape, volume, frequency) typically depend on local demands and on the nearby availability of sand with the desired grain size and color, as well as the availability of equipment to mine the sand. Globally, beach and dune nourishments are by far the most common strategy, with sand placed directly on the beach and dunes.

Sandy shores constantly reshape their active profile in response to the actual hydraulic conditions and efficiently dissipate the incoming wave loads. A sandy coastline tends to rotate perpendicular to the incoming wave angle in the longshore direction, which may result in consistent local sand losses over a longer period. Sand nourishments are typically employed to replenish these persistent losses, but they do not address the cause of erosion and their effect will thus have a limited lifetime depending on volume and local erosion rate.

Despite the limited lifetime of nourishments, sandy strategies seem to be gaining in popularity, for two reasons. First, nourishments allow for adaptive management to changing conditions and unexpected circumstances. This flexibility means that costly maintenance can often be postponed, which can make sandy strategies more competitive than hard alternatives. Second, there is an increasing demand for measures that integrate multiple functions (coastal safety, economy and nature) at once, which a smart sandy strategy can achieve.

Dutch nourishment strategies
The Dutch coastal zone, like many other low-lying coasts, has been subject to persistent erosion over the last centuries. To reduce the risk of flooding, coastal structures were built from the 1700s onward, strengthening the coastline locally with seawalls, breakwaters, and wooden or rubble-mound groins. However, these structures proved not always to be sustainable and effective. A more fruitful way of mitigating erosion was introduced more recently (in the 1950s) by using sand nourishments. After the success of initial nourishment projects, it became government policy to preserve the Dutch coastline at its 1990 position at all costs, with sand nourishments as the primary tool.

Since then, sand nourishments have been applied successfully in the Netherlands to mitigate coastal recession. Initially, nourishments were implemented as beach and dune nourishments, with sand placed directly on the beach and dunes (Figure 1a). However, theoretical and field-based studies showed that placing the sand on the foreshore can be effective as well, is cheaper, less intrusive to beach amenities, and much more acceptable to the public. Consequently, shoreface nourishments have been widely applied along the Dutch coast since the late 1990s (Figure 1b). Such a nourishment typically consists of about one to two million m^3 of sand and has a lifetime of about three to five years. These nourishments are generally cheaper for the same volume (costing about 50% less) and use natural marine processes in the surf zone, which transport the sand towards the coast allowing the beach to widen over time.

At present, most beach nourishments in the Netherlands are implemented as shoreface nourishments. However, this practice has a few disadvantages. Every nourishment buries part of the marine ecosystem (Chapter 5), and it takes several years for the system to recover. Consequently, five-yearly nourishments tend to leave the ecosystem in a continuously disturbed state. Moreover, nourishing only the upper part of the shoreface tends to lead to over-steepening of the coastal profile, which causes more offshore-directed sediment transport, making it necessary to nourish ever more frequently in the long run. The Sand Motor introduced the concept of concentrated mega-nourishments (Figure 1c), where both marine and aeolian processes are used to redistribute the sand both cross-shore and alongshore. This approach gives the marine ecosystem ample time to recover, since no new nourishments are expected in the next twenty to thirty years.

Trends in Dutch sandy strategies
An alternative type of concentrated nourishment was introduced in 2018: delta nourishment in a tidal inlet system. A sand volume of 5 million m^3 was placed at the outer delta of the tidal inlet of Ameland as a pilot. The marine processes will spread

Figure 2.
Spatial and temporal scales for Dutch nourishments.
(Figure by Quirijn Lodder, Rijkswaterstaat)

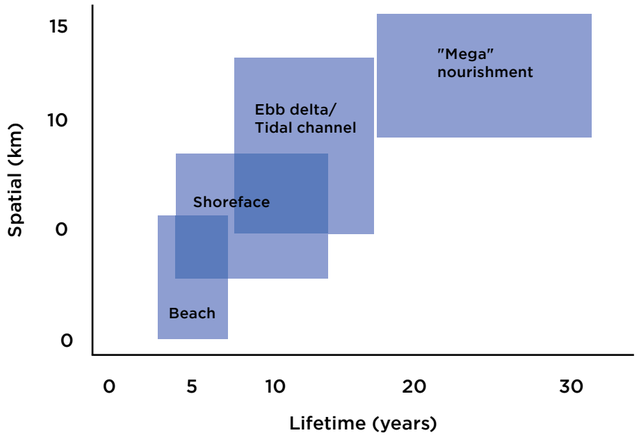


Figure 3.
a Hondsbossche Duinen (below left; photo courtesy HWBP)
b Prins Hendrik Zanddijk (below right; impression by HHNK)
c Houtribdijk (far lower right; photo courtesy Ecoshape)

the sand in the system to adjacent beaches to feed these with sand. By shifting the nourishment location, (part of) the nourished sand can also be used to i.e., feed the Wadden Sea to let it grow with sea-level rise. The trend in coastal management at Rijkswaterstaat over the last 30 to 40 years has been towards nourishments with longer lifetimes and which indirectly feed larger areas. Since 1990, annual nourishment volumes have increased to about 12 million m^3 per year for the entire Dutch coast (as of 2018). This annual nourishment volume will increase as we are forced to cope with sea-level rise. Recent estimates for the Dutch coast show that annual nourishment volume will need to increase by a factor of 3-4 (for a 0.4 m sea-level rise), up to a factor of 20 (for a 2 m sea-level rise in 2100). This represents tens of millions m^3 per year, in the worst case well above 200 million m^3 per year.

Another clear trend is that "engineering with vegetation" is becoming a more important aspect in designing successful sandy strategies. This is first because vegetation can help stabilize a sand body at a specific location. In addition, planting vegetation can influence how the landscape evolves (i.e., by stimulating dune formation). We would like to end this chapter by introducing three recent projects that incorporate vegetation into the design of the sandy solution, as can be seen on Figure 3. They differ in size, shape and application and represent the latest components of the Sandy Strategies and Building with Nature family.

The *Hondsbossche & Pettemer Zeewering* no longer met current safety standards (Chapter 2). Therefore, the dike was reinforced in 2015 with a soft, natural barrier of 30 million m^3 of sand on the seaside of the dike (Figure 3a). The design consists of a soft shallow foreshore (the beach), with various dune habitats. These connected systems make up the primary flood defense and provide the demanded spatial quality. The initial topography in combination with vegetation creates the starting conditions for landscape evolution for nature and recreational objectives.

The three-kilometer long *Prins Hendrikdijk* on the Wadden Sea island of Texel also no longer meets the safety requirements and is undergoing unique, natural reinforcement with sand. A diverse sandy area will be constructed in front of the current dike (Figure 3b). The innovative improvement method, involving a flexible design that accommodates future sea-level rises and enhances natural values in the Wadden Sea, will keep flood risk management up to par. The purpose of the vegetation is to reduce the nuisance of wind-blown sand and stimulate new dune development.

Finally, the sandy foreshore solution in the pilot *Houtribdijk* aims to dissipate incoming waves during storms before these waves can reach the dike behind, thereby enhancing safety against flooding, while creating a new muddy habitat at the same time. Several vegetation types (willows, reed, herbs) and various initial soil conditions have been assessed as effective methods to establish vegetation (Figure 3c). The purpose of the vegetation was to stabilize the sand in front of the dike to guarantee a certain amount sand volume in front of the dike for coastal safety.

Figure 1.
Global interest in the mega-nourishment concept. Locations indicated in green circles have been actively studied and presented in this book. (Negril photo courtesy Couples Resort; Lima photo by Christian Córdova)

Bacton Beach, UK

Scania Beach, Sweden

Negril Beach, Jamaica

Lima Beach, Peru

Arjen Luijendijk and Alexander van Oudenhoven

EXPLORING OTHER SANDY SHORES

INTRODUCTION TO INTERNATIONAL CASES

The Sand Motor has attracted attention from inside the Netherlands and from far outside. As described on Page 138, hundreds of international delegations have visited the Sand Motor since 2011, to learn more about its workings and to see it for themselves. In addition, several organizations and policy actors have approached the NatureCoast research team with specific questions about their own local coastal erosion problems. The four cases that will be described in the following pages, from Bacton (United Kingdom), Scania (Sweden), Negril (Jamaica) and Lima (Peru), could not be more different from each other. Not only is the morphology different, but the political climate, main economic activities and the actual importance of sandy beaches differs in each case. However, representatives from each of these locations contacted us about their eroding sandy beaches, to learn from our experiences, and to see if a solution like the Sand Motor, with the same underlying principles, would work in their case. In the following pages, we will describe the key challenge for each case, characterize the physical conditions and the local governance system, and look into possible ways forward. But first, we will highlight some overall observations and lessons learnt.

Driven by curiosity and desire to be innovative
In all cases, we were contacted by stakeholders who were not afraid to be different, to stray from the usual path. Hard engineering was generally regarded as not cost-effective and/or unattractive from a tourism and ecological point of view. Thus, innovation was an important driver for the stakeholders' interest in our work. We quickly discovered, however, that innovation should not equal experimenting. Unlike in case of the pilot Sand Motor, there was too much at stake in each of these cases for anything to turn out differently than expected. The perceived uncertainty made it challenging, albeit not impossible, to establish a partnership or consortium to tackle the coastal erosion problem in each of these cases.

Agreement needed on problems and solutions
A gas terminal, holiday residences, a tourism hotspot, and the capital of Peru: the stakes seem obvious and sufficiently high that everyone should to care. However, collaboration between public, private and local stakeholders often developed slowly and poorly. What caused this? Often, the stakeholders who expressed their concerns first were not the actual decision makers. They were inspiring pioneers, rather, with a hunger for innovation and an impressive knowledge of the local system. However, there was often no consensus about the key problem, as well as about the potential solutions. This resulted in misinformation, miscommunication and mistrust. If issues like coastal erosion, and even climate change, are not on the radar of key stakeholders, the search for solutions becomes difficult.

On top of that, the fate of an innovative solution always depends on the volatile and highly unpredictable context of decision making. Decisions can be overturned in a heartbeat, funding and support can disappear just like that. Sudden events, such as unexpected election results can change plans overnight (as was the case in Lima). Although this unpredictability seems unavoidable, it is fair to say that a thorough understanding of the political and governance issues at hand is instrumental for a successful project. It also shows that most policy actors are at least as interested in short-term solutions as they are in longer term ones.

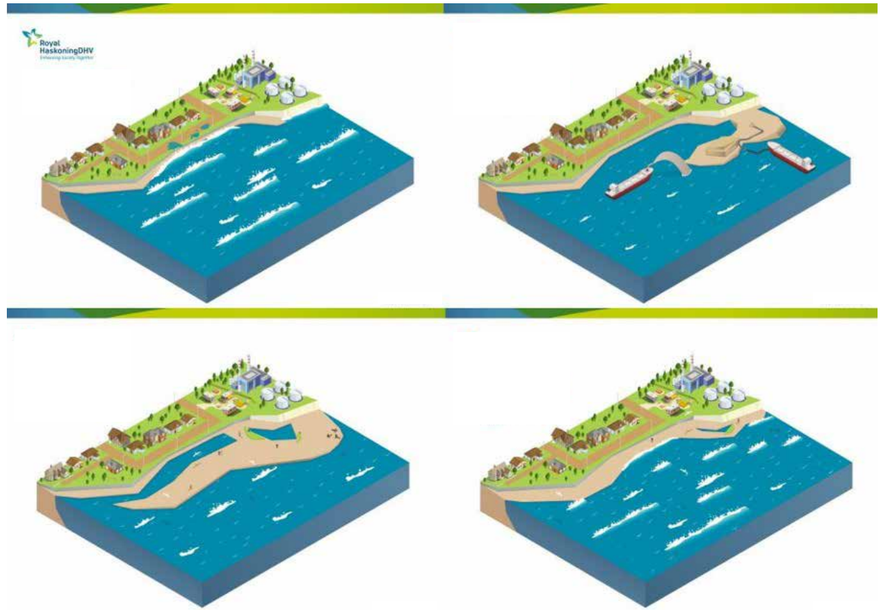
The Sand Motor cannot be copied blindly
With sufficient knowledge of the physical and governance system at hand, the concepts of Building with Nature and sandy solutions can work elsewhere. Most of our contacts were enthusiastic about the possible solutions presented by NatureCoast. In the Bacton case, our involvement even extended into the design phase and Environmental Impact Assessment study. In 2019, a solution based on the feeder concept of the Sand Motor will be constructed at the Bacton Terminal.

We learned that the Dutch Sand Motor should not be copy-pasted to other coastal sites around the world, as the solution depends on the governance, societal and physical context. In many regions in the world, sand might simply be too costly to mine, so coastal erosion will require different solutions than beach nourishment. When we were invited, we shared our experiences with the Sand Motor and the NatureCoast program, but we always proposed site-specific solutions, inspired by multifunctional, interdisciplinary thinking. With a broad consensus on the underlying problems and an inspirational leader and motivator, you end up with a "perfect storm" leading towards inspiring new sandy solutions.

Figure 1 (left). The cliff coast at Bacton Terminal showing small-scale protection works. (Photo by Royal HaskoningDHV)

Figure 2 (right). Cliff erosion threatening residences. (Photo by Maurice Gray)

Figure 3. The four stages of the Bacton nourishment: present situation, construction of the nourishment, and the situation after 5 and 20 years. (Figures by Royal HaskoningDHV)



Arjen Luijendijk and Vera Vikolainen

SANDSCAPING INSPIRED BY THE SAND MOTOR

INTERNATIONAL CASE: BACTON, UNITED KINGDOM

The challenge
Coastal management in Europe is shifting toward soft coastal protection strategies to deal with flood risk and erosion. An interesting example of this transition is the coastal enforcement project for the Bacton Gas Terminal (operated by Shell and Perenco) at Bacton, North Norfolk. The terminal is threatened by cliff erosion, and "Sandscaping" was included as an option to protect the terminal and nearby villages from coastal erosion. In this initiative, with Sandscaping being akin to "Building with Nature", British partners collaborated to translate the Dutch Sand Motor to the different physical and socio-political context of the UK. Royal HaskoningDHV, one of the partners in the Sandscaping initiative, was responsible for the design of the long-term sandy solution. Jaap Flikweert, Flood Resilience Leading Professional at Royal HaskoningDHV, invited the postdocs of NatureCoast to share the latest findings of the Sand Motor during the design phase of the Bacton coastal enforcement. Besides the technical challenges of making accurate morphological forecasts of the sandy solution, the main challenge lay in establishing the public-private venture of Bacton Gas Terminal and the North Norfolk District Council.

The system
Long-term coastal erosion is depleting the beaches of North Norfolk, leaving cliffs and seawalls exposed. Severe storms in 2007 and 2013 caused significant cliff erosion and flooding along the coast of East Anglia, underlining the project's urgency. The Bacton Gas Terminal is an important energy asset for the UK as it provides about a third of the UK's gas supply. To protect the terminal and the associated pipelines, a sustainable solution was preferred that will allow the terminal to continue operating into the future. Due to its nature-friendly and green nature, Sandscaping created a great opportunity for Bacton Terminal and neighbouring villages to collaborate.

In 2017 it was decided that the coastal enforcement would be based on the long-term solution of Sandscaping. Royal HaskoningDHV was appointed to design the solution whereby over 1.5 million m^3 of sand will be placed along the coast to protect a 5 km coastal stretch including the terminal and its neighbouring communities. The solution will enhance the natural coastline without leaving a permanent mark and can also be easily adapted and extended if needed in the future. The Bacton solution is a great example of a design that provides multiple functions and generates benefits for different stakeholders while also receiving multi-party funding.

The way forward
The nourishment is scheduled to be constructed in 2019, after which a multidisciplinary monitoring program will observe its evolution in detail. During design sessions in the UK, we shared our ideas on the dispersive behavior of the sand, the aeolian transports to be expected after construction, and the relevance of the sediment composition. In addition, the interdisciplinary NatureCoast project inspired those involved with the Bacton re-enforcement to also develop a knowledge program around the project.

Our research on governance in the UK showed that the context in England is generally restrictive for coastal innovations like Sandscaping. In the UK, coastal protection is simply not an issue of national importance, and the scale of the issues is regional. Therefore, an overarching coordinated approach would not be realistic in the British context, although it might make things easier. The Bacton case shows that flexibility is essential when complex and dynamic governance situations make a fully planned development risky and a more adaptive management style inevitable. Here, all the project partners worked together and the private actors play an active role; both civil service and ministerial levels have been involved in the case, and different funding sources have been combined, with a flexible division of responsibilities.

The Bacton case clearly illustrates that many aspects of the pilot Sand Motor and NatureCoast can serve as valuable input and inspiration to sand replenishment projects elsewhere.

Figure 1 (top left). Coastal erosion in Ystad.

Figure 2. (top right). Example of a hard coastal protection structure at the coast of Löderup, in 2015. Hard engineering solutions are still widely favored in Sweden, due to perceived uncertainties related to soft engineering.

Figure 3. (right) The nourished beach with the still visible groins at Ystad Sandskog, in 2015.

All photos by Lotte Bontje.

Alexander van Oudenhoven and Lotte Bontje

GETTING LOCAL BEACH EROSION ONTO THE NATIONAL AGENDA

INTERNATIONAL CASE: YSTAD, SWEDEN

The challenge
Only 3% of the Swedish coastline is composed of sandy beaches. However, in Scania county in southern Sweden, sandy beaches form around 25% of the coastline. During the past decades, erosion has been observed at several places along Scania's coast. Especially the Ystad municipality in Scania has suffered (Figure 1). Beach erosion in Ystad affects both public and private properties, including more than 1000 summer holiday residences along the coast.

Even though the Ystad municipality requires support, licenses and approval from national authorities, it is responsible for maintaining its own public infrastructure. Coastal erosion, and potential solutions to tackle it, remains the responsibility of the municipality. However, getting the local problem of coastal erosion, and the related need for beach nourishment onto the national policy agenda has proven challenging. Armed with the lessons learnt from the pilot Sand Motor (Chapter 2), governance researchers of the NatureCoast program set out to identify why beach nourishment had not been embraced by national decision makers.

The system
Many coastal erosion interventions were implemented in Ystad between the 1950s and 2000. However, these hard solutions, such as breakwaters, groins, and revetments have proven largely ineffective and in many cases have even made the situation worse (Figure 2). Houses could be seen falling into the sea in the 1970s, and the groins could not prevent further erosion. Local revetments could sometimes save houses from erosion in the short term, but also resulted in new and larger long-term problems.

Not content with the outcomes, Ystad was the first Swedish municipality to start a beach nourishment. The proposed project would supply sand at multiple locations using 340,000 m^3 of sand in total. Although the nourishment permit was received in 2001, the permit for offshore sand extraction was rejected several times. Only ten years later could the first two beach nourishments take place, followed by another round in 2014 (Figure 3).

This delay was the result of a complex decision-making process, different priorities at different levels, and several perceived uncertainties. First, Ystad had to apply for two different permits from two different national authorities, one assessing the environmental impact of the nourishments, the other evaluating the impact of sand extraction. On top of that, a regional administrative body, representing the government, formally has to approve all spatial plans of the municipality and check that they correspond to national interests. Frustratingly, although the regional authorities have always acknowledged that coastal erosion is a local threat, they also acknowledge that their agenda is determined by the national government. NatureCoast researchers observed that, just like in the UK (Page 168), beach erosion in Sweden is not generally perceived as problematic on the national level, but rather as a naturally occurring phenomenon. In addition, people involved with granting permits were concerned about the environmental impacts of beach nourishments and the continued availability of sand resources. The researchers concluded that the diverse perceptions of uncertainties and the communication about these uncertainties were underlying causes of the delay in granting the permits.

The way forward
As we saw in Chapter 2, the pilot Sand Motor demonstrated that policy change is more likely to occur when involved actors are convinced that there is a problem and that something needs to be done about it. The Ystad authorities are continuously searching for such policy windows. In this case, there is currently no consensus that coastal erosion constitutes a problem for which structural policy changes are necessary. In addition, not everyone is convinced that beach nourishments are the go-to solution.

One sign that this status quo has changed somewhat was the appointment of a national erosion coordinator in 2003. This authority focused mainly on sharing knowledge and creating awareness of the coastal erosion problem and the potential solutions, such as beach nourishment. This awareness raising could prove useful, particularly in view of the negative effects hard solutions have had on coastal erosion in the Ystad area.

Another solution could lie in connecting coastal erosion with a more widely accepted problem, namely climate change. This might lead to changes in administrative and planning systems and, hence, open new policy windows. Perceptions of beach nourishment as a solution might also change, as more and more monitoring results from beach nourishment projects throughout Europe are published. In 2021, the current beach nourishment licenses will end. If Ystad intends to continue with beach nourishments, it will have to apply for new licenses and, as a result, will have to reopen the discussion on coastal erosion and beach nourishments. Perhaps, by then coastal erosion will have made it onto the national policy agenda and beach nourishments will become a more mainstream solution.

Figure 1. (above) Tourists enjoying another carefree day in Negril, Jamaica.

Figure 2. (top right) Stickers with a slogan opposed to the breakwater plan in Negril. Many local stakeholders felt that they had not been heard in the breakwater plan and feared it would have negative impacts on both tourism and the environment.

Figure 3. (far right) Negril just after the construction of the coastal road, in 1972.

Figure 4. (bottom right) The one location on Negril's beach where the coastline is not visibly eroded. The building behind this lush vegetation was constructed well beyond the high water line, thus giving the beach ecosystem opportunity to be its flexible self.

Photos 1, 2 and 4 by Alexander van Oudenhoven; Photo 3 by Robin Farquharson.

Alexander van Oudenhoven and Arjen Luijendijk

PARADISE DIVIDED OVER A SEAWALL

INTERNATIONAL CASE: NEGRIL, JAMAICA

The challenge
Negril is among Jamaica's most popular tourist destinations. Its many high-end hotels together receive about 20% of all the nation's tourists. For decades, Negril has maintained the image of a laid-back and natural beach resort (Figure 1). However, it is estimated that up to a meter of its beautiful coastline has disappeared annually since the 1990s. In 2012, the opportunity arose for Jamaica's government to tackle the coastal erosion problem. Almost 10 million dollars became available through a climate change adaptation fund, to be spent on coastal infrastructure. The funding would be spent on a submerged breakwater that would shield the coastline against incoming wave energy.

This decision resulted in a public outcry (Figure 2). Various stakeholders, including hotel owners, local fishermen and NGOs feared that this hard structure would impact both tourism and the environment negatively. Moreover, the stakeholders felt that they had not been consulted adequately. In 2014, the Negril Chamber of Commerce contacted NatureCoast with the question whether a more nature-friendly option might be available for Negril, based on lessons learnt from the Sand Motor.

The system
Prior to our visit in 2016, the beach had actually recovered slightly, due to a lack of severe storms in recent years. Long-term residents of Negril knew, however, that one severe storm would all but vanish the beach. Especially in these hurricane-prone Caribbean regions, erosion is a naturally occurring phenomenon; beaches erode and then slowly accrete. Negril's beach has never been very wide; as can be seen from the aerial picture taken in 1972 (Figure 3).

The main problem in Negril is not that the beaches erode, but rather that, in recent decades, the sand simply has not returned after a storm.

To understand why, take another look at the aerial picture. The newly constructed road separates a swampy wetland on the right from a coastal forest on the left. Moving into the seaward, the white sands are covered by seagrass and beyond, the darker colors are the coral reefs. This beach would flood regularly, but the wetlands would buffer the storm water and then desalinize the soil. Though the beach would erode, the seagrass and coral reef would prevent the sand from leaving the system. As a result, the beach would recover during calmer periods.

Very little of this ecosystem has remained intact. The wetlands are being drained on a large scale and are heavily polluted. Hotel construction and expansion is continuing, and their swimming pools and terraces are constructed beyond the high water line. The beach has nowhere to go, certainly not inland. To make it worse, most of the seagrass is being removed by hotel owners, allegedly because of its nuisance to swimmers. Over half of the coral reefs are also heavily degraded, due to dynamite fishing in the past and current water pollution, overfishing and trampling by tourists. Many local stakeholders remember the old days and how the coastal ecosystem used to be in balance, a glimpse of which is still visible at one location in Negril (Figure 4). It is understandable that the stakeholders reacted so passionately to not being heard. The knowledge, concern and involvement of local stakeholders is crucial to the future of Negril's coastline and its economy.

The way forward
During our visits in 2014 and 2016, it became clear that both short-term fixes and a longer term solution were needed. Areas directly threatened by erosion would have to be strengthened through targeted beach nourishments, because otherwise surrounding hotels would lose their appeal. However, we stressed the need for continuous monitoring, which will provide insight into beach morphology and sand transport, especially after storm erosion.

On the long term, the Negril ecosystem should be allowed to function again, with help from its inhabitants. The wetlands have to be restored, and water sanitation infrastructure will have to be improved considerably. All buildings beyond the high water line are a threat to the coastline, as is the regular removal of seagrass. However, the most important role will have to be played by the coral reefs. They will have to be strengthened and restored, so that they can regain their role as wave breakers, fish nurseries, and natural structures to trap the sand—and of course serve as the basis for ecotourism.

A wide range of solutions is available, and concerned stakeholders managed to halt the construction of a breakwater for now. The time had come to think about other approaches. We know from the pilot Sand Motor how important stakeholders inclusion and agreement is. They should agree on both the problems as well as the potential solutions and desired functions of the beach. Negril's beach is running out of sand, and its people are running out of patience. To date, in early 2019, the situation in Negril has remained unchanged, with the risks still imminent.

Figure 1.
Artist impression of two Sand Motors at the Costa Verde in Lima, Peru (created by Nahuel Beccan Davila and Adrian Puentes of Beccan Davila Urbanismo).

Arjen Luijendijk

FINDING COMMON GROUND FOR A “MOTOR DE ARENA”

INTERNATIONAL CASE: LIMA, PERU

The challenge
We were approached by MAP Office, an urban planning bureau based in the Netherlands and Mexico, who were involvement with the Masterplan “Costa Verde” (Green Coast) for Lima, the capital of Peru. The artist impressions they developed included two Sand Motors with the idea of creating a flourishing beach area in front of the cliffs of Miraflores. The postdocs of NatureCoast were asked to think about the physical feasibility of the proposed large-scale nourishment. We presented our findings during a well-attended stakeholder workshop organized by the office of the mayor of Lima.

It turned out that the policy goals focused more on urban development, aesthetics and adequate infrastructure than on coastal protection. The problem in this case was the lack of cooperation between the district municipalities, the Costa Verde project organization, and the other stakeholders along the coast. In addition, the legal and institutional framework turned out to be fragmented at the national level.

The system
Costa Verde is a coastal stretch of about 20 km divided into 6 district municipalities. Among other problems, Costa Verde faces environmental degradation of the coast, lack of spatial organization and quality, and issues related to coastal safety. To date, land along the coast of Costa Verde has been reclaimed from the ocean using rocks and the construction remains from demolished buildings. As a result, the coast is unappealing and polluted. From an environmental and aesthetic perspective, a sandy beach would be more attractive than the current stony beach.

The narrow beaches of Costa Verde are currently squeezed between the ocean and the cliff. The cliff is unstable and eroding, as it is made up of soft river deposits, and because of the pressure from on-going construction atop the cliff. At the same time, there is increased coastal erosion from the ocean as well as the risk of tsunamis. The current infrastructure to protect the coast from the ocean is deemed insufficient.

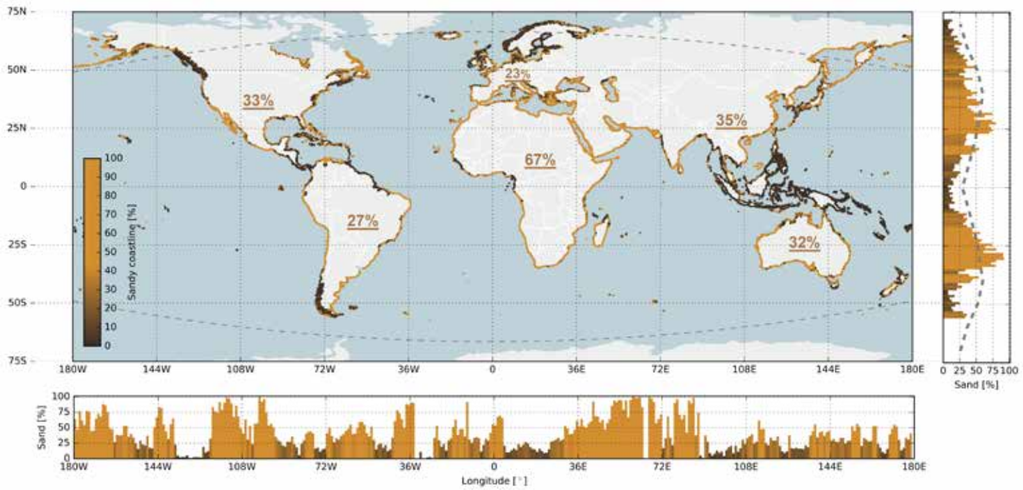
A large volume of suitable sand is required for a large-scale nourishment. Sand from the relatively nearby desert is not suitable, as the properties of this sand differ significantly from that of marine sand. The availability of sand at the sea bed is, however, largely unknown. Some reports and data show that sandy layers are present offshore up to at least 15 m water depths, but they probably would not provide sufficient sand volume to construct a large nourishment.

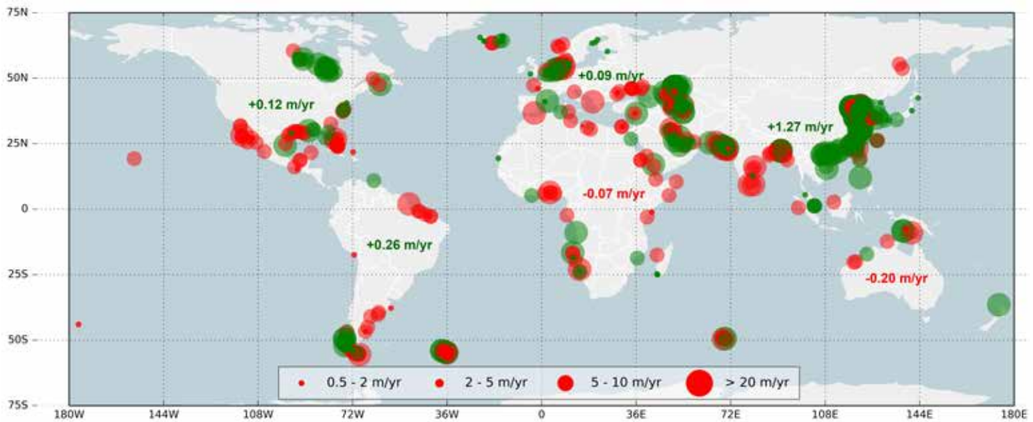
Except for the law protecting the surf waves (Ley de Rompientes), there were no legal limitations for the Sand Motor. Furthermore, the authorities expressed willingness to include a Sand Motor type of solution in the Costa Verde Master plan.

The way forward
The Sand Motor concept is meant to serve multiple societal goals, with a variety of functions including costal safety, nature, and recreation. As occurred in the Netherlands, we believe the concept of a multifunctional coastal solution can unite the various parties involved here. The goals of the district municipalities, the Costa Verde organization and other stakeholders should first be analyzed to find common ground and define individual goals. These goals can then be incorporated into the conceptual design of a Sand Motor. In addition to this, societal goals should be considered to frame the Sand Motor in the local context. During our study we identified the following societal goals: tourism and recreation development, aesthetics (attractive landscape with the ocean), environmental sustainability, and harmonious development. The Sand Motor’s harmonious design with nature and benefits for environment could be emphasized alongside its coastal protection benefits.

These findings and suggestions were presented and discussed with the Costa Verde organization office at the time. In the months thereafter, the focus shifted almost entirely to elections for a new mayor of Lima, and all ongoing initiatives, including the Costa Verde Masterplan, were put on hold.

It should be noted that this case description is based on our interpretation of reports and data, and only one workshop and a few meetings in Lima; it can only be seen as reporting our own viewpoint. The Lima case has taught us that a large-scale, dynamic, multifunctional solution offers many opportunities for uniting a group of stakeholders with a variety of perspectives. The active involvement of stakeholders from the initiation phase is paramount to ensure that all voices are heard.





Arjen Luijendijk

A GLOBAL VIEW ON BEACH EROSION

Coastal zones have long attracted humans and human activities, due to the economic opportunities they offer, their aesthetic value, and the diverse ecosystem services they provide. As a result, coastal zones throughout the world have become heavily populated and developed, with 15 of the world's 20 megacities (population >10 million) being in the coastal zone. The global coastline is spatially varied and comprises different coastal landforms, such as barrier islands, sea cliffs, sandy coasts, tidal flats, and river deltas. Of these different coastline types, the sandy coasts are highly dynamic in time and space and constitute a substantial part of the world's coastline. Sandy coasts are highly developed and densely populated due to the amenities and aesthetics they offer, but erosion of these coasts over the last few decades is already causing coastal "squeeze." The impact of climate change on these coasts will only exacerbate this situation.

Despite the utility and economic benefits that coasts provide, no reliable global-scale assessment of historical shoreline trends is available. Using freely available optical satellite images captured since 1984, in conjunction with sophisticated image interrogation and analysis methods, we conducted a global-scale assessment of the presence of sandy beaches and the rates of shoreline change at those locations. Applying pixel-based supervised classification, we found that 31% of the world's ice-free shoreline is sandy. Africa has the highest percentage of sandy beaches (66%), while in Europe only 23% of the shoreline is sandy (Figure 1).

Applying an automated shoreline detection method to the sandy shorelines that were identified resulted in a global dataset of shoreline change rates for the period 1984 - 2016. Analysis of the satellite-derived shoreline data indicates that 24% of the world's sandy beaches are eroding at rates exceeding 0.5 m/yr, while 28% are growing, and 48% are stable. About 18% of the sandy beaches are experiencing erosion rates exceeding 1 m/yr.

More severe erosion rates are found at various locations across the globe. About 7% of the world's sandy beaches experience erosion rates classified as severe (i.e., more than 3 m/yr). Erosion rates exceed 5 m/yr along 4% of the sandy shoreline and are greater than 10 m/yr for 2% of the global sandy shoreline. From a continental perspective, Australia and Africa are the only continents with net erosion (−0.20 m/yr and −0.07 m/yr, respectively), with all other continents showing net accretion. The main causes of this accretion are land reclamations, natural sediment supply by rivers, and nourishment strategies. For example, the country-mean change rate for the Netherlands is 2.8 m/yr since 1984.

The database is publicly available at *shorelinemonitor.deltares.nl*. The Shorelinemonitor tool can assist in understanding the coastal dynamics over the last 33 years for every beach in the world. This database allowed us to identify the coastal stretches that are eroding around the world (i.e., erosion hot spots). A hotspot is defined as a coastal section of at least 5 km of sandy shoreline where all considered transects showed erosion larger than 0.5 m/yr over the 33-year data set. The numerous hotspots shown in Figure 2 illustrate that erosion affects large sandy beach sections around the globe. Combining this data with the information on urban development, derived from nightly satellite images, we can identify the hotspots for coastal "squeeze." These are areas that may need coastal protection measures to mitigate coastal erosion in urban areas, either now or in the future. Investigating the feasibility of sandy strategies in these areas would be very valuable.

In addition to encouraging nourishment to mitigate coastal erosion, we should investigate ways to optimize existing nourishment strategies, or even consider constructing artificial beaches on non-sandy coasts. Any such assessment or proposal will need to start with a comprehensive understanding of the physical conditions and the ecosystem, as well as the governance setting.

Figure 1. (top left)
Global distribution of sandy shorelines; the coloured dots along the world's shoreline represent the local percentage of sandy shorelines (yellow is sand, dark brown is non-sand). The subplots present the relative occurrence of sandy shorelines per degree latitude and longitude. The underlined percentages indicate the percentages of sandy shorelines averaged per continent.

Figure 2. (bottom left)
Global hotspots of beach erosion and accretion; the red (green) circles indicate erosion (accretion) for the four relevant shoreline dynamic classifications (see legend). The numbers presented in the main plot represent the average change rate for all sandy shorelines per continent.

Marc Bierkens and Gu Oude Essink

OPPORTUNITIES FOR FRESH GROUNDWATER RESOURCES IN A MEGA-NOURISHMENT

REFLECTION

Marc Bierkens is a professor of Hydrology at Utrecht University and senior researcher at Deltares; Gu Oude Essink is a senior researcher at Deltares and a (part-time) associate professor at Utrecht University. Both worked on project S5, which focused on studying fresh groundwater resources and the soil quality of the Sand Motor.

The Sand Motor was originally thought of as a bold and innovative mega-size sand nourishment for eroding sandy coastlines. It was expected to take advantage of the protective abilities of beaches and dunes, but unlike traditional linear beach nourishments, the disturbance to ecosystems would be concentrated while creating opportunities for new ecosystems to develop. However, the coastal scientists who set out the NatureCoast research program, had the visionary idea that a large body of sand would also collect fresh groundwater, which would represent an additional benefit of concentrated mega-nourishments.

As the Sand Motor was a completely new phenomenon in coastal protection, there were no studies available on how such a structure would affect the development of fresh groundwater. However, based on the understanding of the dynamics of fresh groundwater systems in coastal environments simple estimates could be made. An elevated ridge like the Sand Motor should create a groundwater table storing water above the surrounding land surface; we would expect the table to be higher the less permeable the subsoil and the wider the elevated ridge. Moreover, as fresh groundwater floats on saline groundwater, the depth of the fresh-salt water interface will be approximately 40 times the height of the groundwater table. So, if we expect the groundwater table at the Sand Motor to be on average 0.5 meters above mean sea level, the fresh-salt water interface would be approximately 20 meters below mean sea level. With an average sand porosity of 0.35, this would mean a water storage of ~7 m^3 water per m^2. The rate at which this fresh groundwater collects will depend on the groundwater recharge rate. In the Netherlands, groundwater recharge in permeable sands is about 350 mm/year, which means that it would take about 20 years to reach maximum water storage.

Figure 1. (left page)
Satellite image (Sentinel-2) of March 12th, 2016 showing the freshwater plume (and sediments) of the river Rhine entering into the North Sea.

These are interesting preliminary estimates, but reality is a bit more complex. Fresh groundwater will not only collect in the Sand Motor itself. Even after it has been completely dispersed along the shore, the wider beaches and dunes that result from the project will increase fresh groundwater storage in the neighboring dune systems as well. Since the morphology of the Sand Motor will drastically change over its lifetime, the relative storage of groundwater in the sand body and the connected dune system will also be affected. As a matter of fact, fresh groundwater dynamics under changing morphology have hardly been studied before. Finally, apart from a slowly changing morphology, the fresh groundwater system inside the Sand Motor will be subject to tides and storm surges. How will these affect the volume of fresh groundwater stored?

Our project set out to study this complex system by combining groundwater level and salinity observations on the Sand Motor and neighboring dunes with detailed electromagnetic measurements of salinity over many tidal cycles and during storms. These data were used together with regional-scale high-resolution salt-fresh groundwater models to assess the past and future development of fresh groundwater resources in the Sand Monitor and its surroundings. Based on this, we expect a total 10 million m^3 of additional fresh groundwater to be stored through 2050. This is an additional 0.3 million m^3 per year on average, which would be sufficient to supply drinking water to 5000 people. It should, however, be noted that 90% of the volume will occur in the neighboring dune system, as the Sand Motor disperses, and the coastline expands. The Sand Motor harbors about 1-1.5 million m^3 of fresh groundwater, and this volume built up rather quickly during the first 5 years of the Sand Motor's existence.

We are currently assessing the potential of mega-nourishments such as the Sand Motor for creating freshwater resources around the world. Obviously, creating a Sand Motor for the sole purpose of fresh groundwater storage is not economically feasible. If that is the primary goal, there are better alternatives such as artificial recharge and aquifer storage. However, as a byproduct of coastal protection, this certainly has potential on sandy erosive coastlines, which represent 17% of the global shoreline. Moreover, this approach will depend on the type of sand (permeability), climate (recharge rates), the rate of coastal erosion, the frequency of storm surges, and amplitude of tides. We estimate that about 50% of sandy erosive coastlines would be suitable for developing fresh groundwater resources, particularly sites where dune systems already exist.

General manager Hydronamic

JAAP VAN THIEL DE VRIES – BOSKALIS

INTERVIEW

In what way is the Sand Motor unique?
"First, the Sand Motor is physically unique. This nourishment is larger in scale and volume than anything we have done before, which makes the project groundbreaking and offers new opportunities to coastal zone planning. Its scale gives the opportunity to shape a nourishment in a completely different way, thus creating an interesting landscape from various perspectives."

"The Sand Motor is also unique in terms of involved parties and stakeholders, and the way in which they have worked together. It is a "Living Lab", in which many people have embraced the Sand Motor as a place to recreate and work. Many natural and societal functions have developed on the Sand Motor that were unforeseen, and which resulted in various positive interactions between the natural system and people that we had not considered beforehand."

How do you see the role of scientific research at the Sand Motor?
"Crucial. The Sand Motor was designed for the Delfland coast and we had a certain idea how it would develop. Due to scientific research we are capable to understand the observed developments over the past years by really unravelling these. The latter is crucial, because if you were to apply solutions of this scale elsewhere in the world, these would always behave different than at the Delfland coast. That knowledge, the real understanding of what you observe, in terms of physical processes, ecological processes, governance processes and the interactions between these is very important if you want to design something that would perform equally well at a different location."

How relevant is multidisciplinary research on the Sand Motor?
"The Sand Motor is a solution where the initial conditions are created by building with sand and water, after which the ecosystem and people can take advantage of it. The interactions between the ecosystem and people determine whether the design will ultimately be a success. Understanding these interactions is thus a prerequisite for successful design."

What are the main findings of the NatureCoast program?
"First of all, the Sand Motor and the NatureCoast program have been established by a unique collaboration within the sector, that can serve as a blueprint for future projects and initiatives. The fact that this collaboration works, knowing what the pitfalls are, what you have to discuss between partners, and what you have to organize upfront, are very important lessons to shift the boundaries of knowledge and coastal protection."

"But it is also about hard knowledge. To protect our coast in the future against the rising sea level, more sand for coastal nourishments will be needed. Preferably these nourishments have a longer lifespan, so that we can create ecological benefits and add social value. The Sand Motor is great example strategy of how this could be realized. The next big challenge is that we really embed this successful pilot strategy in our mainstream way of working: the Sand Motor as stepping stone towards a different approach to coastal management."

Is the knowledge resulting from the Sand Motor research relevant to Boskalis at other locations?
"We present many of the concepts and the philosophies behind the Sand Motor to our clients and we make alternative value propositions inspired on the Sand Motor to address our client needs. In doing that, we often use the Sand Motor as a case, to zoom in on a specific location, and use it as start point of a search to a tailor-made solution that fits the local needs. Depending on the client's request, the challenge can be to control sand movement along the coast, but also on how you can integrate multiple functions in a strategy. The research findings from the NatureCoast program help to substantiate these design challenges. For example based on the knowledge developed, we can tell our clients how the volume associated with a "sandy strategy" will behave at a larger scale. In a broader perspective the NatureCoast program contributed substantially to the Building with Nature innovation program. Based on the knowledge and design guidelines available from this program we can offer extra value to our customers in many locations around the world."

JAAP FLIKWEERT – ROYAL HASKONING DHV

INTERVIEW

In what way is the Sand Motor unique to you as end-user?
"First and foremost, it offers a unique opportunity to engage in a large-scale and complex innovative experiment, one that we always hoped for. The fact that it proved possible, in the Netherlands, to spend over 70 million euros on such an experiment and to include all the research by the NatureCoast program and the monitoring by *Rijkswaterstaat*, gives me, as an end-user, a sense of confidence."

"It is also unique since the experiment is probably even larger in scale than most real-world applications of the concept in other places. For example, "our sand motor" in the United Kingdom is a lot smaller, but the fact that "yours" has already been constructed on such a large scale and that it appears to be working gave those involved here a lot of confidence. After all, it is unique that everyone is happy with it, not only from a technical perspective but also from a multifunctional perspective. The decision makers, the financiers and the stakeholders at our location, everyone actually thinks it works. I don't think I would have succeeded in realizing such a project in the UK, if I hadn't been able to present such a compelling example from elsewhere to my client."

How do you see the role of scientific research at the Sand Motor?
"We had to apply our sand motor in a different context, but the knowledge and experience developed at NatureCoast certainly contributed to this. For example, we were able to apply knowledge about wind-blown sand that was developed at the Sand Motor. But we also brought Arjen Luijendijk in as an external reviewer for our project in the UK, and he made a real contribution to improve our work, especially the computer modeling. I can tell our client that scientific research is being conducted, and that researchers involved with the Sand Motor have participated, which creates a sense of trust."

How relevant is multidisciplinary research on the Sand Motor for you as end-user?
"That too is essential. Our clients in the UK explicitly see their sand motor as a multidisciplinary and multifunctional project. In terms of impact, but also in terms of the opportunities it could create. Although I think that the technical aspect is ultimately the make-or-break factor, this multifunctionality provides considerable added value. And the fact that there is a multidisciplinary research program out there is extra inspiring. We would also like to have such a program on the project, but it is proving more difficult to find money as compared to in the Netherlands. However, NatureCoast has certainly inspired us."

What are the main findings of the NatureCoast program for you as end-user?
"The technical content that we applied most specifically, is the knowledge about wind-blown sands. Our clients wanted to know how the wind-blown sand transport would affect the project. NatureCoast drew up calculation rules that indicate how much sand is displaced by the wind. This deals with the negative effects of wind-blown sand. Our sand motor project is adjacent to a gas terminal, and nobody wants too much fine sand entering the system of the terminal. There were no formulas to model this precisely, but the NatureCoast research provided us with first insights."

"There are also important, more general conclusions to be made. Looking at the pilot Sand Motor as a whole, everyone involved seems to be content. This is certainly an indication that the project works, both in terms of coastal processes and other aspects. Of course, there were a few hiccups, for example that the coastal processes worked a little slower than expected. To some extent, this leads to confidence at the location where you place it, but it also means that another location elsewhere that would like to receive the sand, will have to wait a little longer."

"NatureCoast findings, combined with our own calculations for the project in the UK, have influenced our design here. For instance, we might be able to promise a longer life of the sand motor at the gas terminal. But for the villages further down the road, where the sand also plays a role, we could not rely purely on natural processes. By considering the pros and cons identified by the NatureCoast research, we were able to create a more dependable design."

Is the UK also interested in interdisciplinary research, and if so what is the reason for this?
"It is generally acknowledged that an integrated approach is difficult to get done, but it still is something that everybody wants. Everyone agrees that it is smarter to take as many factors as possible into account when designing a project. The fact that NatureCoast succeeded and that the story can be told in this way, ensured that our client in the UK wants to cooperate in this specific application of Building with Nature. We have not yet succeeded in setting up a similar research program here, but the bottom-up stimulus from clients and researchers is inspiring and together we are trying to work in that direction."

EIGHT | **REFLECTIONS**

Figure 1. (top left) During one of many PhD-days, Emily van Egmond shares her design for the "Sand Motor 2.0" based on the insights of her research.

Figure 2. (top right) Simeon Moons in dialogue with end-users at the final NatureCoast symposium 2017.

Figure 3. (bottom left) Jantien Rutten explaining the sand movement of the Sand Motor during the excursion at the 2016 Rijkswaterstaat conference.

Figure 4. (bottom right) NatureCoast researchers, end-users and members of society discussing after the symposium.

Alexander van Oudenhoven and Arjen Luijendijk

THE MERITS OF INTERDISCIPLINARY RESEARCH

NATURECOAST PERSPECTIVE

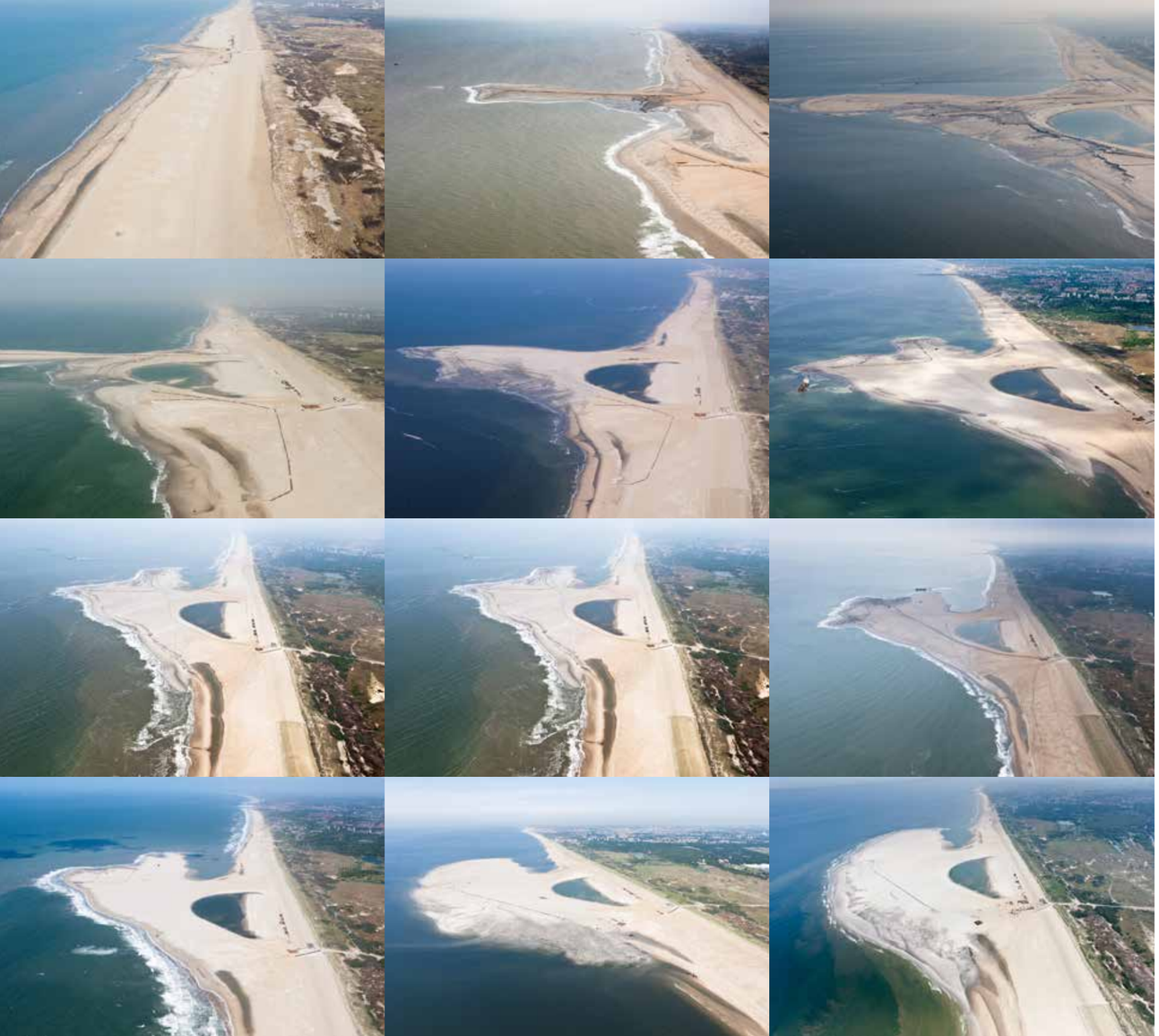
Before handing over to key experts and end-users with their reflections on the NatureCoast program and the pilot Sand Motor, allow us to reflect on our own experience, from the perspective of post-doctoral researchers with the task of integrating, applying and disseminating the research done by twelve PhD researchers. We will do so in four steps, guided by the four pictures on the left page.

Implications for design connect us all
What connects twelve keen, young minds, each working at different institutes and on very specific topics? We always emphasized the potential implications and the context of the research, specifically for future designs of sandy solutions. Thanks to NWO-TTW, we could organize numerous writing weeks, field trips, and in-depth discussions, which made each researcher aware of the usefulness of their own work. It also opened their eyes to other scientific disciplines and ways of thinking. For example, when we asked each researcher to design the "Sand Motor 2.0" based on their own findings (Figure 1), we ended up with apparently wildly different ideas, which after discussing, did not seem to differ that much in the end. Unfortunately, producing concrete outputs, such as papers and ongoing collaborations, proved challenging. After such meetings, the PhD researchers understandably prioritized their own project above "side-projects" related to integration. This is an inevitable consequence of organizing a research project around 12 individual PhD research projects.

End-users make it "real"
Regular and in-depth interaction with end-users was a fundamental part of the NatureCoast program. The end-users made the research "real", by offering practical knowledge and raising valuable questions to better understand the the Sand Motor's behavior. During these biannual end-user meetings, our researchers pitched their latest findings to all, before sharing more detailed findings and questions with end-users involved in that particular research topic. Although these meetings were usually attended by between 50 and 80 people, it proved challenging to mobilize an equal number of end-users for each research topic, which sometimes disappointed the PhD researchers. However, many successful collaborations did result in co-authored scientific papers and guest presentations at the end-users' institutes. Moreover, the interaction has made the PhD researchers more aware of the implications of their research. It also provided them with an excellent opportunity to present themselves to their potential future work field. The final symposium (Figure 2), which was held in the summer of 2017, was attended by over 150 people, 30 of whom came from abroad. Interestingly, only one-third of all attendees were from academic institutes. About the same number came from private companies, followed closely by policy institutes and applied research institutes.

In dialogue with society
Apart from end-users, NatureCoast researchers were regularly subjected to questions and requests from other members of society, who seemed to have an almost insatiable desire to learn more about the Sand Motor. Through dozens of excursions each year, we were able to spread the word about sandy solutions and scientific research (Figure 3). In addition, many researchers were invited to give guest presentations and attend discussions with numerous stakeholders, ranging from policy administration, restaurant managers, the Rotary and artist collectives. Although it demanded time and effort from our researchers, the benefits of this dialogue with society are twofold. NatureCoast researchers became very adept at explaining and communicating research in an engaging and accessible way. In addition, during the past five years our researchers spread the word about Building with Nature and the Sand Motor, while speaking at scientific conferences, invited workshops, and while engaging with foreign delegates visiting the Sand Motor on location.

Integration makes it truly interdisciplinary research
Throughout the book, many end-users have emphasized numerous innovative aspects of the Sand Motor and the NatureCoast project. We would argue that one of the most important innovations of NatureCoast is the fact that a separate work package and, thus, resources were allocated for integration, both within and between work packages. This integration had the overarching goal of connecting research to end-users and society at large, as well as exploring the opportunities for using the new knowledge to contribute to sandy solutions elsewhere in the world. Although this approach presented us with challenges, and we might at times have demanded too much from the researchers and their supervisors, it has been rewarding to work in such a pleasant and truly interdisciplinary setting. However, in many ways we have only just begun working together. Many scientific papers are still being written and published, and the PhD researchers are just starting off on their new careers. The NatureCoast program has created a group of truly special people, or, as was stated during the final symposium (Figure 4), "a unique 'breed' of researchers". Researchers who always went the extra mile, with a great affinity for working with end-users and other scientific disciplines, and who always looked for ways to apply their work, while being firmly grounded in society.



Henk Nieboer – Ecoshape

THE SHOWCASE EFFECT

END-USER PERSPECTIVE

Henk Nieboer is the director of the Ecoshape foundation, which manages the innovation programme Building with Nature, and Consultant at Witteveen+Bos. Henk is also member of the board of Deltares, Aventus, Cleantech Center, and W+B pension fund.

The growing world population and our increased welfare is putting an ever-increasing burden on the world's natural systems. Resources and once fertile soils are being depleted, and biodiversity is decreasing worldwide. Natural systems, however, do not exist in isolation; they also provide services to us (ecosystem services).

To solve societal problems while preserving or even improving the delivery of ecosystem services, we need better solutions than before. Solutions that take nature and natural processes as a starting point and not as boundary conditions. That means we should be building with nature.

In the Netherlands the Ecoshape Foundation is coordinating the innovation program "Building with Nature." From the project's start in 2008, Ecoshape has considered the Sand Motor as an important living lab for Building with Nature concepts. As a consequence, we have always encouraged, supported and followed the NatureCoast program with great enthusiasm.

The focus of Ecoshape and its partners is very much on applied knowledge. Universities, research institutes, public and private parties join forces to create solutions based on Building with Nature principles; they study and monitor the behavior of the solutions and the system and try to learn from it. These results are translated into generic guidelines which are made available through the Ecoshape website (ecoshape.org).

Applied knowledge needs to be supported by fundamental knowledge. For this reason, Ecoshape has always supported the NatureCoast program and strives to learn from it. One of the strengths of NatureCoast is that is has been an interdisciplinary program. Building with Nature is a practice that requires that scientists and practitioners from various disciplines work together and, thus, create results together.

NatureCoast has concentrated its research on the Sand Motor. NatureCoast researchers have discovered that the main success factors of the Sand Motor were innovation, interdisciplinary collaboration, and the showcase effect it had for the principle of Building with Nature.

That coincides with the main objective of Ecoshape: to stimulate innovation through interdisciplinary research work on showcase projects. The Sand Motor and the NatureCoast research program have become examples of how to create a stimulating environment for research, development and innovation, with inspiration for many, not least beyond the borders of the scientific community!

Figure 1. (left page)
A chronological compilation of aerial photographs of the construction of the Sand Motor in the period from March 3rd until July 5th, 2011.

Jaap Kwadijk – Deltares

LEARNING FROM NATURE-BASED SOLUTIONS

END-USER PERSPECTIVE

Jaap Kwadijk is Director of Science at Deltares, the Dutch institute for applied research in the field of water, subsurface and infrastructure. He is also a part time professor of Modeling Water Management and Climate at the University of Twente.

In view of the recent discussions on sea-level rise, I think the publication of this book is "just in time." Over the last two years it has become increasingly clear that the possibility of accelerating sea-level rise may become the greatest challenge for low-lying coastal areas like The Netherlands. If this rise occurs, solutions to cope with it need to be found quickly. Engineering approaches that make maximum use of natural processes, such as the Building with Nature approach, seem to have the largest potential. However, our experience with these solutions is limited. NatureCoast, the research program that studied the Sand Motor, one of the largest experiments with Building with Nature, has added to our knowledge. Such experiments and knowledge are urgently needed.

Pollard and DeConto published a paper in *Nature* in 2016 that woke the scientific community to the issue of sea-level rise. Their results suggested that global warming could cause large parts of the ice sheet of Antarctica to become unstable and slip into the sea more rapidly than has been anticipated. This slipping would increase the contribution of Antarctica to sea-level rise to more than a meter this century. And once this mechanism has started, it will probably prove to be irreversible.

For many years, the debate about global sea-level rise had focused on differences in the order of decimetres, and the contribution of Antarctica was expected to be quite small during the century. Today, the uncertainty regarding sea-level rise during the century is in the order of a meter, or even more, with Antarctica possibly becoming the largest contributor.

On top of that, a recent paper published in *Nature* (Trusel et al. 2018) concluded that the Greenland ice sheet is also melting faster than ever before. In October 2018 a special report of the United Nations' Intergovernmental Panel on Climate Change concluded that the remaining time window to cut greenhouse gas emissions so that global warming is limited to 1.5 degrees Celsius is now disturbingly narrow, 12 years. Unfortunately, we are not yet on track to reach these goals, as the recent figures on emissions show that global carbon emissions in 2018 have jumped to an all-time high. So my message is crystal clear, we need to accelerate adaptation.

Over the last two centuries, engineering has been extremely successful in sustaining human life in deltas by learning from countless failures and making subsequent improvements. The need to keep pace with increased urbanisation, rapid climate change, and sea-level rise makes the sustainability of deltas an immense challenge. This represents such a large challenge that we need to rethink the capacity of our classical engineering approaches to keep deltas liveable in the 21st century.

The concept of nature-based solutions is often mentioned as the silver bullet solution. And there are good reasons for that. They can be cost-effective ways of reducing vulnerability, and they offer multiple benefits to the environment and local communities. Think of sustaining livelihoods, improving food security and sequestering carbon. This explains why nature-based solutions are also attracting the attention of green investors. But our understanding of these solutions and our experience with them is still very limited. Initiatives are often undertaken without a sound scientific basis. Pilots are also generally too small to judge whether the solutions are applicable for larger areas. This is unfortunate, as the importance of learning by doing can hardly be overrated. It took us 200 years of trial and error with traditional engineering to arrive at the high level we currently have. We do not have another 200 years to learn.

When designing these nature-based solutions, we need to seek multiple benefits. Climate change solutions will never be done exclusively to deal with climate change, but only where they also meet other societal goals. We urgently need to identify how adaptation using nature-based solutions can help societies achieve their wider sustainability goals – for health, well-being, regeneration, equity, and so on. In this way, we can make the societal relevance of responding to climate change clear.To maximize their impact, experiments need to bring together climate science, earth system science, and environmental science. This will improve the ability of scientists to make integrated predictions about the impact of large-scale nature-based solutions. This will also create a generation of scientists with more experience with multidisciplinary research.

NatureCoast delivered much of this. It evaluated a full-scale experiment, not only addressing engineering aspects, but also providing guidance for implementing nature-based solutions at this large scale. The stories about this research experiment are spectacular and will attract young scientists. The many kite surfers and walkers show the pleasure that nature-based solutions can bring.

Figure 1.
Panel "Reflection on interdisciplinary research" at Final Conference NatureCoast in September 2017 at TU Delft.
From left to right: Roeland Allewijn, Rijkswaterstaat; Baukje Kothuis, TU Delft; Henk Nieboer, Ecoshape (Page 188); and Jaap Kwadijk, Deltares (Page 190).

Roeland Allewijn – Rijkswaterstaat

MULTIDISCIPLINARY RESEARCH TO INFORM SOCIETY AT LARGE

END-USER PERSPECTIVE

Roeland Allewijn is Director Safety and Water Use at Rijkswaterstaat, department Water, Transport and Living Environment (WVL).

For *Rijkswaterstaat*, the Sand Motor is unique, and that has much to do with the concept "Building with Nature": working with nature and letting nature do part of the work. That is a kind of "flip-thinking", as it differs strongly from traditional hydraulic engineering. The Sand Motor is one of the first really large-scale applications of the Building with Nature concept. In addition, the idea of a "sand motor" has rarely been implemented in practice. It is therefore truly unique that we dared to do this in the Netherlands, and on such a scale.

While *Rijkswaterstaat* is formally the end-user of the knowledge developed in this research program, who is ultimately the end user of the Sand Motor? I think it is society, with our overarching goal of wanting to live safely in the Netherlands. Of course, a large project like this only becomes worthwhile when a good cost-benefit ratio has been established, and making this analysis was one of our tasks at *Rijkswaterstaat*. Beyond the cost-benefit analysis, a key task for us as the manager of the Dutch coast is to keep our knowledge of flood risk management cutting edge. We endeavor to fulfill that task more and more from the perspective of ecological responsibility and sustainability. That is the future goal.

Rijkswaterstaat is part of the so-called "Golden Triangle" in the pilot Sand Motor: knowledge institutions such as the universities and Deltares, governmental parties tasked with managing and implementing the project, and market parties - the hydraulic engineers and the engineering firms. In order for this Golden Triangle experiment to work, input from each of these three legs was essential. One can propose everything, but for a plan to really come together one needs to know about the entire coastal system as well as have solid modeling results and field measurements. The scientific basis is necessary for a successful project.

Multidisciplinary research at the Sand Motor is crucial for *Rijkswaterstaat*. Our assignments are no longer one-dimensional, and today we no longer look just at hydraulic aspects and the morphological system. We also require insight into the ecosystem, and need to know how to optimize a design from a sustainability perspective, for example making it energy neutral. Knowing how to deal with the environment and with involved stakeholders is also indispensable. In such complex projects, the different aspects of "hard" natural science and social science inevitably come together. As a result, these projects can only be completed by combining research from different disciplines.

As manager of the Sand Motor I would like to mention two specific things that NatureCoast has contributed to. First, the NatureCoast researchers produced high quality data. In addition, and directly linked to this, they set up an excellent data management system. NatureCoast paid close attention to not only collecting and storing the data properly, but also making it easily accessible to everyone. As an end-user, we can continue to build on this after the research program, and that is of immense value to us.

Figure 1. (right)
Integration by postdocs was envisaged as mediating the influence between Knowledge development and Utilization in the original NatureCoast proposal. Revisions for the future are proposed in red based on experiences with the NatureCoast program.

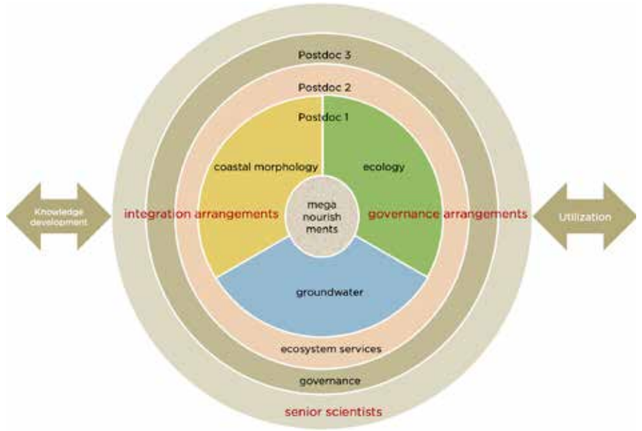


Figure 2. (below)
The Mega Perturbation Experiment, MEGAPEX2014, conducted on the Sand Motor in September and October 2014, an inter-organisational, national and international multidisciplinary collaboration that represented a milestone in NatureCoast integration. (Photo by Timothy Price)

Jill Slinger – Delft University of Technology

THE INTERDISCIPLINARY CHALLENGE

ACADEMIC PERSPECTIVE

Jill Slinger is an associate professor at the Faculty of Technology, Policy and Management at Delft University of Technology. She was involved in the development of the NatureCoast program proposal and has worked to integrate the governance research within the program.

Interdisciplinary research can be compared to the ancient craft of weaving a fishnet. The knot used for this net is obviously important. The quality, size and form of the final product depends on the skill of the weavers, the choices they make in the design and their ability to picture how the different components will come together to form a useful whole. By analogy, when conducting a large, multidisciplinary project, the scientific methods (the knots), the skills of the scientists (the weavers), the initial choices made for the project design, and the scientists' collective ability to integrate their findings across disciplines to form a synthesized whole, will determine the quality, number and form of the final products. In the NatureCoast project, scientists from six disciplinary research themes (see Chapter 1) met with the end-users to design the research approach at the proposal stage. From the outset, they hoped that the broad approach would produce useful interactions between knowledge development in different disciplines and utilization in the field (Figure 1). But, did the anticipated integration occur, and did it produce the desired interactions between the development of knowledge and practical applications?

To address this question, let me give two positive examples, as well as one critical note. First, there is the six-week multidisciplinary field measurement campaign, the Mega Perturbation Experiment, or MEGAPEX2014, conducted on the Sand Motor in September and October 2014 (Figure 2; also Page 74). The campaign was set up in conjunction with *Rijkswaterstaat* and the NEMO research project of Delft University of Technology (Page 19). It represents a triumph of inter-organizational, national and international collaboration that generated a unique set of data covering bathymetry, sediment composition, currents, the surf zone, beach and dune morphology, dune vegetation, fish and bird counts, groundwater levels, geochemistry, wave height, salt spray, and sand transport into the dunes. The field measurement campaign succeeded in forging bonds between the PhD researchers, postdocs and their supervisors, particularly those focused on understanding the biogeomorphological evolution of the Sand Motor. The campaign transformed the NatureCoast project from a series of individual research pathways towards a concerted, common research endeavor, and represents a significant milestone in research integration.

Second, we have research at the governance - ecosystem services interface that produced a scientific paper by Van Oudenhoven et al. (2018) entitled "Mind the Gap" (Page 138). Unlike the MEGAPEX2014 campaign, which integrated different technical fields, this project attempted to bridge the hypothesis-based and social constructivist-based sciences. The paper represents the culmination of a shared research endeavor between the PhD researchers studying governance (Chapter 2), postdocs on governance and ecosystem services (Page 138), and senior scientists. During the research for this paper, a number of issues had to be resolved: consistent text coding in the governance study, ethical considerations (e.g., potentially using interview data for purposes other than originally indicated to the interviewees), and correctly interpreting ecosystem services terms used in the interviews. Contrasts were discussed between normative interpretations of the ecosystem services concept and the "logic of appropriateness" that underpins strategic decision making. This gradually led to a novel conceptualization that could be used to understand whether and how ecosystem services played a role in decision making on the Sand Motor. In my opinion, this research exemplifies the interdisciplinary integration hoped for when the NatureCoast project was first proposed.

On a critical note, senior scientists contributed little to integration in the NatureCoast program. This was not from lack of interest or an unwillingness to collaborate across disciplinary divides, but rather inherent to the way research is funded. Only the senior scientists in the project management team received (limited) compensation for their time, and others received no funding. This limits the time and effort that they can devote to interdisciplinary tasks. In my view, this is the single factor that most limits enhanced integration and interdisciplinary collaboration in Dutch science today.

In conclusion, the anticipated interactions between knowledge development and utilization were seen in MEGAPEX2014, the bi-annual user meetings, and the paper on integrating governance and ecosystem services. However, interdisciplinary integration could be improved by specifying integrative arrangements and governance arrangements at the research proposal stage in future (indicated in red in Figure 1), and by funding the involvement of senior scientists in interdisciplinary integration.

Mark van Koningsveld – Van Oord & Topsector Water

NATURECOAST AS ONE OF THE FIRST “LIVING LABS”

END-USER PERSPECTIVE

Mark van Koningsveld is a professor of Ports & Waterways at Delft University of Technology and Manager R&D Engineering at Van Oord. Mark is also secretaris Topteam at Topsector Water & Maritiem.

The NatureCoast project was a unique project because it brought together several puzzle pieces in space and time. The pilot Sand Motor pilot was conceived, designed and implemented at a time when the EcoShape consortium was actively promoting the “Building with Nature” concept. This had already resulted in well-established relationships between researchers from different backgrounds from all over the Netherlands, as well as with practitioners. This in turn contributed to a basic research agenda for the Sand Motor that truly integrated different disciplines, and was also broadly supported. This broad support resulted in substantial co-funding contributions by parties like Rijkswaterstaat, Van Oord, Boskalis, Deltares and Wageningen Marine Research (contributing €1.4 million cash & in-kind out of a total project budget of €5.1 million). This provided a huge boost to the project.

The NatureCoast project was coupled to an unprecedented field experiment in the form of the pilot Sand Motor. This resulted in a tangible research object, where the researchers could physically convene and discuss. Today, the term “Living Lab” is frequently mentioned, which is an instrumented physical environment for research and evaluation. When NatureCoast started, this was still not such a common concept, but policy makers currently expect Living Labs to help bring academic research closer to practice (vertical integration). Furthermore, working on a physical pilot project is expected to encourage researchers from different disciplines to work together more closely (horizontal integration). I am sure that positive experiences during the NatureCoast project contributed to the current popularity of Living Labs.

Due to the nature of acquiring research funds, and the generally very low success rates, it is normally extremely difficult to obtain funding for a field experiment on the scale of the Sand Motor. Fortunately, this worked almost perfectly in the case of NatureCoast. It must be said that Delft University of Technology was very proactive, starting some of the valuable bathymetry measurements even before the final grant was awarded.

Data was shared in a common format, and a centralized database was successfully constructed. This was again presumably due to the active role of the EcoShape consortium at the time of the NatureCoast project. Normally, developing a shared database takes a lot of time, but the OpenEarth system already developed within EcoShape was adopted, meaning that a well-developed system including clearly documented protocols was available right from the start. This made it easier to store all data from NatureCoast and make it available to researchers during and even after the NatureCoast project. Just as NatureCoast learned from previous work conducted within EcoShape, the NatureCoast example has now become a useful guide for subsequent projects and proposals. This approach, developing a project based on preceding ones, is clearly working and should be continued.

All these elements together have surely contributed to making the NatureCoast project so successful, and as a result the NatureCoast approach has become an example for many research programs that are being developed. The benefits of aligning research programs, field experiments and data management have clearly been demonstrated, and I hope that we will see more projects in the near future that use a similar approach.

Todd Bridges

MESSAGES FOR THE INTERNATIONAL COMMUNITY

EPILOGUE

Todd Bridges is the U.S. Army's Senior Research Scientist for Environmental Science. He is the National Lead for the Engineering With Nature® initiative of the U.S. Army and U.S. Army Corps of Engineers. This initiative includes a network of research projects and field demonstrations to promote sustainable and resilient infrastructure systems.

The Sand Motor is an extraordinary project, as evidenced by its scope, the diversity of its components, and the investment in research that was integrated into the project. As such, it provides an appealing vehicle for illustrating four important messages for the international community.

Big problems call for big solutions. There is some comfort to be found in small projects. Small projects may (sometimes) be more manageable. Large projects may (sometimes) entail more execution risk. However, many of the challenges we confront in the context of water infrastructure, coastal management, flood risk management—e.g., climate change, sea-level rise, coastal storms—cannot be addressed in a piecemeal fashion. These and other challenges pose big problems that call for big solutions, which can operate over large spatial scales, include many component parts and facets, and unfold and mature over long timescales. For these reasons and others, developing big solutions requires the use of a systems approach to project development. Becoming successful overtime with executing big solutions will involve some "learning by doing," at the individual and organizational level, as experience is gained in developing and implementing comprehensive, system-scale solutions.

Innovation is achieved by granting yourself license to experiment. Innovation is hard. The easy path is to copy yesterday's project to address tomorrow's problem. The easy path may work over the short-term, but eventually the easy path ends in failure and sometimes catastrophe. For organizations that are responsible for infrastructure, innovation is the outcome of intentional, coordinated decisions at multiple levels — in other words, it is an organizational choice. In a sense, organizations must grant themselves permission or license to try something different, accepting and managing the risks involved in enterprise-level experimentation. The "reward" for taking those risks is discovering a new and better solution. It may be difficult for organizations to accept the fact that there will be failures (or, if you prefer, less than fully successful projects) along the path to innovation — however, "nothing ventured, nothing gained." One of the most difficult steps on the path to innovation is institutionalizing a new discovery or invention, e.g., translating new knowledge and/or technology into new policy and standards. It must be understood that innovation is not truly achieved until the new approach is put into practice.

People want and expect diverse value from projects. There may have been a time when everyone was satisfied with a project that delivered a single-purpose value, e.g., a flood risk reduction project that produced positive economic benefits in the form of avoided damages, and nothing more. Currently, government authorities, project sponsors, partners, stakeholders and the public increasingly expect projects to produce multiple streams of value, including environmental and social value in combination with economic benefits. The exciting challenge of the 21st century is to plan, design and build such multi-purpose projects. This presents many specific challenges to practitioners, notable among these is the issue of governance. By their very nature, multi-purpose projects will involve more partners, interests, and stakeholders. As a consequence, the social complexity and dynamics of the project will be more central to the success of a solution and a project team's membership and capabilities will need to reflect this fact.

Value is magnified by translation. The Sand Motor project has many lessons to teach practitioners working on sandy coasts. Making the effort to learn those lessons and then share them with others (as done through this book and other products) provides a means for others outside the project team to learn, apply and produce value in the form of new projects. It is commonly understood, though perhaps not universally, that solutions to complex problems along sandy coasts cannot be produced with a "cookie cutter" -what worked in one place/context may not work in another- because the particulars matter. However, there are many types of lessons. One lesson illustrated by the Sand Motor, and other projects around the world, is the great potential to produce value through strategic placement of sediment, i.e., placing sediment at one location with the plan that natural processes will move it to other locations to achieve specific purposes - leveraging nature's forces rather than trying to control or defeat them. There is a great need and opportunity for action, worldwide, to create value by restoring landscape features and processes along coasts and rivers that depend on sediment. By sharing our experiences in implementing these projects across disciplinary boundaries and organizational borders, we will magnify the value of our collective efforts across the community of practitioners worldwide.

Stefan Aarninkhof

THE SAND MOTOR: STEPPING STONE FOR A COASTAL CLIMATE LAB?

EPILOGUE

Stefan Aarninkhof is a professor of Hydraulic Engineering at Delft University of Technology. He holds the chair of Coastal Engineering, which he took over from emeritus professor Marcel Stive. Stefan Aarninkhof was both involved with the genesis of the Sand Motor and NatureCoast, and lead the NatureCoast project during the final phase.

Worldwide, the Sand Motor is considered an icon of Building with Nature. Its unique character and ever changing coastal landscape raise the permanent interest of scientists, engineers and managers. Over the years, the Sand Motor has taught us many important lessons.

Lessons on the importance of early stakeholder engagement. Long before the preparation of any engineering design, the Sand Motor initiators showed the wisdom to engage key stakeholders in a pre-project ambition agreement. This agreement, signed in 2008, explicitly stated distinct objectives for coastal safety, nature and recreation, and innovation. In the years that followed, this multi-objective approach governed key decisions throughout project development and shaped the Sand Motor as we know today.

Lessons on the importance of a full-scale demonstration project. Both the complex interplay of morphological and ecological processes, as well as societal response to large-scale coastline changes can only be studied in the real world. Besides, a tangible pilot project encourages focus of research efforts, and helps to bridge the gap between academic science and coastal zone management practice.

Lessons on the importance of multidisciplinary collaboration. NatureCoast has clearly demonstrated the added value of a multidisciplinary research program. Key to success was the continuous strive for demand-driven research, realised by embedding twelve fundamental research studies in an interactive, interdisciplinary working environment. This resulted in improved awareness of the broader impact of the work. In this way, NatureCoast has played an eminent role in raising the future leaders in coastal science and engineering.

These are the lessons we should take along while addressing the major challenge we are presently facing: climate change. Projections for climate-induced sea-level rise range from 0.4 to 2 m in 2100, depending on uncertainties in the collapse of Arctic ice sheets and the feasibility of the Paris agreements on the reduction of CO_2 emissions. Such rates of sea-level rise are associated with an enormous increase in the need for beach nourishments worldwide. For the Dutch coast for instance, Deltares recently estimated an increase of the annual nourishment volume ranging from a factor 3-4 (for a 0.4 m rise) up to a factor 20 (for 2 m sea-level rise in 2100). This corresponds to tens of millions cubic meters per year, worst case well above 100 million m^3/year.

Technically, these volumes are feasible – it was achieved in the past for major land reclamations like the Palm Islands (Dubai, UAE) and the *Maasvlakte II* (The Netherlands). However, many questions arise if assessing the feasibility of such mega-scale nourishment programs for highly-developed, densely populated shorelines: How to optimize the required sand volume and what is the most efficient way to place it in the nearshore? How to minimize ecological impacts and maximize benefits for nature? How to accommodate added values for other functions like recreation and freshwater supply, and how to predict the long-term evolution of these benefits so that they can form the basis for an integral financing scheme? And finally, how to generate societal support for sandy coastline extensions as a sustainable measure for climate change adaptation?

Bearing in mind the lessons of the Sand Motor, the time is there to start preparations for a Climate Lab Coast: a large-scale seaward extension of the shoreline, along a 15-25 km stretch of coast with the goal to create a climate-resilient coast while adding value for nature, economy and society. Such full-scale pilot implementation would enable us to address the questions raised above. It will yield indispensable insights in the eco-morphological, economic and societal feasibility of large-scale nourishment programs for different sea-level rise scenarios, including the maximum level beyond which upscaling of present-day policies is no longer possible and fundamentally different solutions are to be explored. In this way, we are timely prepared for the nourishment of hundreds of kilometres of shoreline that need to be treated afterwards.

I wish that future generations of coastal engineers, scientist and managers will conclude that the Sand Motor and its associated NatureCoast program have been the stepping stone for successful implementation of large-scale nourishment programs, as a sustainable solution for climate change adaptation along highly-developed, densely populated shorelines.

Groups of Grote Sterns (Sandwich Tern) and Visdieven (Common Tern) visiting the Sand Motor for a few days before heading to warmer regions. One of the Sandwich Sterns (ring number: W-N75) spends the Dutch winter period in the southern hemisphere where he has been seen in Namibia (Source: birdring.nl). (Photo by Marius van der Flier)

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The Grote Mantelmeeuw (Great Black-backed Gull; ring number: JYY84) is a returning visitor of the Sand Motor. Since its birth in Nordjylland, Denmark, he visits the Sand Motor every year from July to November. (Photo by Marius van der Flier)

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COLOPHON

THE SAND MOTOR: A NATURE-BASED RESPONSE TO CLIMATE CHANGE
FINDINGS AND REFELECTIONS OF THE INTERDISCIPLINARY RESEARCH PROGRAM NATURECOAST

Edited by *Arjen Luijendijk and Alexander van Oudenhoven*

Production *B Business Energy, Amsterdam*
Graphic design & cover design *steef liefting*
English language advice *Sören Johnson*
All interviews by *Baukje Kothuis*

Publisher *Delft University Publishers, TU Delft Library*
Printing *Quantes Printers, Rijswijk*

Publication of this book has been funded by *NWO-TTW*: Dutch National Science Foundation - Applied and Engineering Sciences (formerly NWO-STW) as part of Perspectief Program NatureCoast (P11-24).

NWO | Applied and Engineering Sciences

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NUR 950
ISBN 978-94-6384-021-7

Special thanks to
Matthieu de Schipper for proofreading the final draft of this book. His sharp eye and constructive feedback have been indispensable.

Boskalis, Deltares, Province of South Holland, Rijkswaterstaat, Van Oord and Wageningen Marine Research, for making the contents of this book possible by funding the NatureCoast program. In particular, Rijkswaterstaat for sharing all data of the monitoring program.

All end-users of the NatureCoast program for sharing their knowledge, data and time. We hope that this book does justice to the research to which you contributed so actively and enthusiastically.

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- Pages 184 (Figures 2 and 4) and 190:
  Deltares, Welmoed Jillerda.

For all other images and photos courtesy is mentioned in the caption of the figure when requested, or was freely granted by authors, editors and interviewees concerned.

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NatureCoast is the largest research program that focused on the Sand Motor, a large sandy peninsula, constructed in 2011 on the Dutch North Sea coast near The Hague. This unprecedented pilot project involved placing 21.5 million m³ of sand on and in front of the beach with the aim that it would spread along the coast. The Sand Motor is a unique beach nourishment due to its size, the design philosophy behind it, and its multifunctionality. It combines the primary function of coastal protection with the creation of a new natural landscape that also provides new leisure opportunities. From the outset, "learning by doing" has been a crucial part of the project and NatureCoast was an integral part of this. Because of its innovations, the Sand Motor has triggered considerable political and scientific interest from all over the world. Broad research consortia were formed to conduct interdisciplinary research on the Sand Motor.

The NatureCoast program was carried out by a consortium of knowledge institutes and universities, and the research was conducted in cooperation with end-users from private companies, research institutes and governmental organizations. The Dutch Technology Foundation (NWO-TTW) provided the largest share of the project funds. The research in NatureCoast focused on six themes: coastal safety, dune formation, marine ecology, terrestrial ecology, hydrology and geochemistry, and governance. This book presents countless facets of the Sand Motor, but we also hope it demonstrates the scientific merits of interdisciplinary research and how, ultimately, societies can benefit from it.

NUR 950
ISBN 978 94 6384-021-7

Applied and Engineering Sciences

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RESEARCH PROGRAM NATURECOAST – Luijendijk and Van Oudenhoven (eds)