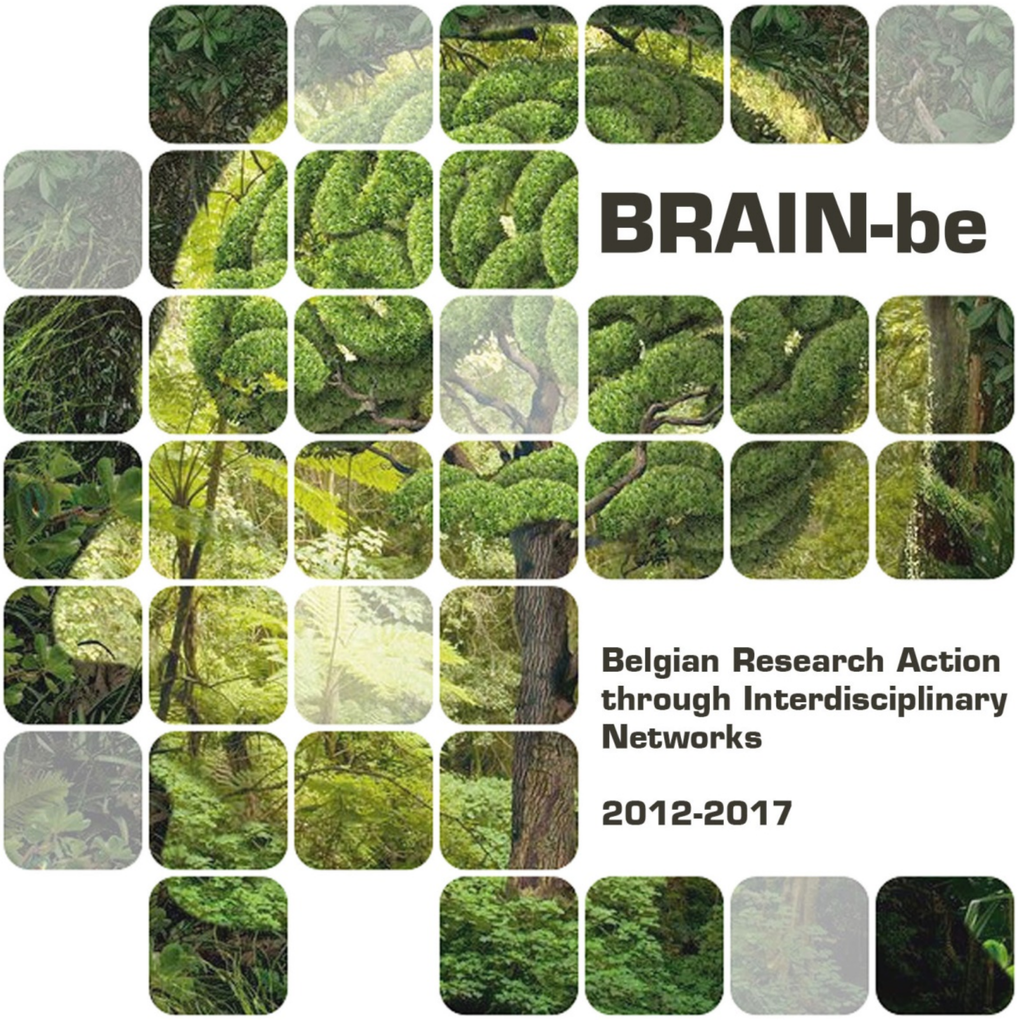

TILES

Transnational and Integrated Long-term Marine Exploitation Strategies

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TILES

Transnational and Integrated Long-term Marine Exploitation Strategies

Contract - BR/121/A2

FINAL REPORT

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SUMMARY

Context

Mineral and geological resources can be considered to be non-renewable on time-scales relevant for decision-makers. The sustainable management of these invaluable resources requires a thorough and careful balancing of available quantity and quality *versus* rapidly changing societal and economical needs. The need for such an approach is recognized in the EU's **Raw Materials Initiative,** which highlights the optimization of the geological knowledge base as a key element in ensuring sustainable supplies from within the EU borders. Comprehensive knowledge on the distribution, composition and dynamics of geological resources therefore is the backbone of long-term strategies for resource use in a rapidly changing world.

During the last decade, socio-economic demands for marine aggregate resources in the North-East Atlantic or OSPAR region have increased at an unprecedented pace. During the past few years, hundreds of millions m^3 of offshore sand and gravel have been extracted for coastal maintenance, harbour extensions and onshore industrial use. For two reasons, future aggregate demands will be even higher. First, increasing volumes of nourishment sand are needed as accelerating **sea-level rise** will leave our coastlines ever more vulnerable. Secondly, vast quantities of sand and gravel will have to be extracted to realize the **large infrastructural works** that are the key components of many visions on **coastal zone and offshore development**. Some of these resource demands are already incorporated in **Marine Spatial Plans**. The feasibility of these plans depends on the availability and sustainable supply of sand and gravel.

Objectives

With direct relevance to the Belgian and southern Netherlands part of the North Sea (BPNS/sNPS), the ambition of TILES was to:

(1) Develop a **resource decision support system** (DSS) containing ***tools*** that link 3D geological models, knowledge and concepts to 4D numerical environmental impact models. Together they quantify natural and man-made changes to define sustainable exploitation thresholds. These are needed to ensure that recovery from perturbations is rapid and secure, and that the range of natural variation is maintained, a prerequisite stated in Europe's **Marine Strategy Framework Directive**, the environmental pillar of Europe's **Maritime Policy**.

(2) Provide **long-term adaptive *management strategies*** that can be used for all non-hydrocarbon geological resources in the marine environment, locally and more globally.

(3) Propose **legally binding *measures*** to optimize and maximize long-term exploitation of aggregate resources within sustainable environmental limits. These proposed measures feed into policy plans that are periodically evaluated and adapted (e.g., Marine Spatial Planning and the Marine Strategy Framework Directive (MSFD), being Federal Authority's strategic priorities).

Methodology

The project objectives were achieved through **interdisciplinary** and **transnational** research on the nature and dynamics of geological resources and on the environmental impact of extraction. State-of-the-art **transnational 3D geological models** were developed by transforming layer models, defining stratigraphic unit boundaries, into so-called **voxel models** (consisting of '*tiles*' or volume blocks) and assigning to each voxel lithological and other resource-relevant characteristics. A

methodological framework was developed for marine applications, combining borehole data and seismic lines (Hademenos et al., in press). Models and data were subjected to uncertainty analyses, a necessary step to assess confidence in data products, and critical to detect '*true*' seabed changes in environmental monitoring. The geological models were coupled to **4D numerical impact models** quantifying natural dynamics and forecasting environmental impact of extraction in scenario analyses. A **multi-criteria DSS** was built as a web application. It allows producing geographic output from specifying **flexible criteria** on underlying data and their uncertainty. Aim was to adequately reflect user preferences on the different attributes incorporated in the voxel model and to combine this with third party data. The overall workflow was published as a book chapter promoting oceanographic and marine cross-domain data management for sustainable development (Van Lancker et al., 2017). Dealing with data uncertainties and data quality in DSSs was discussed in De Tré et al. (2018).

Results

Extensive, but **comprehensive databases** have been compiled on the lithology of BPNS and sNPNS. **Data portals** provide free access to the original and newly standardized and quality-controlled data. Data quality aspects in marine sediment databases were published in van Heteren & Van Lancker (2015). A **portfolio of sediment and habitat maps** can be produced, some of which are already publicly available through the **EMODnet**-Geology and Seabed Habitats data portal. Such maps have been the basis of many MSFD assessments in Europe.

The resource suitability of the geological layers within the Quaternary was evaluated. For the BPNS, a new Top-Paleogene surface has been published (De Clercq et al., 2016). Since it is the basis of the Quaternary, hence the theoretical limit of exploitable sands, it is an important reference layer for the future extraction of marine aggregates. The Pleistocene is highly variable in lithological characteristics and thick reserves only occur within the 12 nm zone; the Lower Holocene, representative of an estuarine environment, is limitedly present with an important preservation only in the near coastal Ostend valley. The Upper Holocene is representative of the present-day hydrodynamic regime; offshore the highest probabilities of medium to coarse sands are found. Extraction is recommended in this layer only. Thick deposits (> 10 m) are restricted to the sandbanks.

As a world premiere a **transborder voxel model** of lithological characteristics has been produced for the BPNS and sNPNS. It reflects the relative scarcity of sand in the Belgian part, and the rapid increase of sand resources towards the northeast. This is related to the overall geology of the area: the BPNS lying on top of the London-Brabant Massif, whilst The Netherlands being part of a larger sedimentary basin. The influence of the Rhine-Meuse river system, depositing coarser sands, diminishes from east to west.

Resource extraction scenarios accounted for the first time **geological boundary conditions** (i.e. derived from the voxel model). Particularly, the importance of parameterization and initialization of modelling studies using multiple sediment fractions was demonstrated. Simulating an extraction of ~310×10^6 m^3 in the Upper Holocene layer in the current concession zones, changes in erosion/deposition patterns were shown aligning with the nature of the underlying geological layer. Furthermore**, regeneration/depletion rates** of the seabed in extracted areas were calculated based on actual depth data and vessel-derived extraction quantities. Results showed seabed responses differing with seabed nature, dynamics and extraction intensities. Results of a 16-yr long hindcast of sediment transport further allowed assessing **natural system variability**. Altogether, these analyses assist in minimizing environmental impact: i.e. by spatial optimalization of exploitation, restricting the extent of impacts, and by estimating the recovery potential of the seabed after exploitation.

The **web-based** DSS (http://www.bmdc.be/tiles-dss/) allows extracting resource qualities and quantities within acceptable uncertainty ranges. Information can be retrieved at any location, also within predefined areas such as those designated in the Belgian marine spatial plan. A user can make dynamically a series of tailor-made **suitability maps** that assist in resource assessments. **Cross-sections** are an extra functionality, allowing easy exploration of sandbank architectures, being invaluable for **outreach** and **educational purposes**. The DSS further allows users to anticipate on actual and future resource supplies and needs. **Long-term adaptive management strategies** for the exploitation of geological resources are proposed. They include a reservation of the thickest geological reserves for extraction purposes, a more efficient exploitation, and a better prediction of long-term environmental impacts. Their relevance should be seen in the context of **marine spatial planning**, the **Marine Strategy Framework Directive** and **integrated coastal zone management**. It accounts also for EU recommendations on **'Efficient use of resources'** and **ICES Guidelines** for the management of Marine Sediment Extraction. Finally, TILES output has been used to propose new concession zones and thresholds for extraction that are **legally binding**.

Conclusions and recommendations

The transnational, harmonized geological knowledge base functions as a critical platform for the exchange of data, information and knowledge. Beneficiaries include a wide range of seabed users, hence supporting **Europe's Maritime Policy**, as well as its environmental pillar the **Marine Strategy Framework Directive**. The latter contributes to the integrated management of the marine environment in line with the EU's commitment at the 2002 **World Summit on Sustainable Development** and the sustainable development goals of Agenda 2030.

Recommendations align with a need for **more holistic environmental assessments** incorporating other ecosystem components in the voxel models, as well as more systematically understanding connections and feedbacks within a **coupled human-natural system**. Furthermore, the **socio-economic dimension** need further expansion and weighed against geological and environmental parameters. A **'Code of Sand'** was conceptualized stimulating the debate on addressing **sustainability of marine resources on the longer term**. Technological innovation will be key, but above all cooperative action.

Keywords: Raw materials, Resource Suitability, Sustainability, Decision Support, North Sea

ABSTRACT

Mineral and geological resources are non-renewable on time-scales relevant for decision-makers. The sustainable management of these invaluable resources requires a thorough and careful balancing of available quantity and quality versus rapidly changing societal and economical needs. The need for such an approach is recognized in the EU's Raw Materials Initiative, which highlights the optimization of the geological knowledge base as a key element in ensuring sustainable supplies from within the EU borders. Comprehensive knowledge on the distribution, composition and dynamics of geological resources therefore is the backbone of long-term strategies for resource use in a rapidly changing world.

As a world's first, a trans-border geological knowledge base is now available for the Belgian and southern Netherlands part of the North Sea comprising volumetric 3D pixel ('voxel') models of its subsurface, environmental impact models accounting for geological boundary conditions, a geological data portal and a voxel-based decision support module on marine aggregate extraction. The newly developed tools assist in the preparation of long-term adaptive management strategies, and in scientifically underpinning new legally binding measures to optimize and maximize long-term exploitation of aggregate resources within sustainable environmental limits. Such measures feed into policy plans that are periodically evaluated and adapted (e.g. Marine Spatial Planning and the Marine Strategy Framework Directive, the environmental pillar of Europe's Maritime Policy).

Keywords: Raw materials, Resource Suitability, Sustainability, Decision Support, North Sea

1. INTRODUCTION

Mineral and geological resources, including fossil fuels and aggregates, can be considered to be non-renewable on time scales relevant for decision makers (e.g. Reid et al., 2010; Mudd, 2010). In the vast majority of places, they are more rapidly consumed by humans than they can be replenished by nature, meaning that truly sustainable resource management is not possible (Prior et al., 2012). Comprehensive knowledge on the distribution, composition and dynamics of geological resources, therefore, is critical for developing long-term strategies for optimized resource use.

With growing land-use constraints and depletion of terrestrial aggregate resources, marine sand and gravel have gained importance (ICES, 2016). On a global scale, the stock for these widely demanded bulk resources may be assumed infinite (USGS, 2016). Regionally, though, exploitation is limited by a diversity of interacting social, economical, technological, geological and political factors (Habert et al. 2010).

With increasing needs for sand and gravel, there is an urgency to determine most adequately the quantity as well as the quality of extractable sediments. Additionally, a range of cross-domain variables needs to be assessed before and monitored during and after resource exploitation. Marine management has to consider a growing number of conditions that need to be fulfilled for sand and gravel extraction to be permitted (Radzevičius et al., 2010; ICES, 2016). However, thorough assessment frameworks are most commonly lacking, and environmental impact assessments are rarely based on best available knowledge (Velegrakis et al., 2010). From a resource-management context it is therefore important to deal with a multitude of cross-disciplinary information. This has been the scope of the TILES project.

The study area comprises the Belgian and southern Netherlands part of the North Sea (further abbreviated as BPNS and sNPNS), in total ± 7400 km² (Figure 1). Today, most of the Belgian resources are extracted from sandbanks (Degrendele et al., 2010; Degrendele et al., 2014). In the Netherlands, sand is also extracted in other, usually deeper, morphological settings (Stolk & Dijkshoorn, 2009). From south to north, the area is marked by increasing resource availability. The BPNS is relatively depleted of extractable sand and gravel, with Quaternary sediments being only 10 m thick on average (Le Bot et al., 2005), and less than 2.5 m thick or even absent in many of the swales separating the tidal sandbanks. The sNPNS has only few areas with such limited resource availability, although gravel is rare. Just north of the study area, in the extraction pit for the latest Rotterdam Harbour extension, sand was extracted to about 20 m below the seabed (de Jong et al., 2014).

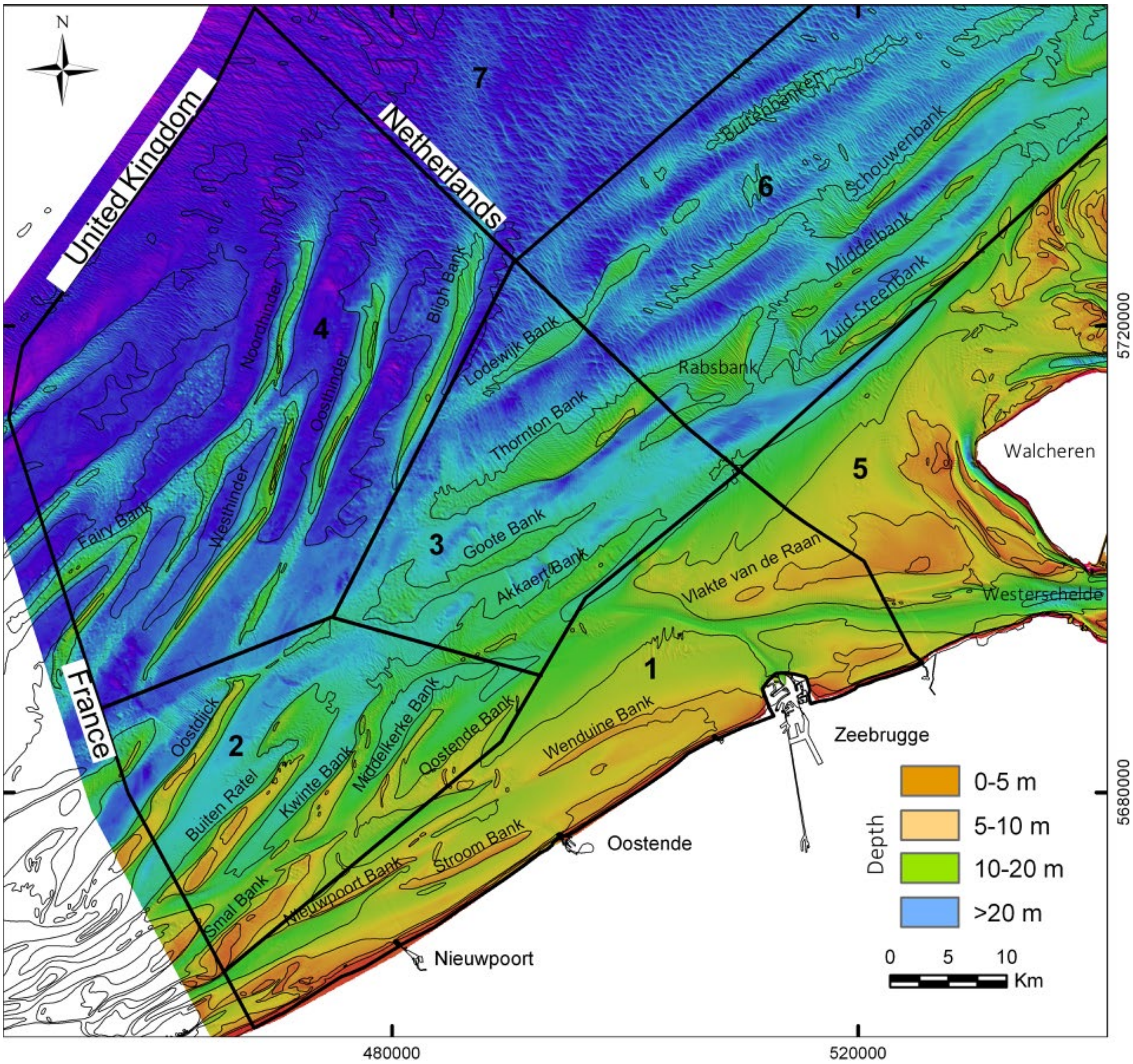


Figure 1. The Belgian and southern Netherlands part of the North Sea, a typical sandbank environment in the southern part of the North Sea, northwestern Europe. The different sandbank systems are: (1) Coastal Banks; (2) Flemish Banks; (3)(6) Zeeland Banks; (4) Hinder Banks; (5) Ebb-tidal-delta shoals; (7) Transition into sandwave fields.

2. STATE-OF-THE-ART AND OBJECTIVES

Sustainable development, as originally defined in the Brundtland Report (WCED, 1987), involves three equally important primary dimensions: safeguarding long-term ecological sustainability, satisfying basic needs, and promoting intragenerational and intergenerational equity (Holden et al., 2014).

To secure the basic needs for the expansion of Europe's Maritime Policy and Blue Growth initiatives, the European Commission provided recommendations in 2008 (with later updates in 2011 and 2012) on resource use through its Raw Materials Initiative. Improvement of the EU knowledge base was recognized to be a key condition to maximize sustainable supply from within the EU (EC Enterprise and Industry, 2010). Comprehensive information on all geological resources was regarded particularly important, not only for stock assessment, but also to underpin the preparation of marine spatial plans (European Commission, 2010; 2011) (e.g. Solar et al., 2012). Recognizing that improved resource assessments by themselves are not enough for extraction sustainability, the flagship initiative Europe 2020 targets an efficient use of these resources, emphasising the need for structural and technological improvements to reach the 2020 milestones (including proper valuation and protection of natural capital and ecosystem services, and resource efficiency as a shared pan-European objective). In both initiatives, scientific support is regarded an essential element in making informed decisions on the exploitation of most-suitable resource supplies that meet the demands of society and member-state economies.

In parallel with the stimulation of economic growth, Europe also recognized the importance of long-term ecological sustainability and required that marine regions need to safeguard a good environmental status (GES). Maintaining or achieving GES is the main 2020 goal of EU's Marine Strategy Framework Directive (MSFD; European Union, 2008). To facilitate monitoring the evolution of any particular region towards GES, a series of descriptors was defined. Related to physico-chemical seabed attributes, seafloor integrity and hydrographic conditions are the most relevant descriptors in the context of the sustainable management of marine sand and gravel (ICES, 2015). MSFD Article 9 stipulates that GES for seafloor integrity refers to the structure and functions of the ecosystems that need safeguarding, ensuring that benthic ecosystems are not adversely affected. GES for hydrographic conditions means that permanent alteration of these conditions, for example due to exploitation, does not adversely affect marine ecosystems. 'Not adversely affected' should be interpreted as meaning that impacts may affect the seabed, but that all impacts are sustainable such that natural levels of diversity, productivity, and ecosystem processes are not degraded (Rice et al., 2012).

Objectives

The TILES project contributes to solving this research question by focusing on the following main objectives:

a) Development of a **resource-tailored decision support system** (DSS) containing tools that link 3D geological models, knowledge and concepts to numerical environmental impact models. Jointly they quantify natural and man-made changes to define sustainable exploitation thresholds. These are needed to ensure that recovery from perturbations is rapid and secure, and that the range of natural variation is maintained, a prerequisite stated in Europe's MSFD, the environmental pillar of Europe's Maritime Policy.

b) Provision of **long-term adaptive management strategies** that can be used for all non-hydrocarbon geological resources in the marine environment, locally and more globally.
c) Proposal of **legally binding measures to optimize and maximize long-term exploitation** of aggregate resources within sustainable environmental limits. These proposed measures feed into policy plans that are periodically evaluated and adapted (e.g. Marine Spatial Planning and the MSFD, being Federal Authority's strategic priorities).

To achieve these project objectives a flexible, integrated and innovative approach was followed, answering the call for adaptive management in an era of rapid environmental change and fast-changing socio-economic boundary conditions. TILES results have a broad and generic applicability in the integrated management of the marine environment and contribute, through their anticipation on Europe's MSFD, to the EU's commitments made at the 2002 World Summit on Sustainable Development.

Societal relevance

There is an urgent need to use the finite aggregates of the BPNS wisely at a time of growing total demand. Anticipating on accelerating sea-level rise during the 21st century, long-term coastal-safety plans are increasingly centred around large-scale nourishment (http://www.kustvisie.be), requiring huge quantities of marine sand. With depletion of land-based resources, sand and gravel for building and infrastructure works is increasingly extracted offshore. Windmill parks need aggregates for erosion protection and to secure cable routings, and they render aggregates within their bounds non-exploitable. The future realization of visions for energy islands, offshore grid platforms (North Sea 'plug sockets'), shelter islands for enhanced maritime safety, recreational islands, new navigation routes, and transformation of sandbanks into islands for coastal protection would require tens to hundreds of millions m^3 of additional sand in short periods, far more than presently extracted annual volumes. Yet, no well-constrained estimates of sand and gravel existed for the BPNS, and no integrated tools were available to assess the environmental impact of large-scale extraction. Such new knowledge on resource availability, its nature and dynamics, and the interaction with human activities, assists in defining legally binding measures on maximum aggregate-exploitation volumes and rates. This is in line with the strategic vision of the Continental Shelf Service of the Federal Public Service Economy, SMEs, Self-employed and Energy, in its advice to the Minister of Economy, Consumer Affairs and the North Sea (Chamber of Representatives of Belgium, 07/01/2013).

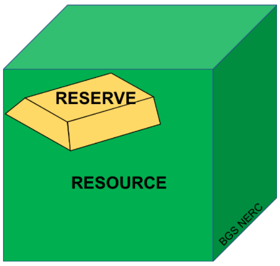
3. METHODOLOGY

With an interdisciplinary partnership of geologists (UG-RCMG/TNO/RBINS), physical modellers (RBINS) and IT professionals (UG-DDCM) originating from governmental organizations and academia, a geological knowledge base underpinned with an effective resource-tailored DSS was developed that can cope with data imperfections and uncertainties and is driven by real-world requirements. Key in this development was sustainable resource management; therefore, sustainability criteria were defined first. In follow-up actions, four work packages (WP) logically worked toward the DSS: (i) Data Information and Knowledge; (ii) 3D Geological Models; (iii) 4D Process Models; and (iv) Scenario Analyses and Predictions.

3.1 Definition of sustainability criteria

Building upon the definition of mineral resource potential (Taylor & Steven, 1983), the TILES geological knowledge base is built around the concept of 'resource potential' or 'resource reserve'. In the context of marine resources, it is based on three main components (Figure 2, 3). The first encompasses a detailed inventory of resource quality and quantity in which the link between geological knowledge and both seabed habitats and biodiversity is concretized (e.g. Degraer et al., 2008; Van Lancker & van Heteren, 2013a,b). The second relates to defining sustainable exploitation practices. Here, knowledge on natural sediment dynamics is indispensable to advise on where to extract and which areas to avoid (e.g. Van Lancker et al., 2010a) if environmental impacts are to be minimized. The third component holds information on competing use of marine space that constrains resource availability, both now and in the future. Regular updates of this information are needed, as marine spatial plans are revised from time to time. Even though it is difficult to look too far ahead, with short-term gain ruling politics, this final component provides new insight into resource availabilities for the next generations, a cornerstone of sustainability.

The importance of defining practical sustainability criteria is further highlighted by Europe's MFSD, which puts forward that recovery from human perturbations in the marine environment should be rapid and secure. In other words, levels of diversity, productivity, and ecosystem processes should not show persistent decrease to values outside the natural range (Rice et al., 2012). In constraining the envelope of natural variability, knowledge on the dynamics of the geological resource (e.g. sediment dynamics) is critical. Since sediment type is most closely related to predictions of biodiversity (e.g. Degraer et al., 2008), some member states (e.g. Belgium) have put forward that the distribution and extent of EUNIS level 3 habitats (e.g. sandy mud to mud, muddy sand to sand, coarse sediments, gravel beds in infralittoral and (offshore) circalittoral environments) should remain constant within the accuracy limits of maps presented in the Initial Assessment (Belgische Staat, 2012). Applied in a resource-exploitation context, this means that extraction is only allowed in geological units with the least spatial variability in lithological characteristics. Hence, 'no habitat change' is an important criterion when defining sustainable exploitation.



(1) Right sand type (quality / lithological class)

(2) Absence of undesired admixtures or heterogeneities

(3) Deposits with high certainty of suitability

(4) Resource volume large enough for extraction

(5) Minimal extraction-related environmental impact

Figure 2. User criteria to define the concept of resource to reserve. The geological resource is the maximum availability. The reserve is constrained to what is most suitable and certain for extraction within the contemporary socio-economic context and with minimal environmental impact.

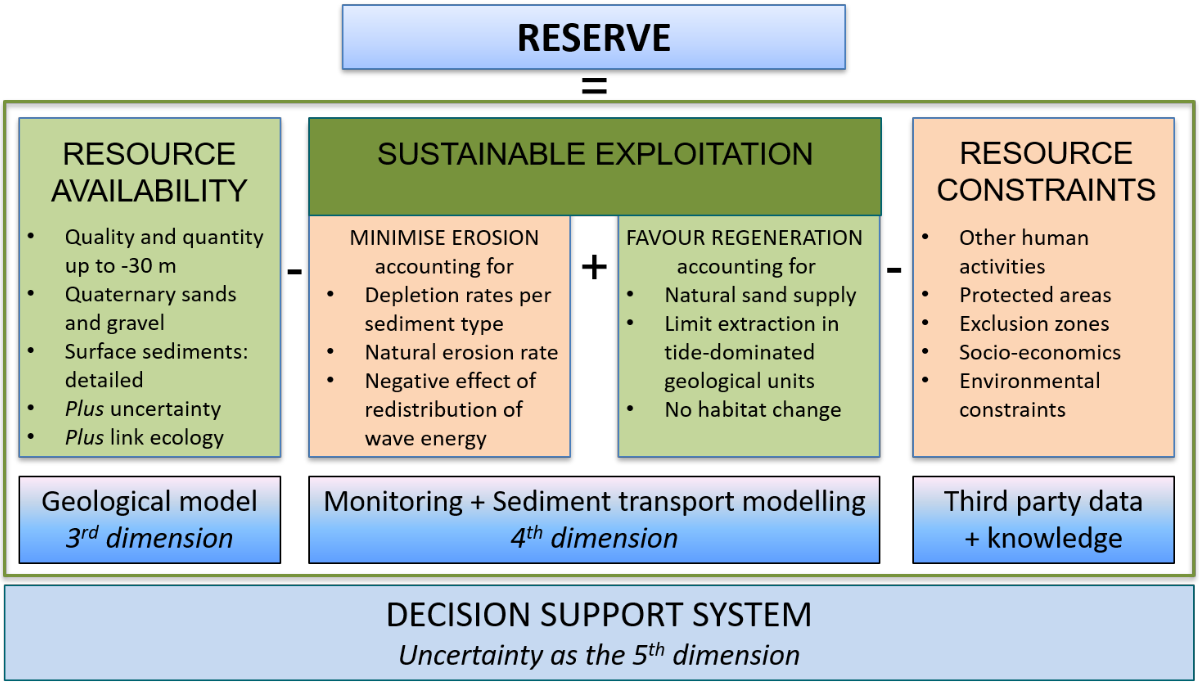


Figure 3. The TILES approach in defining the resource potential or reserve. Three information pillars provide input for a DSS on sustainable sand and gravel extraction: resource availability, sustainable exploitation, and resource constraints. Integration of cross-domain information yields sustainable extraction thresholds to be used in scenario analyses that will help to ensure that extracted volumes stay within sustainability limits, a prerequisite within Europe's MSFD.

3.2 Data, Information and Knowledge

Data and information sources

Available data, information and knowledge on geological resources were compiled, if needed digitized, and integrated as well as harmonized in databases. These related to the Paleogene, Neogene and Quaternary deposits in the southern part of the North Sea (e.g. Le Bot et al. 2003, 2005; Rijsdijk et al. 2005; Mathys 2009; De Clercq, 2018), as well as to the dynamic nature of the deposits (e.g. Van Lancker et al. 2007, 2012). The TILES website (https://odnature.naturalsciences.be/tiles/) provides an overview of data and information on seabed and subsurface data, seabed habitats, aggregate resources, and relevant policies.

Borehole data were standardized following European guidelines (e.g. EU-FP7 Geo-Seas for geological and geophysical data; EU-FP7 SeaDataNet for oceanographic data). Main lithology (e.g. gravel, sand, clay), Wentworth classes (e.g. fine, medium, coarse sand) and (adjusted) Folk (e.g. sandy mud, gravelly sand, muddy gravel) were mapped consistently for the BPNS and sNPNS. Secondary components (admixtures) were also added to the database (e.g. shell content, percentage fines (clay-silt, or < 63 µm) and/or gravel; organic and glauconite content) since they may render an aggregate less suitable for industrial applications. All terms used in the conversion are linked in the metadata to INSPIRE-compliant vocabulary organized in different hierarchical levels. The standardized formatting allows further integration into European geological data portals (e.g. EMODnet-Geology, European Geological Data Infrastructure EGDI). Importantly, all data were subjected to extensive quality control, and lithological descriptions were coded for easy querying and data extraction.

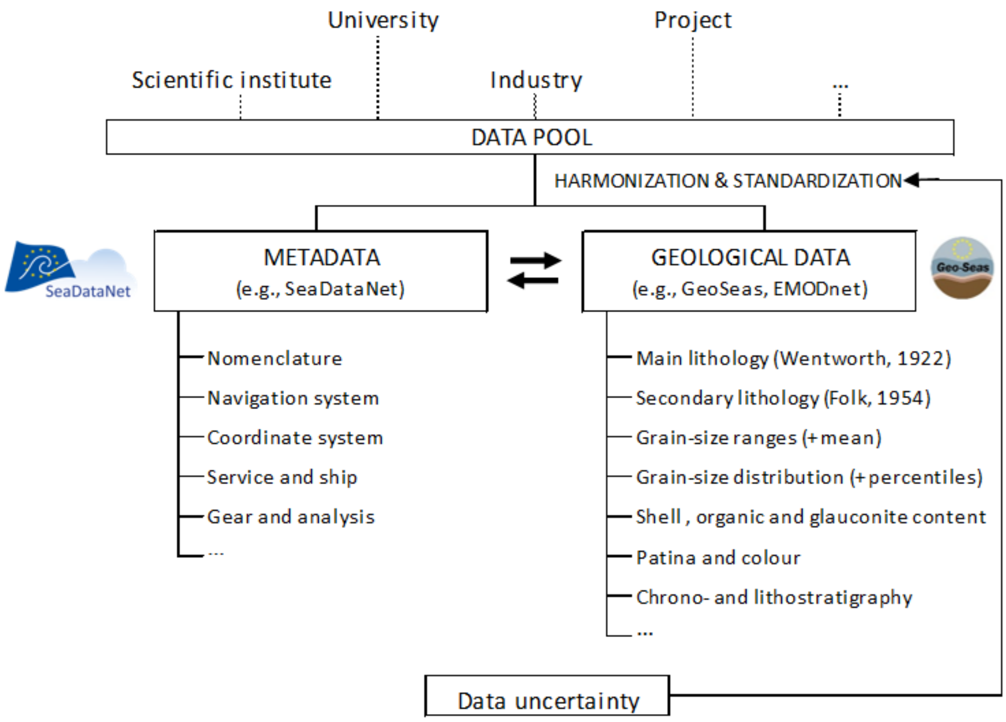


Figure 4. Overview of lithological description data, associated metadata, and the codes that were derived to facilitate the development of geological models.

Seismic data were also compiled for both the BPNS and sNPNS, building further upon the work of Mathys (2009). For the BPNS, more than 17,300 km of high-resolution seismics were available, with a significant contribution of new data added from recent surveys (e.g. from the IWT-SBO Se-ARCH project; Missiaen et al., 2017).

Combination of the borehole and seismic data allowed new lithological and lithostratigraphic interpretation in a transnational context.

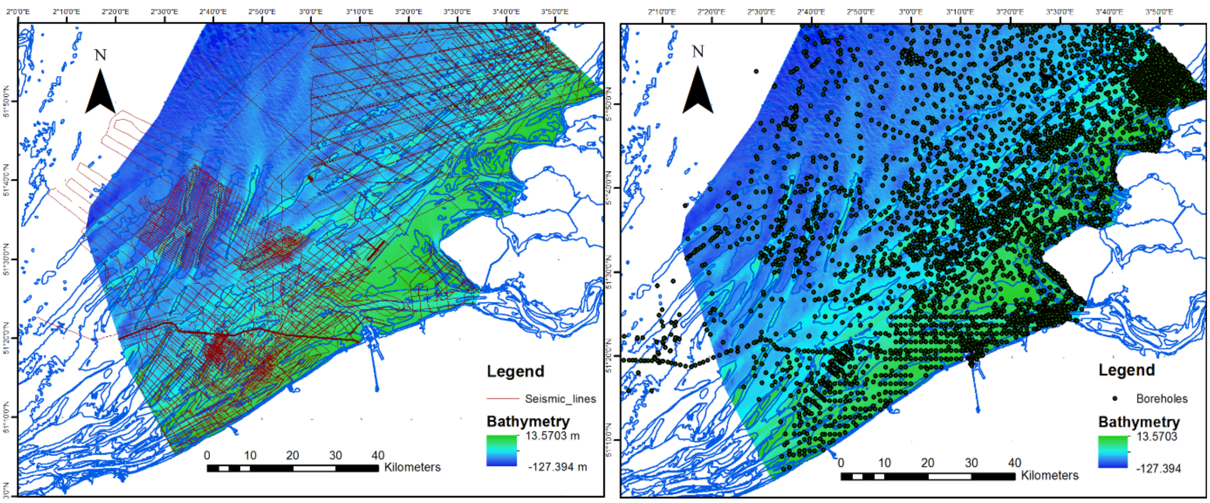


Figure 5. Seismic (left) and borehole (right) data available for the BPNS and sNPNS.

Data quality and data-related uncertainty

Data uncertainty relates to vintage (time of sampling, relevant because the seabed changes through time), positioning, sampling technique and analytical procedures (van Heteren & Van Lancker, 2015). To quantify these uncertainties metadata were scored following newly developed protocols (Table I). Thus, data quality and other uncertainty factors can be incorporated into resource calculations. Scores from 0 to 100 were applied to generate maps that are compatible with the probability maps on geological characteristics; more simple scores of 0 to 5 were assigned to each metadata field to be provided in geological log sheets from the newly developed geological data portal (see Dissemination and Valorization).

Table I. Overview of the simple quality flags assigned to the main metadata fields contributing to uncertainty. At present, a combination of the timestamp and modelled residual sediment-transport values are considered for vintage (GIS@SEA, Van Lancker et al., 2007). For sampling, the quality flag represents a score determined using the dominant sediment type of the interval described. *DGPS: differential global positioning system.

Navigation system	Accuracy [m]	Flag
Theodolite (e.g., sextant)	100-200	1
Decca Navigator System	50-100	2
Decca Hi-fix/6 System,	20-50	3
Hyperfix	10-20	3
Syledis, Trisponder	2-10	4
(Differential) GPS	0-2	5

Year	Low SD*	Medium SD	High SD
<1940	0	0	0
1940-1950	1	0	0
1950-1960	2	1	0
1960-1970	3	1	1
1970-1980	3	2	1
1980-1990	4	2	2
1990-2000	4	3	2
2000-2010	5	3	3
>2010	5	4	3

*SD = sediment dynamics

Sampling	**Flag**						
Gear	*Clay*	*Silt*	*Fine sand*	*Medium sand*	*Coarse sand*	*Gravel*	*Shell hash*
Box core (Reineck)	5	4	5	5	4	1	2
Flush core (Geodoff)	2	2	2	2	2	2	2
Grab sample							
- Coupe Gilson	3	3	5	5	5	5	5
- Hamon	3	3	3	3	4	4	4
- Shipek	3	3	5	5	5	5	5
- Van Veen	4	2	3	3	3	1	2
Gravity core	5	5	3	3	3	1	1
Hammer core	2	2	2	2	2	2	2
Piston core	3	3	3	3	2	1	1
Vibro core (Zenkovitch, Trilflip)	5	5	5	5	5	5	5
Other cores							
- Puls	2	2	2	2	2	2	2
- Slag	2	2	2	2	2	2	2
- Steek	5	5	5	5	5	5	5

Uncertainty was also quantified for the seismic data. The analogue and digital seismic data, collected during the past 45 years, were catalogued and assigned with a quality indicator following European guidelines (EU FP7 Geo-Seas) with each (navigation) line being assigned a value ranging from 0 (no data) to 5 (good data). This provides insight into the uncertainty associated with seismics-based layer models covering specific areas and enables the selection of the highest quality lines for future work.

3.3 Three-dimensional Geological Models

Voxel modelling

Applying 3D modelling techniques to marine datasets is challenging given that the offshore environments under consideration may have been heavily reworked through time, commonly leading to thin and discontinuous deposits with significant lateral heterogeneity. Geological layer models are not suitable for depicting internal facies variability; therefore, voxel and stochastic modelling was preferred. Because of their structure, voxels (volume elements, which due to their shape are also called 'tiles') are well-suited to define complex geology and heterogeneities within geological layers (Stafleu et al., 2011), which is critical in aggregate-resource exploitation. Furthermore, they allow in-depth analyses of a multitude of properties (and their associated uncertainties) that jointly define a lithological layer. In TILES, several 3D geological models were developed for the BPNS and sNPNS by transforming geological layer models, defining stratigraphic unit boundaries, into so-called voxel models filled with lithological properties.

Voxel modelling was first applied in the earth sciences in the 1990s (Marschallinger, 1996), but its full-scale application to large subsurface databases did not start until about a decade ago. Applications were mostly for land data and based on closely spaced borehole data (Van der Meulen et al. 2005, 2007; Mathers & Kessler 2010, Stafleu et al. 2011). In TILES, this has now been done, for the first time, on a large marine dataset and in a transnational context. As offshore borehole data are scarce in comparison to onshore, integration with seismic data was essential in producing the layer models that form the basis of the voxel models. These seismic data were well-suited to the mapping of unit boundaries as well as clay layers unsuitable for extraction, which commonly produce strong reflections of the sound waves used in this method. The combination of data from single locations (boreholes) and data collected along transects, along with the large variation in associated data quality and density (especially for seismic data), was challenging to deal with and required adjustment of modelling protocols. A methodological workflow, dedicated to marine datasets, is accepted for publication (Hademenos et al., in press).

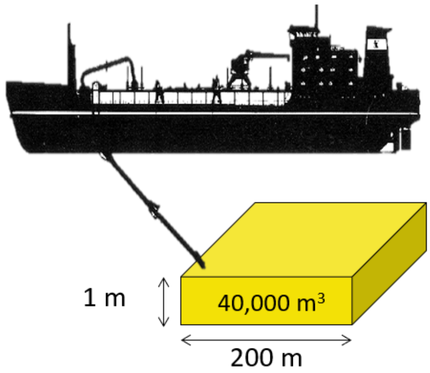
Assessing data quality: modelling uncertainty

Interpolation-related uncertainty, inherent to geostatistical modelling, is included in the voxel model. It is translated into probabilities, evaluated based on 100 statistically equally probable 3D spatial interpolations to fill the empty voxels in locations for which no field data are available. Each of these interpolations uses available sediment data (from boreholes and seabed surface samples) and a random combination of already simulated voxels in the neighbourhood of the target voxel. Using all simulation results, every voxel is attributed to the most likely lithological class, based on the number of simulations that assign a voxel to each different class. There is a probability, and thus an uncertainty assessment, for all sediment classes considered, and this parameter can be visualized separately.

To capture the variability of the simulations for all sediment classes, the information entropy approach of Wellmann & Regenauer-Lieb (2012) was used. The information entropy of a voxel is a single value ranging from 0 to 1 that can easily be calculated from each of the probabilities of lithological classes. An entropy value of 0 means that there is no model uncertainty (every simulation yields the same lithological class for the voxel), whilst a value of 1 occurs when all lithological classes have the same probability. Values in between 0 and 1 account for both the number of lithological classes with a probability higher than 0 (the more classes, the higher the entropy) and the differences amongst the probabilities (the greater the differences, the lower the entropy). The method was applied successfully in voxel models for onshore parts of the Netherlands to reflect model uncertainty on the lithological class attribute for each voxel (Stafleu et al., 2014).

The newly generated voxel model, containing all resource-associated attributes (including uncertainties), formed the basis of the resource DSS. It also served as input to the 4D process models. Voxel modelling was done at a resolution of 200 x 200 x 1 m. To test the influence of resolution on volume calculations, a more detailed voxel model (100 x 100 x 0.5 m) was developed for the aggregate concession zone 4 at the Hinder Banks (see Hademenos et al., in press).

Table II. Attributes of the voxel model, presently at a resolution of 200*200*1 m.



- Location (x, y, z)
- Geological unit (layer)
- Most likely lithological class from 100 model runs
- Probabilities of occurrence of clay, silt, fine sand, medium sand, coarse sand, gravel
- Admixtures of mud, shells and gravel
- Model uncertainty (entropy)
- Data uncertainty (positioning, vintage, sampling)

Modelling admixtures constraining resource suitability

Three relevant types of admixture, shell content, percentage fines (denoted in database as clay, mud, silt; and meaning all particles <50, <63 or <75 µm, depending on method or classification used) and percentage gravel, were mapped also (see Section 3.2). Co-kriging was used for their interpolation in the 3D volume. No distinction between geological layers was made here. Interpolated values were added to the voxel model as extra attributes. In the TILES DSS they can be queried. There are no set limits constraining extractability. Allowable thresholds vary depending on the industrial application and may be counteracted by pre- and post-processing.

3.4 Four-dimensional Process Models

Coupling of geological models with environmental impact models

Three-dimensional voxel models are an invaluable tool to assess data and information on the current state of the resource. However, for prospective resource management, evolution of resource volumes and qualities through time need to be addressed as well. Therefore, the 3D voxel model was coupled to a numerical model to form a 4D modelling suite, which has not yet attempted before. For offshore applications this is important since marine resources are subject to both natural processes (bedform migration, erosion and deposition; Dyer & Huntley, 1999) and human influences (e.g. dredging and disposal of dredged activities, extraction; Degrendele et al., 2010; Van Lancker et al., 2010) that cause their quantity and quality to change. To understand past and predict future behaviour of the resource in this 4th dimension (time), it is necessary to integrate this evolution in the 3D voxel model by adding, removing and changing the parameters of top voxels, or by using these top voxels to optimise the initial conditions of the 4D impact models.

The model suite used in TILES contains a hydrodynamic model of the continental shelf (COHERENS; Luyten, 2010), which is completed by a sediment-transport module (simulating sediment erosion, transport and deposition) and a seabed-morphology module (simulating changes in seabed composition and bathymetry). The model suite is coupled to a third-generation wave model (SWAN; Booij et al., 1999) to realistically account for the wave constraint on hydrodynamics and sediment transport and, in return, to evaluate the prospective effect of profound seabed changes on wave dissipation. This suite simulates the driving forces acting on the seabed and is crucial for a quantitative understanding of past as well as future resource changes resulting from natural seabed dynamics and human impact. A coupling framework including some or all these components is not unique (e.g. Liang et al., 2007; Tang et al., 2009; Van den Eynde et al., 2010; Warner et al., 2010), and was already used to investigate the effect of sand extraction on sediment transport in the BPNS (Van den Eynde et al., 2010). Here, additional coupling with the voxel model offered an opportunity to initiate and parameterize the model suite to quantify the evolution of the aggregate resource at an unprecedented level of detail and accuracy.

The sediment-transport and seabed-morphology modules include the possibility to simulate different sediment fractions and seabed layers. Relevant information contained in the voxel model can be transferred to the numerical model suite (Figure 6): various voxel attributes are used to define initial conditions (as a measure of expected sediment concentrations and erodibility) and to distil the most suitable parameters (e.g. particle size, settling velocity, cohesion, or any other relevant parameter) that characterize the different sediment fractions and stratigraphic units in the seabed sediment and shallow subsurface.

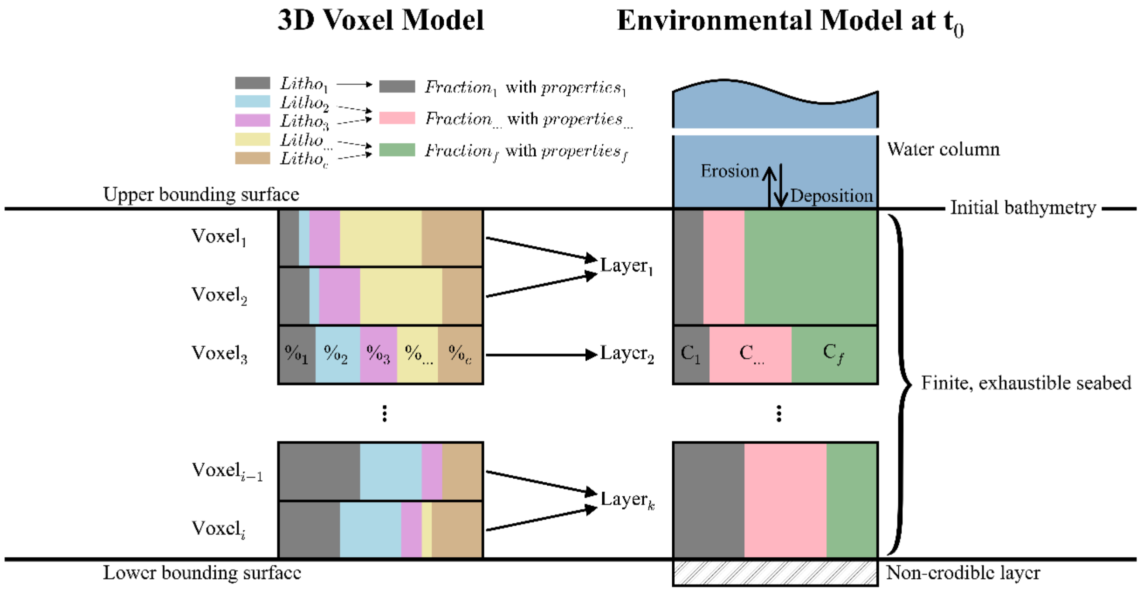


Figure 6. Coupling between the 3D voxel model (left) and the suite of environmental impact models (right). The voxel model provides percentages (%) of the different lithological classes (Litho), which are translated into concentrations (C) of the different sediment fractions to initialize the seabed of the numerical model. Properties of the sediment fractions (e.g. particle size) are provided as well to parameterize the numerical model. Owing to computational constraints, the different lithological classes of the voxel model must be grouped into broader sediment fractions in the numerical model (i.e. $f \leq c$). Also, highly similar superimposed voxels should be merged before feeding into the numerical model (i.e. $k \leq i$).

A fundamental advantage of this coupling is that sand and gravel in the seabed subsurface, now realistically parameterized through the voxel modelling, can be analysed for the first time as finite, exhaustible volumes. Geological surfaces are used to constrain the aggregate resource: an upper surface represented as the present-day bathymetry and a lower surface below which no erosion or sand extraction is expected (i.e. erosion and sediment concentrations are set to zero in the environmental model to represent a non-erodible geological formation). The definitive volume in between is subdivided into layers characterized by predefined distributions of the different sediment fractions. Each layer has a unique set of quantitative and qualitative attributes.

Statistical modelling of depletion/regeneration rates

Dynamics of very-large dunes were investigated for sandbanks impacted by marine aggregate extraction in the BPNS, comparing FPS Economy, Continental Shelf Service multibeam bathymetry datasets from six areas with extraction rates from vessel monitoring data (e.g. Roche et al. 2011). Procedures were set up to estimate dune-migration distance and direction between successive campaigns, as well as varying bedform dimensions. Dune-migration data were compared to simulated hydrodynamics and sediment transport to gain insight into the driving forces. In the heavily extracted areas, the removal of the seabed signal related to dune migration allowed the detailed investigation of depletion and regeneration rates. Knowledge of these rates under the current extraction practices is critical for assessing environmental impacts.

Long-term hindcast modelling of hydrodynamics and sediment transport

A 16-year hindcast (1999-2014) modelling study of hydrodynamics and sediment transport (bottom shear stress, bottom geometry, total load and bottom evolution) was performed, validated with available bathymetric monitoring series from FPS Economy, Continental Shelf Service (Francken et al., 2014; 2017). The spatial resolution of the models is relatively low (750x750 m), but their temporal resolution is high (30 min). Model outcomes were further analysed statistically following the approach of Dalyander et al. (2013) covering different time spans (seasonal, annual, multi-annual variation) and spatial scales.

3.5 Multi-criteria decision support system

A flexible and easy-to-use DSS

A multi-criteria DSS was built as a web application. It allows producing geographic output by specifying flexible criteria for underlying data and their uncertainty. The aim of TILES was to adequately translate user preferences into requirements for the different attributes incorporated into the voxel model, and to enable adding third party data. The methodology developed in the project uses soft computing techniques (e.g. Dujmović et al. 2010, De Tré et al. 2010). For an overview and comparison of state-of-the-art techniques for multi-criteria decision-making, see Dujmović & De Tré (2011) and De Tré et al. (2018).

Main DSS attributes relate to the integrated data, information and knowledge (3.2), the 3D geological models (3.3) and some first output from 4D process models (3.4). Advanced criteria-evaluation techniques were developed to support the construction of specialized geographical maps of the sea region under investigation. Such maps, hereafter called 'suitability maps', are able to show geological boundaries, distributions of particular resource qualities, and the resource estimation at various cut-off grades, all calculated in a time-efficient manner encouraging online use of the tool. Additionally, user functions of the BPNS, as available from the Marine Atlas (Belgian Marine Data Centre), were incorporated: infrastructure (e.g. pipelines; electricity and telecommunication cables; windmills; navigation routes), human activity (e.g. tourism, safety), legal status (e.g. areas reserved for special activities), economic development (e.g. expansion of industries).

Flexible, human-centric, modelling options were implemented such as: calculating with words (near X, a lot of Y, ...), using linguistic quantifiers (most of the conditions, some of the conditions, ...), expressing relative importance between conditions (mandatory, sufficient, optional, preferable, ...).

Some simpler modelling options were also implemented, inspired from the way 3D maps can be filtered in existing 3D software (ISATIS, Subsurface Viewer). As there is a tendency amongst leading GIS vendors to move to full 3D functionality; 3D raster analysis and visualisation are likely available to decision makers in the near future.

Whilst the full 3D voxel model is queried in the DSS, it aggregates the query result in a top-down view, hence a 2D projection. As such, information of an entire voxel column is compressed in a single, representative value. At present, the predefined projections fall into two categories: (1) for non-numerical attributes, such as lithological class, the most common value is chosen; (2) for numerical attributes, the average is calculated. A third 'custom' projection is also possible and performs a specific computation on the entire voxel column, for example "how many voxels are in this column".

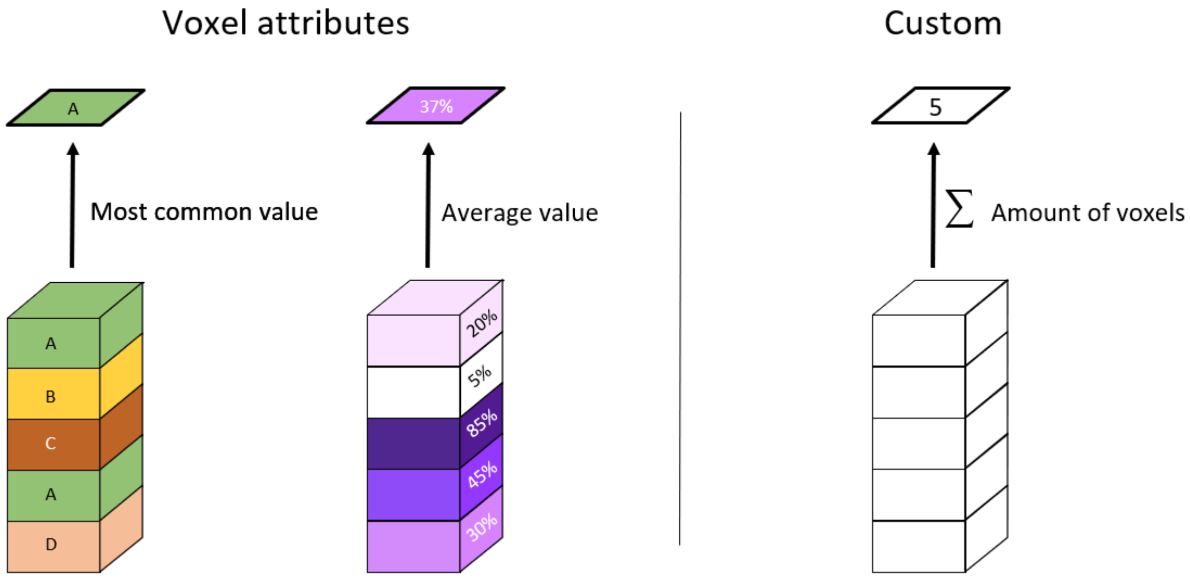


Figure 7. Projections of how queries on the 3D voxel model are represented on 2D maps.

The heart of the DSS lies in its ability to filter voxels. The filter view allows a user to select specific voxels from the model. Voxels can be filtered by their location, depth and properties, but also by data-quality indicators. Filters are conjunctive, which means that if multiple filters are specified, voxels matching all specified criteria will be selected.

Additionally, *ad hoc* cross sections can be made, and displayed without any aggregation or projection. Hence, any desired information from the voxel model is shown, without loss of information. Different voxel attributes can be colour-coded, independent from the top-down view, and active filters are considered. Simple statistics, in terms of volume calculation, are given for each query. More advanced analytics are left to the user once the model is downloaded.

Prototype for future DSS development

A prototype for a future DSS has been developed also. It is based on a new algorithm that enables partitioning of a study area into voxels of different sizes "on-the-fly" (as described above). This algorithm can be further tweaked with parameters such as: tolerance (more tolerant allows larger areas to be identified as homogeneous despite minor differences), minimal resolution (voxels must be no bigger than this resolution), maximal resolution (voxels can be no smaller than this resolution). Voxel models generated in such a way are stored in a custom, binary format to allow full exploitation of its strengths (dynamic zooming, ...), but can be easily converted into existing formats. A remaining weakness is that the generated voxels, though dynamic in size, are not dynamic in shape. This means that all voxels are rectangles with a uniform size ratio 1:1:1. This might produce counter-intuitive results where 3 neighbouring voxels actually represent a homogeneous area but are still shown as separate voxels because surrounding voxels are different and they cannot be merged into a bigger voxel with the same size ratio. Allowing flexibility in size ratios would make the partitioning algorithm much more complicated and is therefore not an option at this time. However, a post-processing technique is able to scan a generated voxel model and aggregate nearby homogeneous voxels into irregular shapes. This algorithm can be parameterized with a set tolerance similar to the partitioning algorithm. The resulting voxel model is extended with additional output parameters so that the suitability maps can be coloured by other parameters than just suitability regarding the modelled query. Because of its irregular shape the model cannot yet be rendered in existing programs. The algorithm itself is heuristic and requires further testing and analyses to determine its value, and might require optimization towards speed versus detail.

4. SCIENTIFIC RESULTS

The TILES project has been pioneering in many ways: producing a first transnational marine subsurface voxel model, quantifying data uncertainties, coupling the voxel model with 4D numerical impact models, developing a voxel-based DSS, and last but not least meeting the many data-visualization challenges. With its flexible approach and its ability to cope with various sources of uncertainty, TILES represents a leap forward in resource assessment and in the associated decision making. Importantly, most of the developments were steered through interaction with stakeholders and their varying needs. The building of the geological knowledge base was published as a chapter in a book promoting oceanographic and marine cross-domain data management for sustainable development (Van Lancker et al., 2017).

4.1. Resource databases

Extensive but comprehensive databases have been compiled on the lithology of the BPNS and sNPNS. Information is updated regularly to the greatest available detail allowing for flexibility in data and information querying, mapping and modelling. Data portals provide free access to the original and newly standardized and quality-controlled data. Data-quality aspects in marine sediment databases were published in van Heteren & Van Lancker (2015).

4.2. Resource maps and models

A portfolio of sediment and habitat maps

The updated numerical grain-size database was used to map sediment type following the Folk classification (5, 7 and 16 classes). Maps were made at a 1:250.000 scale following the procedures of EMODnet-Geology. The maps are publicly available through the EMODnet-Geology data portal (http://www.emodnet-geology.eu/). In combination with depth zonation, tidal and wave energy, and level of light penetration they were further translated into maps of MSFD Predominant habitat types; these are now publicly available via the EMODnet-Seabed Habitats data portal (https://www.emodnet-seabedhabitats.eu/) (Figure 8) and have been the basis of many MSFD assessments in Europe.

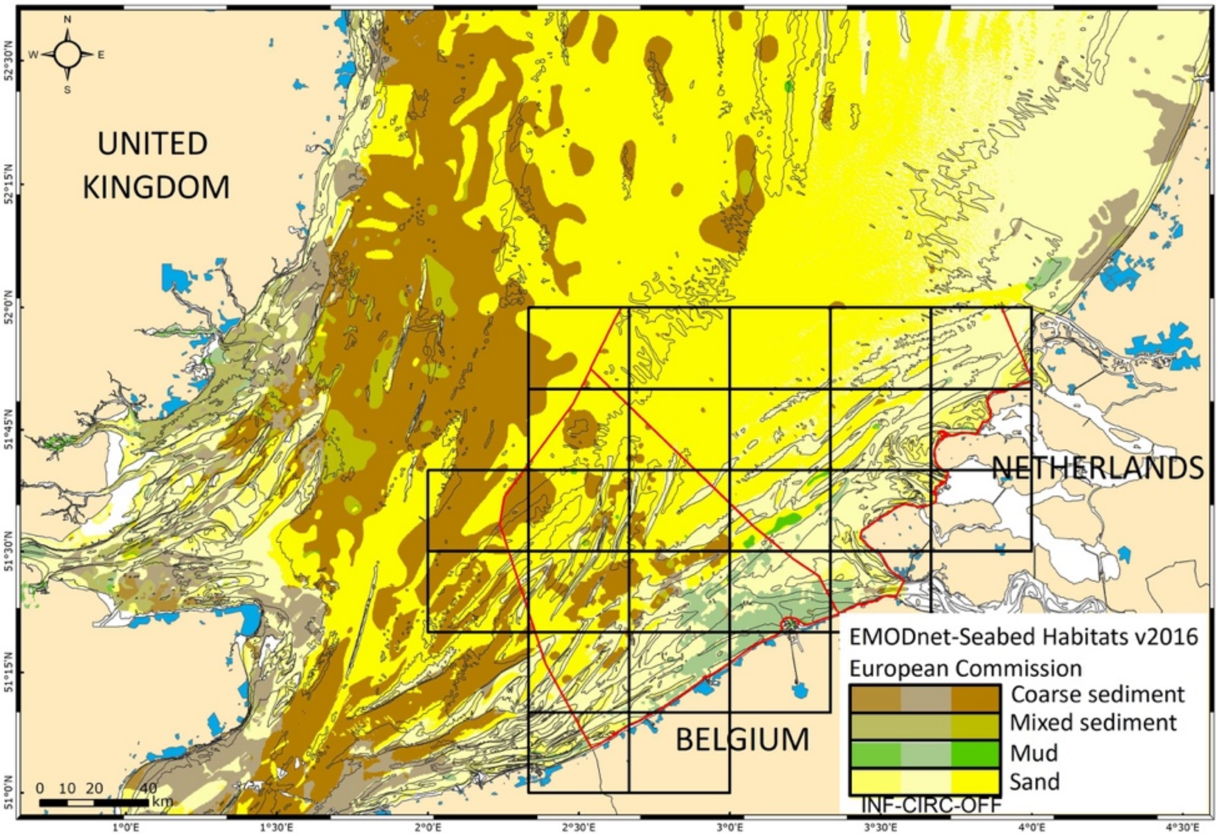


Figure 8. Predominant broad-scale habitat types (EUNIS Level 3) in the southern North Sea, mapped on the basis of substrate type (RBINS SediCURVE@SEA_v2016 database) combined with physiographic characteristics (depth zonation and wave energy) (INF: infralittoral, CIRC/OFF (offshore) circalittoral). The TILES area is delineated by the overlying grid. Available for download via EMODnet Seabed Habitats data portal.

Resource suitability of geological layers

The BCS is a sediment-depleted shallow shelf environment comprising a series of sandbanks. Its location on the edge of a structural high, the London-Brabant Massif, explains the dominance of recycling and redistribution processes that has created a complex and discontinuous Quaternary sediment cover. This thin cover is considered the most viable resource, since the underlying Paleogene strata include an abundance of compacted clays. Towards the border with the sNPNS, alternating sequences of silt and clay are the most common, with sizable units of silty sand, muddy sand and even calcareous sandstone beds (Le Bot et al., 2003). In the sNPNS, located in a structural low (the North Sea Basin), the Quaternary cover thickens rapidly from southwest to northeast. For the BPNS a new Top-Paleogene surface was published (De Clercq et al., 2016). Its geomorphology is characterized by planation surfaces, bounded by scarps and slope breaks, paleovalleys, and elongated depressions (Liu et al., 1992; Mathys, 2009; De Clercq et al., 2016; De Clercq, 2018). These have been infilled or smoothed during the Quaternary. In Figure 10, the Paleogene is undifferentiated. A subcrop map of the Paleogene, with the successions as described above, can be downloaded via http://www.emodnet-geology.eu.

The resource quality of the Quaternary was studied from a lithostratigraphic and lithologic perspective, both for the BPNS and sNPNS. Table III summarises and links the lithostratigraphy in both countries. Seismostratigraphic units are shown also. Typical litho- and seismostratigraphic facies are depicted in Figure 9. From the combined analysis of the seismic and borehole data it was only possible to model consistently three resource-relevant layers: Pleistocene, lower and upper Holocene (Hademenos et al., in press). Important Pleistocene deposits in the BPNS are concentrated in paleovalleys. The near-coastal Ostend Valley has the most voluminous infill (Figure 10). In the sNPNS, the thickness of the Pleistocene deposits increases from southwest to northeast, and toward the axis of the lowstand Rhine-Meuse river linking Rotterdam Harbour to the Hinder Banks area (location, see Fig. 1). As these Pleistocene units were formed during times of high and low sea level, they include muddy as well as gravelly sediments with strongly varying thicknesses and large spatial heterogeneity. Locally, extraction is possible, but it needs to be guided by geological knowledge from seismics and boreholes. The lower-Holocene units are characterized by low-energy deposits accumulated in tidal settings. Typically, these are highly variable in composition, with abundant fine-grained material. They are unsuitable for extraction. Only the upper-Holocene units, deposited under the combined action of waves and tidal currents, are recommended for extraction, especially in the BPNS; they are relatively homogeneous and contain only small percentages of silt to clay fractions. Table IV provides an overview of the main lithoclasses per unit, together with typical admixtures. Figure 10 shows a typical succession of the three layers on the BPNS. The distribution and thickness of the three layers, as well as their lithoclass and admixture distributions, can be queried in the TILES DSS.

Table III. Lithostratigraphic overview of the main resource-relevant geological layers in the Quaternary. In the TILES project all of the borehole data were classified into three main layers: Pleistocene, including reworked transgressive lag (red), lower Holocene (orange) and upper Holocene (yellow).

Lithostratigraphy Netherlands Following Rijsdijk et al., 2005			**Lithostratigraphy Belgium** Following Borremans, 2015			**Deposit type**	**Seismo-stratigraphy**
Southern Bight Formation	Bligh Bank Member					Holocene. Open-marine	U5, U7, TR-2
Naaldwijk Formation	Zandvoort Member		Vlaanderen Formation	De Haan Member		Middle- to Late-Holocene. Shoreface	U6, TR-1
Naaldwijk Formation	Walcheren Member		Vlaanderen Formation	Dunkerque Member		Middle- to Late-Holocene. Tidal	CL-2
Naaldwijk Formation	Wormer Member		Vlaanderen Formation	Calais Member		Early to Middle-Holocene. Tidal	CF, CL-1
Naaldwijk Formation	Wormer Member	Velsen Bed	Vlaanderen Formation	Calais Member		Early Holocene. Lagoonal	U4, PH
Nieuwkoop Formation		Basal Peat Bed	Vlaanderen Formation		Rotselaar Bed	Early Holocene. Swamp and marsh	U4, PH
Southern Bight Formation	Buitenbanken Member					Early Holocene. Open-marine ravinement lag	
Boxtel Formation			Gent Formation	Wildert Member		Weichselian to Early Holocene. Periglacial aeolian and locally fluvial	
Kreftenheye Formation			Adegem and Eeklo (Kaaskerke) Formations			Saalian to Early Holocene. Fluvial	PL
Eem Formation			Oostende Formation			Eemian. Open-marine and coastal-plain	U1, U2, U3

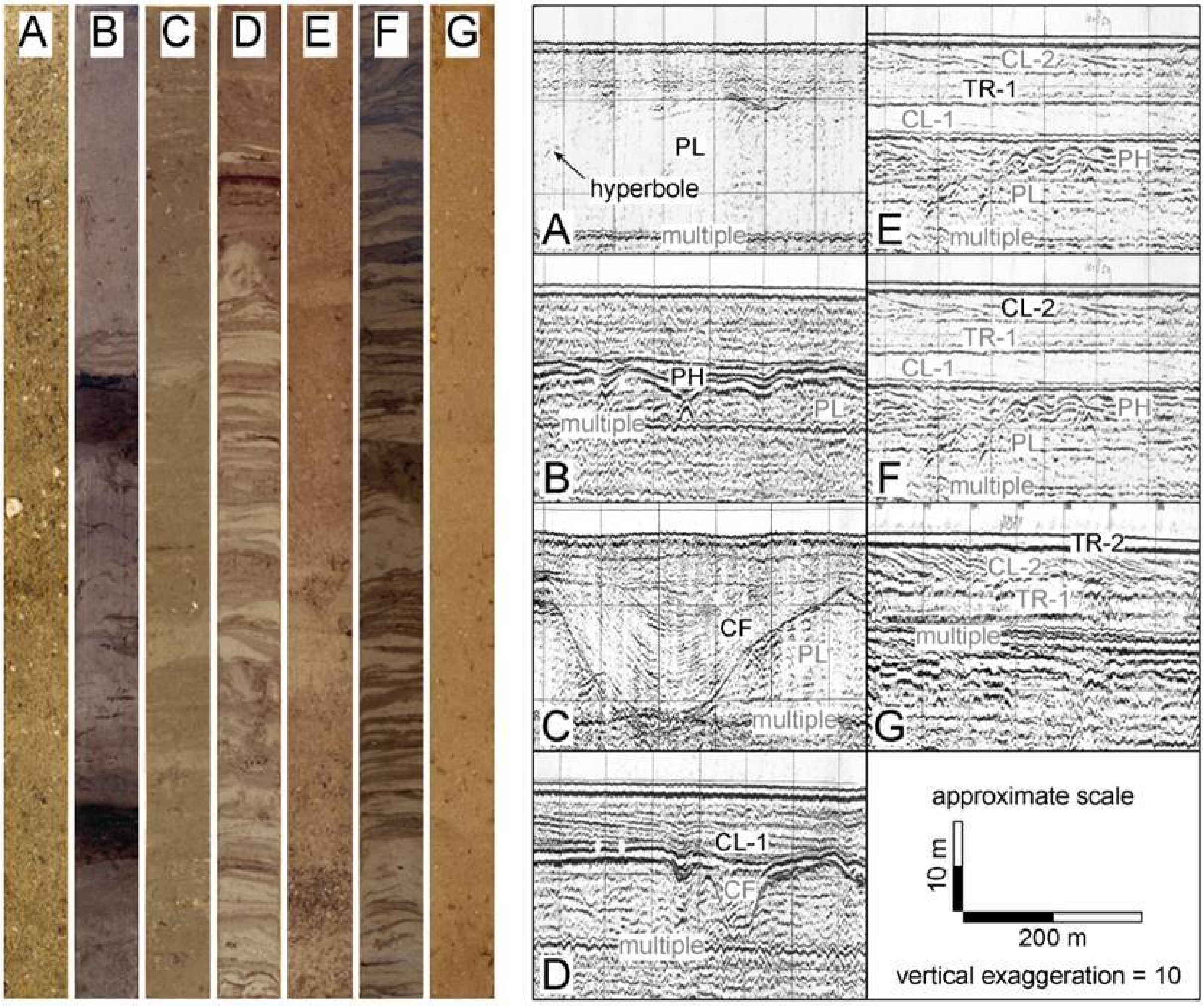


Figure 9. Signature of the Dutch seismo-stratigraphic units (see Table III for correlation with lithostratigraphic units) together with typical borehole sections. Only the upper-Holocene units deposited under the combined action of tides and waves are recommended for sand extraction. They are relatively homogeneous, as depicted in E and G. Types D and F are variable in composition and may contain sizable admixtures of fines; sands are to be extracted with caution.

Table IV. Lithoclass variation and possible admixtures for the main Quaternary units: Pleistocene, including reworked transgressive lag (red), lower Holocene (orange), upper Holocene (yellow).

Lithostratigraphy NL	BE	Lithoclass	Admixture coarse	Admixture fine	Admixture shell
Bligh Bank Member		Fine to very coarse sand with some mud laminae	Fine gravel at the base and between subunits	Locally significant	< 5% open-marine molluscs and debris, more in the south and at the base
Zandvoort Member	De Haan Member	Fine to coarse sand with some clay layers		Rare	Open-marine molluscs and debris in lags and dispersed
Walcheren Member	Dunkerque Member	Strong lateral variability: very fine to medium sand with or without (sandy) clay layers	Locally some fine gravel	(slightly) Silty, muddy	Back-barrier and near-coastal molluscs
Wormer Member	Calais Member	Alternations between very fine-to-medium (muddy) sand and mud	Pebble lags		Back-barrier and near-coastal molluscs and brackish-water gastropods
Velsen Bed	Calais Member	Clay			Brackish-water gastropods
Basal Peat Bed	Rotselaar Bed	Peat			
Buitenbanken Member		Fine to medium sand with coarse layers	(abundant) Gravel		Fresh near-coastal and reworked Eemian molluscs
Boxtel Formation	Wildert Member	Fine sand	Stringers of gravel		
Kreftenheye Formation	Adegem and Eeklo (Kaaskerke) Formations	Fine to coarse sand with silt layers and gravel beds	Locally gravelly (up to 30%, pebbles and boulders)		Generally few reworked Eemian molluscs
Eem Formation	Oostende Formation	Medium to coarse sand with local clay laminae, and very fine to fine muddy sand and clay	Gravel in basal lag and dispersed, highest concentrations in the south	Clayey	High shell content

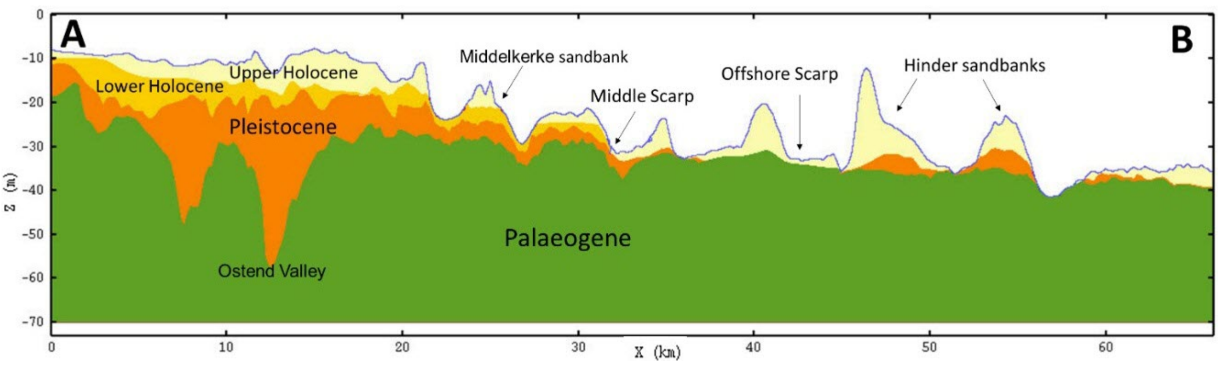


Figure 10. Main geological units on the BPNS: Paleogene (here undifferentiated), Pleistocene, lower and upper Holocene. The depth of the Top-Palaeogene was re-mapped (De Clercq et al., 2016). The Middle and Offshore Scarps, two important geomorphological features, were used to split the model into regions with similar lithological characteristics. Sandbanks have a unique internal structure and may be composed of different layers with specific grain-size distributions and amounts of shell fragments, gravel, clay or other material (Hademenos et al., in press).

First transnational marine voxel model

For all resource-relevant geological units, a portfolio now exists of resource-distribution maps for each Wentworth class (Fine, Medium to Coarse sand; Clay to Silt). Entropy values that reflect the model uncertainty associated with the estimation of lithological class in the voxel model are added as attribute in the voxel model. For the BPNS they are queryable in the TILES DSS. The sNPNS domain will be added by January 2019.

Figure 11 to 17 show the results for the entire TILES area, from the Belgian-French border to Rotterdam, the Netherlands. See captions for a summary of the main findings. For the interpretation of the legend of the probability maps as displayed in Figure 11 to 17, we refer to the IPCC Climate Report: occurrences with values < 0.1: very unlikely; 0.1 - 0.33: unlikely; 0.33 - 0.66: about as likely as not; 0.66 - 0.9: likely; and > 0.9: very likely.

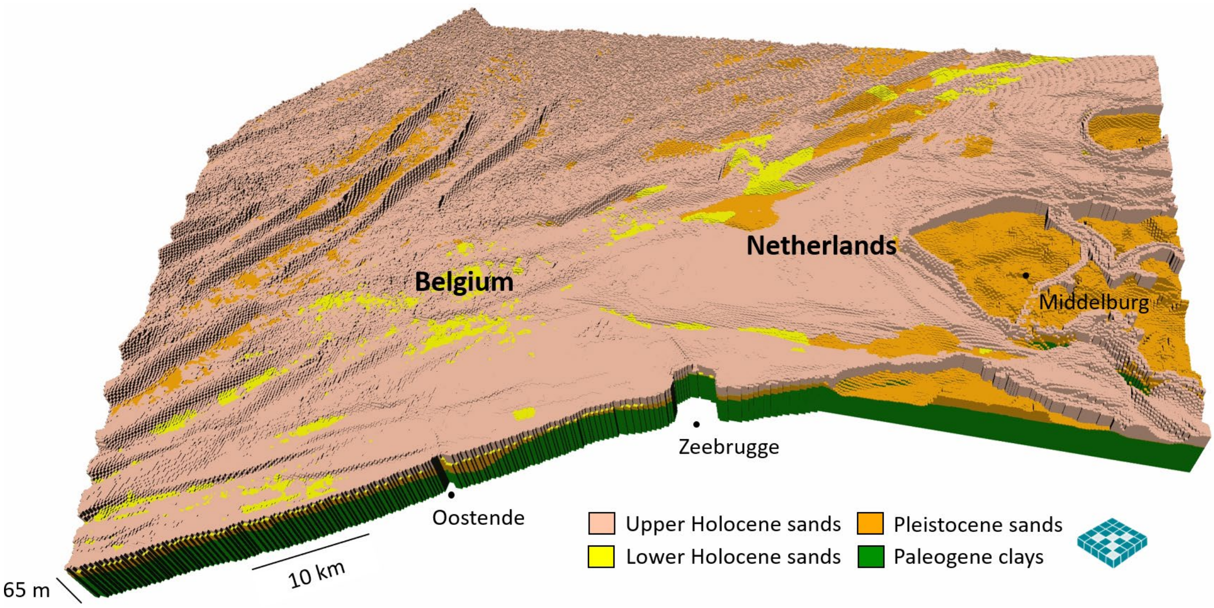


Figure 11. Geological units and their main lithology (Holocene units not mapped for the Dutch onshore area; hence, the top Pleistocene is visible). The base of exploitable resources is the top of the clay-rich Paleogene (green). Despite extensive reworking of sediments during the Quaternary, Pleistocene sands outcrop, e.g., in some of the deeper swales between sandbanks and as infill of some of the paleochannels close to shore. Lower-Holocene sands are very patchily distributed, with the higher chance of them outcropping in swales or other bathymetric lows. Upper-Holocene sands are abundantly present.

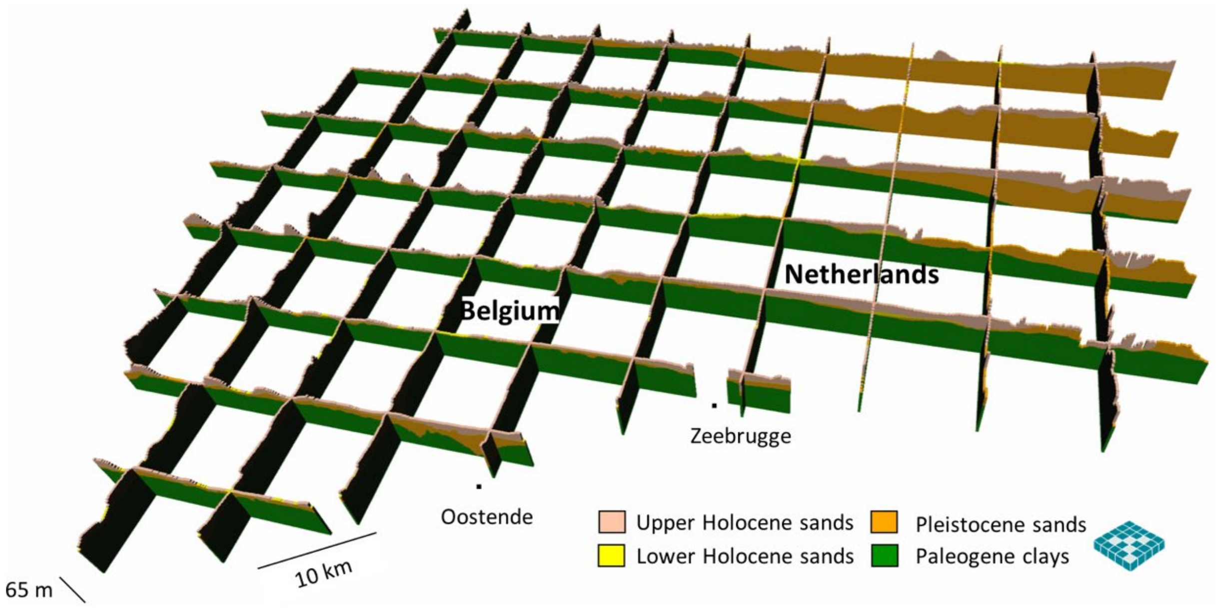


Figure 12. Fence diagram of the geological units and their main lithology. It illustrates the relative scarcity of sands on the BPNS at the shoulder of the London-Brabant Massif, and accentuates the strong increase of Quaternary sand thickness in the sedimentary basin of the Netherlands.

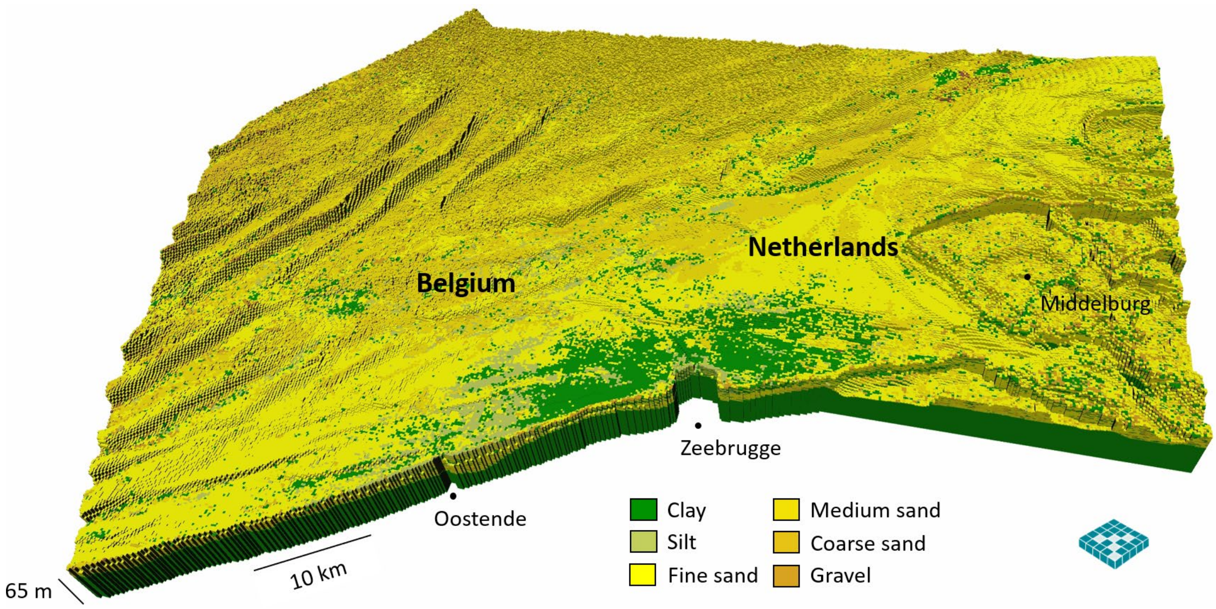


Figure 13. Aggregate quality in terms of most likely lithological class. It confirms the predominance of fine sands in the coastal zone, shifting towards medium sands in the offshore region. Clays and silt are abundantly present in the eastern Belgian coastal zone.

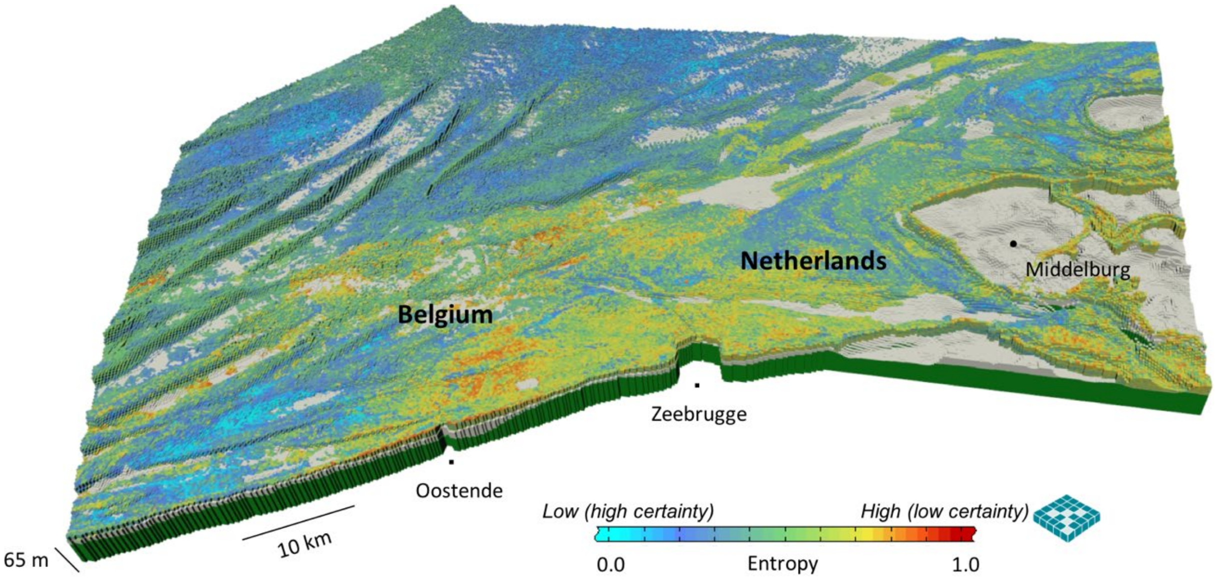


Figure 14. Entropy or model uncertainty of the prediction of the lithoclasses in the Holocene. Entropy not calculated for Pleistocene deposits, here depicted in light grey.

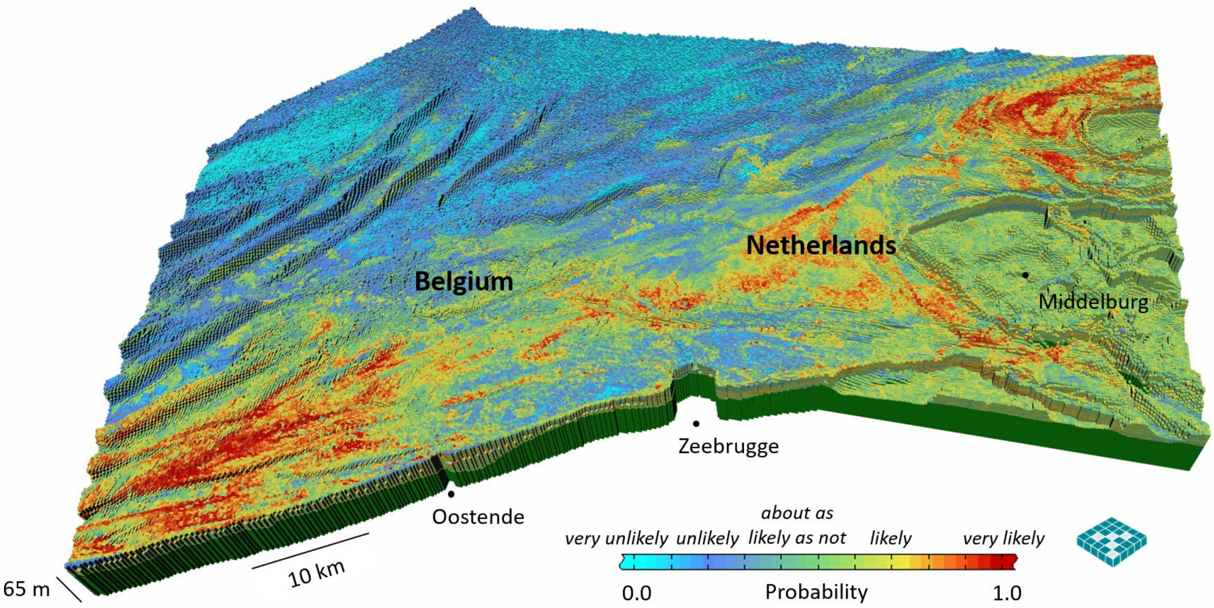


Figure 15. Aggregate quality in terms of the probability that a voxel contains fine sand. Such output provides more in-depth information on where a particular lithological class can be found with higher certainty (yellow to red areas).

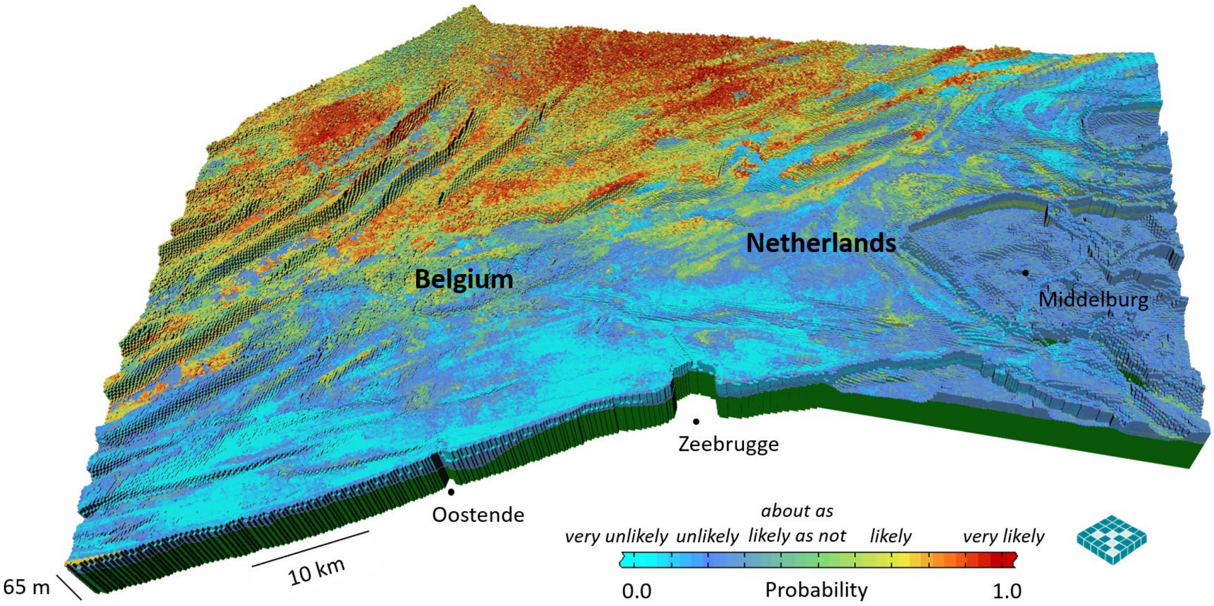


Figure 16. Aggregate quality in terms of the probability that a voxel contains medium sand. Areas farthest offshore have the highest certainty that this important resource is present (yellow to red areas).

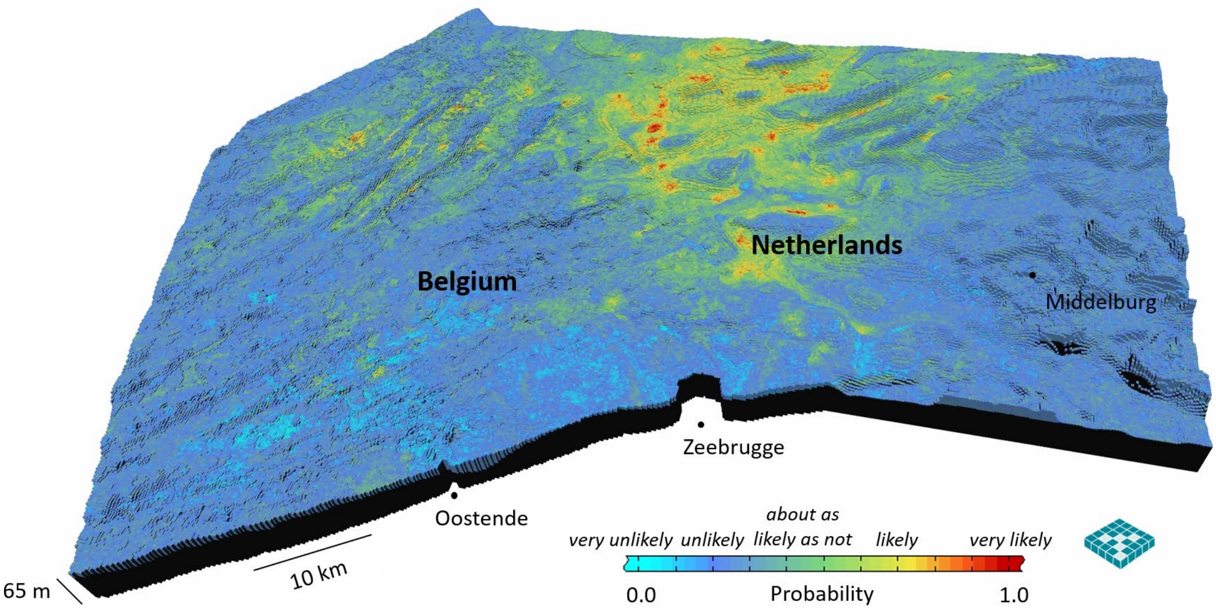


Figure 17. Aggregate quality combining lithostratigraphy and lithoclasses. Here, an example of the probability that a Pleistocene voxel contains medium sand. It illustrates the influence of the Rhine-Meuse fluvial system gradually diminishing from east to west. On the BPNS these deposits have been largely eroded and/or reworked.

Data-gap analyses

In the BPNS, overall borehole density is about 0.3 per km^2, with a very uneven spatial coverage. This low density forced us to incorporate geological knowledge from 2D seismic profiles into the voxel-modelling procedure. The map of data density presented in Figure 18 shows the number of boreholes per 200 x 200 m voxel for a circular neighbourhood of 10 km at 1-m depth intervals. The values vary from 0 to 160 data points per voxel. Areas that are close to the French border (Fairy Banks) and the area south of the Hinder Banks have very low data density; the area directly in front of Zeebrugge has the highest values. Data density reduces with increasing depth below the seabed. Low values of data density, combined with high values of lithological entropy, give an indication of areas where model outcome would benefit the most from additional boreholes. One can also choose to combine data density with geological complexity, as shown in Figure 19. Geological complexity is a proxy of how variable the lithology is over a voxel stack (or virtual borehole) or in lateral space. Data density is queryable in the TILES DSS. Combined with user-defined parameters it is useful in planning new surveys.

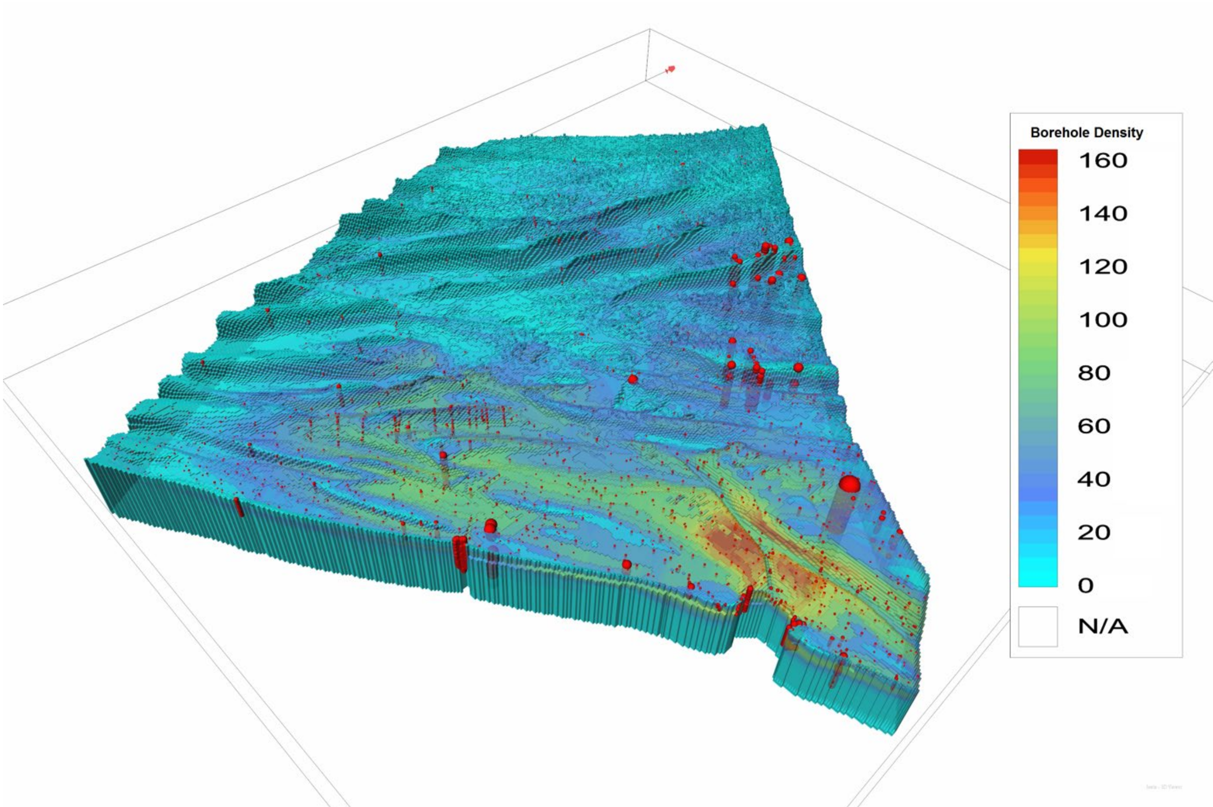


Figure 18. Density of the lithological descriptions used to construct the Belgian part of the voxel model. Data density is lowest in the far western and northern offshore areas.

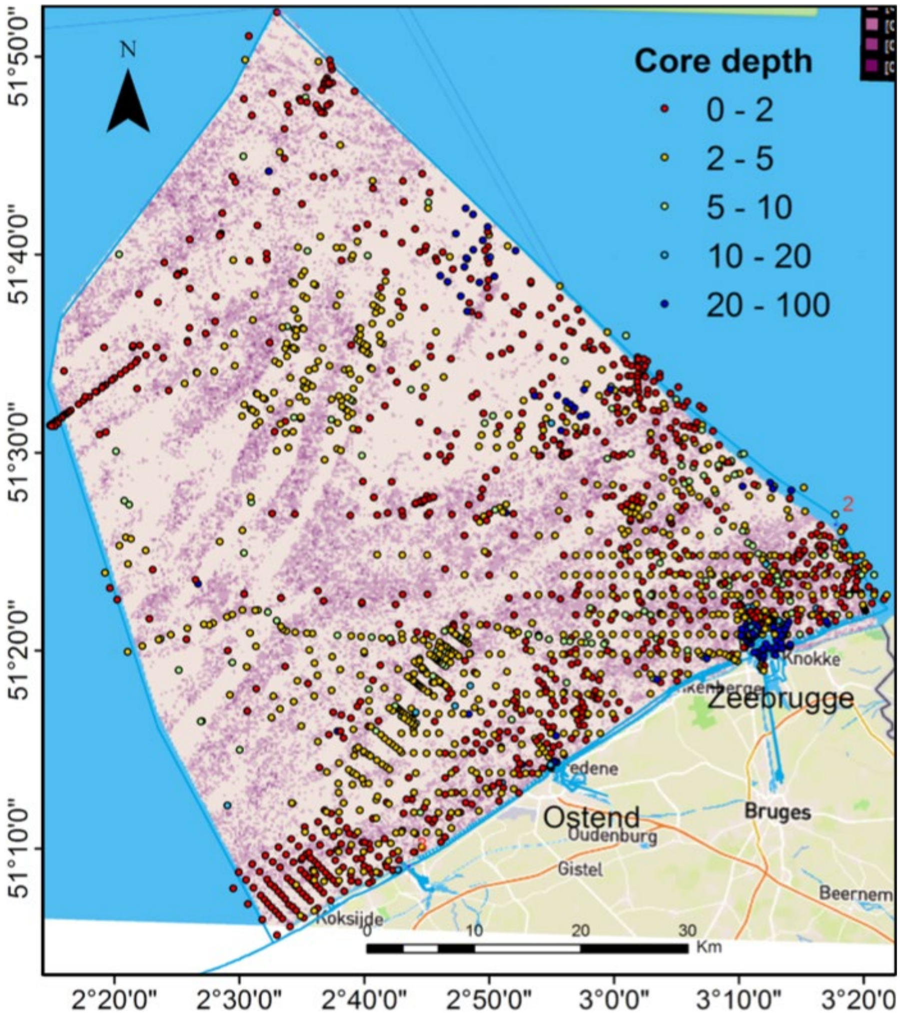


Figure 19. Data density, categorized in core lengths, superimposed on geological heterogeneity (shown in purple). Using the TILES DSS, it is here queried for the top 5 meters of the model. Heterogeneity, or varying lithology, is highest in-between sandbanks. It is a proxy of how different in nature the voxels are in a chosen voxel stack, hence over a user-defined depth interval.

Resource accounting

Thicknesses of the main geological layers provide first insight into the resource potential (Figure 20). Following, resource volumes can be calculated at will. Figure 21 shows the volumes of each of the lithoclasses in the main lithostratigraphic units in the Quaternary, as obtained using the TILES DSS. Experiments were conducted on quantifying resource volumes of a single area, but modelled with different resolutions. As an example, for a more detailed model of the Hinder Banks area, the 200 x 200 x 1 m model gave a volume of 1,673,600,000 m^3, whilst the 100 x 100 x 0.5 m model resulted in a volume of 1,675,345,000 m^3. This may seem a minor difference, but when real, it is highly significant from a resource-user perspective. It corresponds to the average extracted volume of near 2 million m^3 per year for the BPNS. The main added value of the higher-resolution model is that it is better in defining low-percentage sediment fractions (gravel) than the lower-resolution model.

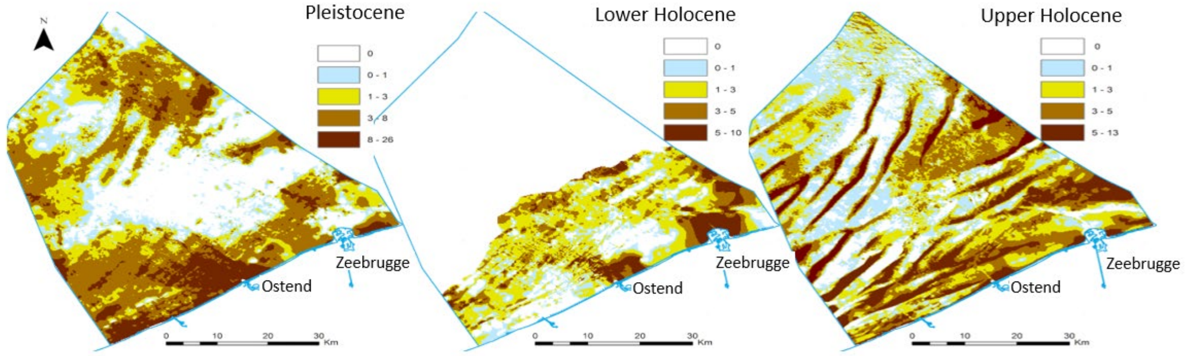


Figure 20. Thicknesses of the main geological layers. See Figure 21 for their lithological variation.

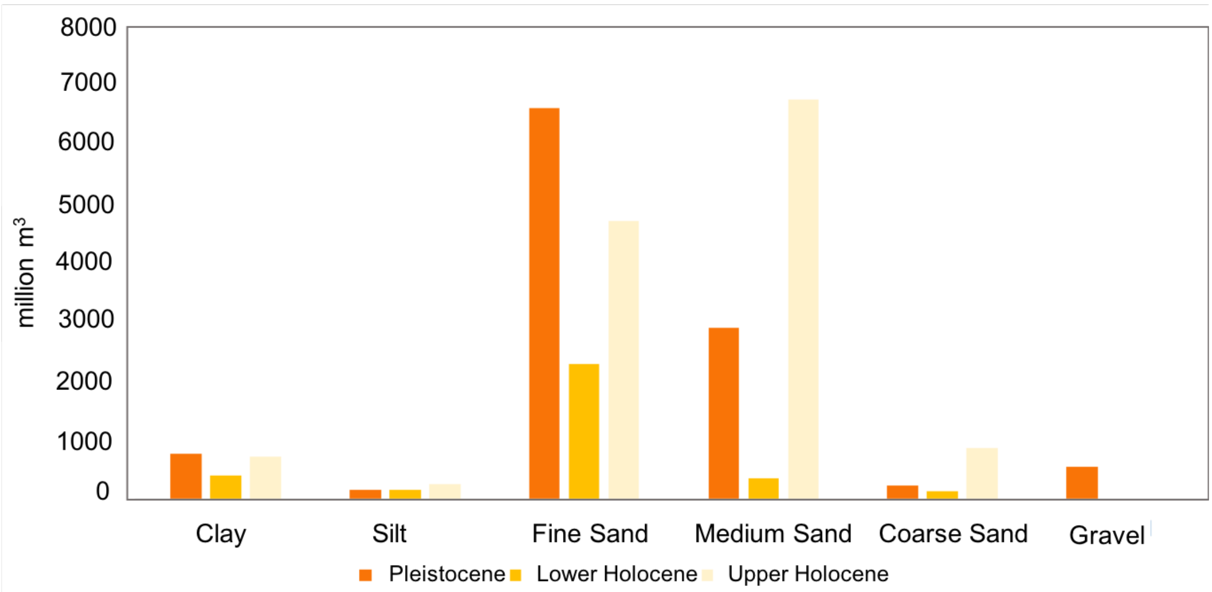


Figure 21. Volumes of lithological classes in the different units of the Quaternary on the BPNS. Note that no unit has a unique lithology. Upper-Holocene sediments have the highest chance of being medium to coarse sands. Overall in the Quaternary, fine sands are predominant (49 %), followed by medium sands (36 %), clay-silt (9 %), and coarse sand and gravel (7 %).

User-defined resource extraction

The TILES DSS allows the production of tailor-made resource maps, combining a suite of parameters defined by a user (Table V). Grain size and several admixtures (shells, gravel, clay) facilitating or limiting sand use or application can be queried separately or in combination. Layer thickness and confidence (e.g. model entropy; data uncertainty) can be included in the query as well to further optimize the location of extraction. With the addition of suitability criteria, the calculated resource volume will decrease (Figure 22).

Table V. TILES DSS search criteria that can be applied to estimate volumes for most optimal aggregate extraction. Here for aggregate sector 2OD, Oostdijck sandbank (location, Fig. 1; see also Fig. 22).

Parameter	**Value**	**Motivation**
Lithostratigraphic Unit	Holocene offshore (value 2) (Upper Holocene)	Recommended layer for extraction; minimum environmental impact
Lithoclass (probability of fine, medium, coarse sand) OR Most common lithoclass	> 0.66 Fine (5), medium (6), coarse sand (7)	Likely to occur
Entropy (model uncertainty)	< 0.6	Acceptable threshold*
Admixtures** *Shells* *Clay-silt* *Gravel*	 Max 10 % < 5% 	Example for concrete**
Data quality filter *Borehole density* *Positional quality*	 > 20 (contributing samples) > 80	 Considered high for BPNS DGPS (<10 m) or equivalent
Depth range	0-5 m below the seabed	Present-day legal threshold for extraction in Belgium

*Experience-based, from calculating the mean of the entropy distribution of various areas in the BPNS (0 means no uncertainty, whereas 1 occurs when all lithological classes have the same probability).
**British Standard for ‘Aggregates for concrete’: BS EN 12620.

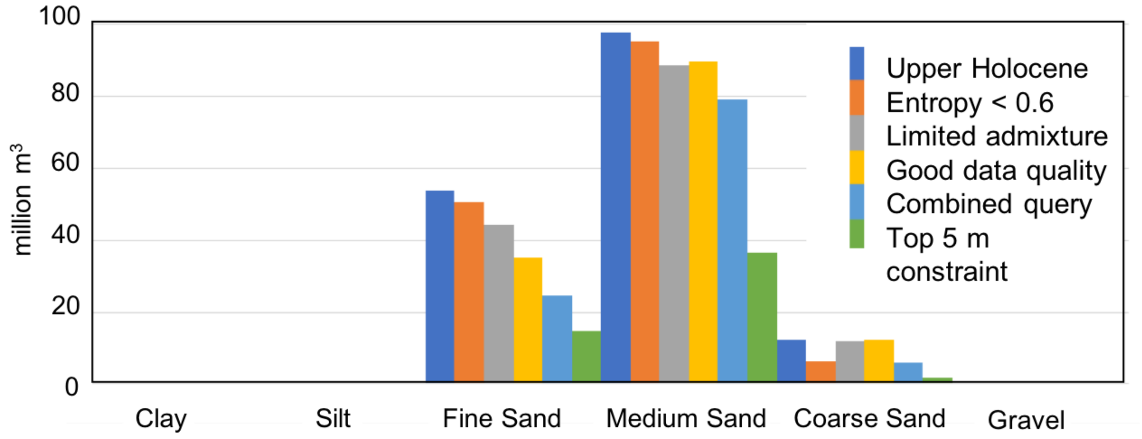


Figure 22. An example of a query in the TILES DSS using different qualitative resource criteria, here for the Oostdijck aggregate sector. Notice the resource volume difference as extra criteria are added to the query. Each filter has a different effect on each lithoclass. The entropy filter reduces more the medium and coarse sands than the data quality criteria on the borehole density and positional quality. This is because the amount of samples containing these lithoclasses are smaller than for the fine sand lithoclass, hence the entropies are higher. With this, it is important to highlight that statistics have a big effect on the model.

4.3. Resource extraction scenarios

Quantitative and qualitative seabed changes over time

When the voxel model, which gives the state-of-the-art instantaneous picture of the current state of the seabed, is coupled to a numerical model suite (see Section 3.4), it provides an opportunity to perform extraction scenarios to assess quantitative and qualitative changes in the seabed. The added value of this procedure is illustrated with an extraction scenario comparing a classical simulation representing one average sediment fraction (in the absence of such information) and a simulation using the qualitative and quantitative sediment information contained in the voxel model to represent multiple sediment fractions.

The scenario investigates the behaviour of the system over a spring-neap cycle under average meteorological forcing (winds) and waves. Figure 23 shows the simulated currents in the Flemish Banks area: they are strongest along the SW-NE axis, leading to the characteristic ellipse of residual currents (Figure 23, right).

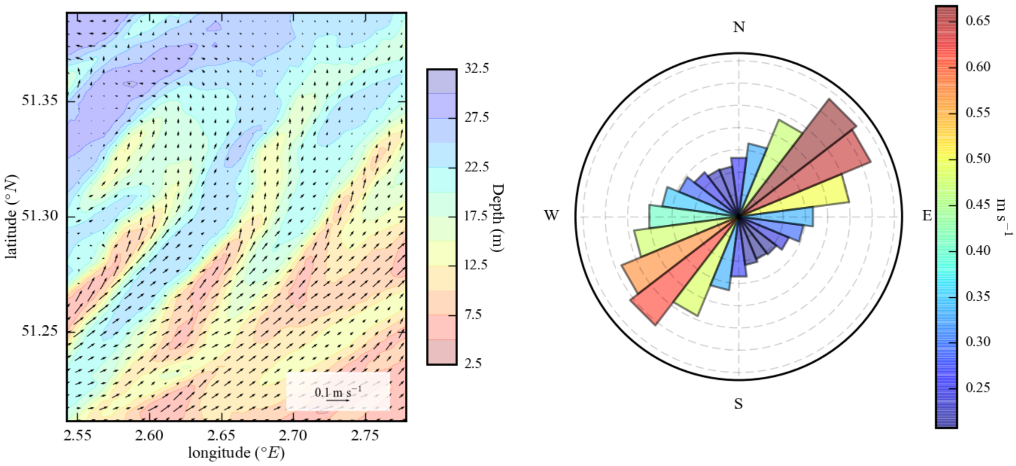


Figure 23. Simulated residual currents in the Flemish Banks: vector plot of the residual currents on top of the bathymetry (left), and tidal ellipse showing the dominant SW-NE axis (right).

When several sediment fractions (representing different lithological classes) are represented in the model, their parameterization (e.g. the particle diameter and the settling velocity) differs, and so does their behaviour in sediment transport (cf. Van Rijn, 1993). This is illustrated in Figure 24, showing the ellipse of transport (bed load) for the Clay + Silt (Figure 24a), Fine Sand (Figure 24b), Medium Sand (Figure 24c), Coarse Sand + Gravel (Figure 24d), and total sediments (Figure 24e). As the sediments get coarser from Figure 24a to Figure 24d, the bedload ellipse narrows: only the currents of higher magnitude along the SW-NE axis have enough energy to mobilize coarser sediments, whose transport in other directions is reduced or absent. In a model simulating only one sediment fraction, only an average behaviour (comparable to the overall results of Figure 24e) can be obtained.

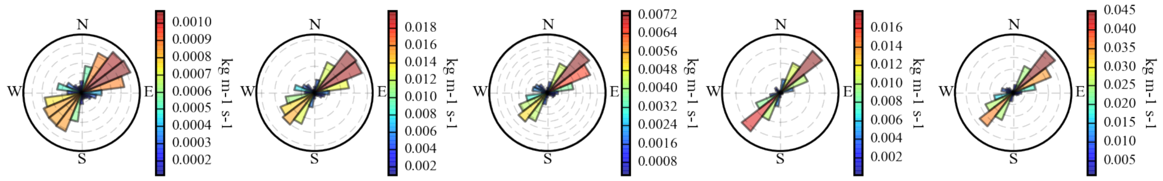


Figure 24. Simulated sediment-transport ellipse for the different sediment fractions and the overall sediment transport. From left to right (a-e): Clay + Silt, Fine Sand, Medium Sand, Coarse Sand + Gravel, and overall transport.

The simulated processes related to sediment transport (bedload, suspended load, erosion, deposition) thus lead to different results as a function of the distinct parameterization between sediment fractions. As a consequence, the simulated qualitative and quantitative changes of the seabed itself are different. To illustrate this, a hypothetical extraction scenario is used. In this scenario, ~310 10^6 m³ sediment are removed from the original bathymetry (Figure 25). This total removal corresponds to ~60% of the total volumes available for extraction as defined by FPS Economy, Continental Shelf Service based on the geological surfaces generated in TILES (Degrendele et al., 2017). At a present rate of extraction (~3 10^6 m³/y), this would correspond to ~100 years of extraction. The extraction in this scenario extends the current extraction spatial pattern until the total quantity is removed.

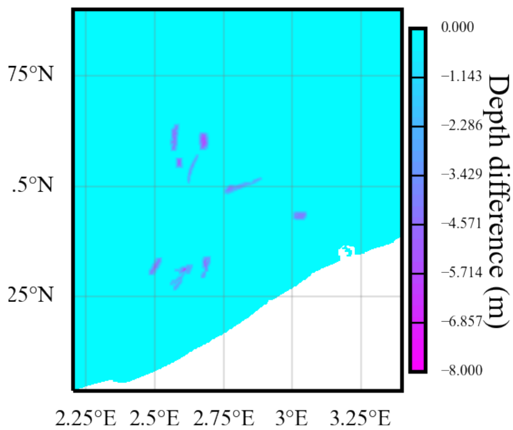


Figure 25. Bathymetric change used in the extraction scenario: the bathymetry is locally deepened according to the projected extraction potential in each extraction zone.

As shown in Figure 25, this would result in a local deepening of the bathymetry up to 8 meters in some sectors compared to the initial situation. Beyond this quantitative change, the removal of the seabed also leads to qualitative changes as seabed composition changes with depth. Composition change implies a supplementary effect, beyond the change in bathymetry, on the dynamics of the seabed (sediment transport as shown above). This effect can now be accounted for thanks to the coupling with the 3D voxel model. Figure 26 shows the simulated changes in depth (deposition in blue *vs* erosion in red) for a simulation with only one sediment fraction (Figure 26a) and a simulation with multiple sediment fractions (coupling with the voxel model; Figure 26b).

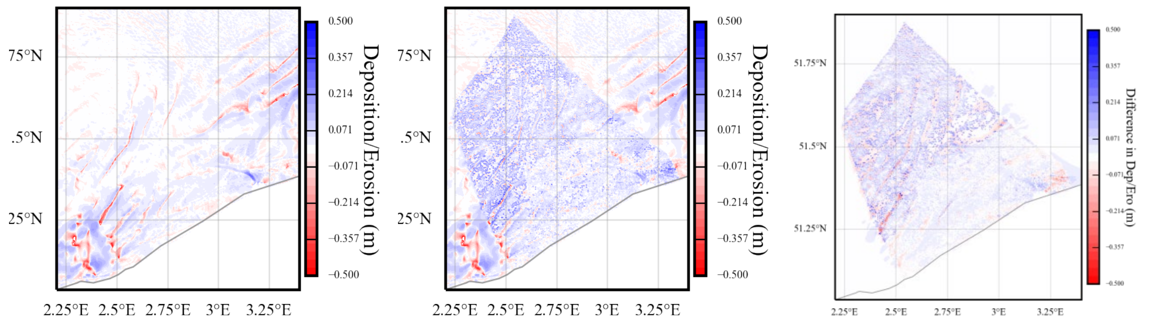


Figure 26. Simulated deposition (blue, positive bathymetric change) and erosion (red, negative bathymetric change) pattern for the three scenarios: simulation with one average sediment fraction homogeneous over the whole area (left); simulation with multiple sediment fractions after coupling with the voxel model (center); and difference map between the results for the two simulations (right), highlighting the importance of the geological information exploited in the multi-fractions simulation.

In Figure 26a, the pattern in erosion/deposition closely follows the bathymetry. This indicates how the quantitative aspect of the seabed (i.e., the bathymetry) is governing the results. In contrast, Figure 26b shows how qualitative aspects of the seabed (its lithological composition) also affect results. This is clearly visible through the area covered by the voxel model where qualitative information is available: outside the BPNS (no data from the voxel model), the results follow the bathymetry, while inside the BPNS (coupling with the voxel model), the contrasted behaviours of the different sediment fractions supplement the effect of bathymetry. Figure 26c shows the difference between the results from Figure 26a (one sediment fraction) and Figure 26b (multiple sediment fractions): this is the component of the pattern in erosion/deposition that is due to qualitative differences in seabed composition (only in the BPNS, for which geological data were used). The importance of the geology is clearly visible, e.g. through the difference in general behaviour between areas up to 10-15 km from the shoreline, where Lower-Holocene deposits are present comprising finer-grained fractions (see Section 4.2), and areas farther offshore.

Altogether, this modelled difference highlights the importance of geology and knowledge-based approaches in modelling studies assessing the behaviour of the seabed. Simulations such as these can typically be used to estimate the effects of extraction on the ecosystem, and to identify areas most/least likely to experience deposition and consequently most/least suitable for extraction (e.g. to produce suitability maps). The importance of geology in such an exercise is crucial, as demonstrated in the TILES project. Consequently, the parameterization and initialization of modelling studies including multiple sediment fractions is of primary importance, and the coupling with a voxel model is crucial progress. It fills a need of the scientific community for a more informed parameterization and initialization, and helps support decisions by policy makers for sustainable development in particular and society in general.

Regeneration and depletion rates of marine sand resources

The regeneration or depletion potential of the seabed is best assessed by investigating *in situ* data. Two sources of information are used to study the behaviour of the seabed in areas of marine aggregate extractions: on the one hand, multibeam echosounder (MBES) data, repeatedly acquired in defined control zones to provide time series of bathymetric data; on the other hand, an electronic monitoring system (EMS) recording position and extracting activity on board of extraction vessels.

On average, bathymetric changes (MBES data) between successive campaigns in monitored areas were observed to correspond to the depth differences expected from human extraction (EMS data; Roche et al., 2011, 2013; Degrendele et al., 2014). This is illustrated for the monitored areas of Zone 2 (Flemish Banks) in Figure 27: in this approach, each area is binned into sectors of extraction intensity (depth difference due to extraction from 0 to 1, 1 to 2, 2 to 3, … 10^3 m^3/ha) within which the mean observed difference in bathymetry is compared to the mean expected decrease in depth due to extraction (see Roche et al., 2011). When the potential systematic error affecting MBES bathymetric measurements is corrected and when additional data from other extracted and monitored areas are used, the volumes of sand extracted estimated from EMS data are in very high accordance with those deduced from MBES surveys (Debese et al., submitted).

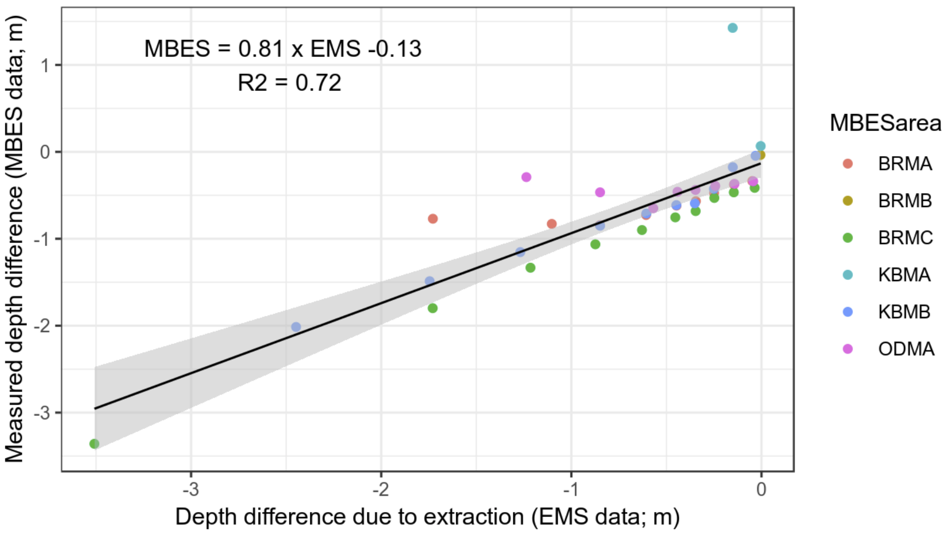


Figure 27. Relationship between the measured depth difference (MBES data) and the depth difference attributed to aggregate extraction (EMS data) in the six areas over the investigated period in this study. To a large extent, the measured depth difference is explained by the depth difference due to extraction (Degrendele et al. (2014). Using corrected and additional data from other extracted and monitored areas, the slope of the regression line is closer to 1. For legend of the areas, see Table VI.

A similar comparison can be made at the full spatial resolution provided by the data, corresponding to 1 m and 25 m horizontally for the MBES and EMS data respectively. Bathymetric difference is investigated between an initial and a final state, derived from the oldest and most recent available MBES grid for each area (at the time of performing this analysis). Table VI reports the dates corresponding to the initial and final campaigns for each area.

Table VI. Monitoring campaigns used in this study for the six areas in the Flemish Banks. BRMA/BRMB/BRMC: Buiten Ratel, Monitoring area A/B/C; KBMA/KBMB: Kwinte Bank, Monitoring area A/B; ODMA: Oostdijck sandbank, Monitoring area A. For location of the sandbanks, see Fig. 1.

Area	Initial campaign	Final campaign	ΔTime (days)
BRMA	8 Oct 2007	19 Nov 2013	2234
BRMB	2 Jul 2008	19 Nov 2013	1966
BRMC	25 Feb 2010	18 Nov 2013	1362
KBMA	3 Mar 2003	13 March 2013	3663
KBMB	12 Jun 2003	12 Mar 2013	3561
ODMA	1 Jul 2008	19 Nov 2013	1967

When a map of the bathymetric difference is produced between two campaigns, two main patterns are dominating the resulting signal (see Terseleer et al., 2016): the deepening of the seabed due to human extraction, which is sometimes locally concentrated and intense (up to > 5 m deepening); and the natural migration of the very large bedforms covering the sandbanks, which results in successive increase and decrease in bathymetry in accordance with the changing position of the bedform crests and troughs. The remaining variability, grouped here as residual variability, is an indication of the behaviour of the seabed beyond these two main patterns and can provide information in terms of long-term depletion/regeneration rates. In the scope of the TILES project, a protocol was set up to assess the residual variability of the seabed beyond the two main sources of seabed changes (migration of very large bedforms, human extraction). It is summarized here (see Terseleer et al., 2016, for details).

First, the effect of bedform migration is removed after estimating the overall bedform migration in each area between the initial and final campaigns. This estimation is obtained through an optimization process, in which the initial bathymetry is shifted horizontally in different directions and over varying distances, selecting the best match with the final bathymetry. The resulting vector corresponds to the overall migration pattern of the largest bedforms (typically, sandwaves on the sandbanks). This produces a shifted initial bathymetry.

Second, the seabed quantities that were removed by human extraction between the two campaigns were restored to the final bathymetry: extracted volumes between the initial and final campaigns, estimated from the EMS data, were reported over a 25 m x 25 m grid to estimate a depth decrease that was then added in order to simulate a final bathymetry as if no extraction had occurred. This produces a restored final bathymetry.

The difference between the shifted initial bathymetry and the restored final bathymetry generates an estimate of the residual variability beyond the major influence of bedform migration and sand extraction. The resulting difference map is positive when the seabed is shallower than expected (accretion is observed) and negative where it is deeper than expected (erosion). When these depth differences are related to the time interval between the two monitoring campaigns, they correspond to net rates of regeneration (accretion, positive change in bathymetry) or depletion (erosion, negative change in bathymetry). Figure 28 shows the maps of regeneration/depletion rates, normalized for one year, for each area.

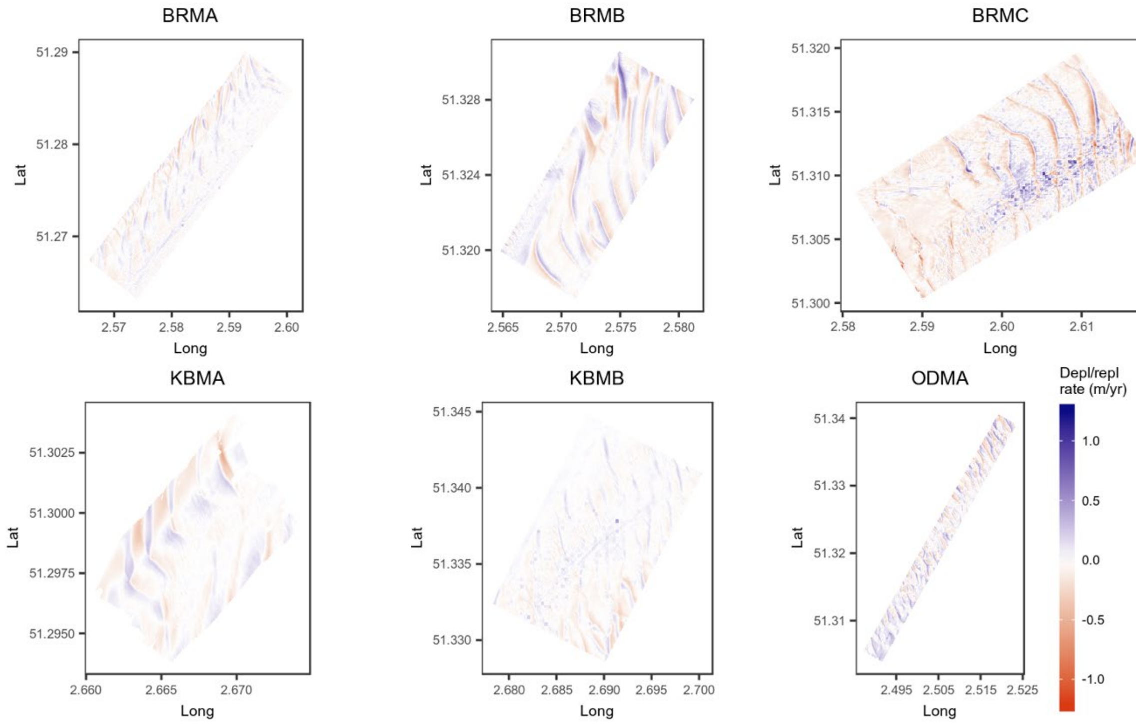


Figure 28. Depletion (negative seabed change, in red) and regeneration (positive seabed changes, in blue) rates in the six areas, beyond dune migration and sand extraction (see text for details).

Figure 28 shows that the elimination of the dune migration is not perfect. Indeed, dune migration is not homogeneous over the dune fields of each area, and successive bands of accretion and erosion are locally visible where the migration was not fully compensated by the optimized overall dune migration. Yet, this effect is reduced and the remaining variability is considered to reflect the residual behaviour of the seabed. Figure 29a shows the density plot of these depletion/regeneration rates for the six areas, and the boxplots in Figure 29b summarize the values.

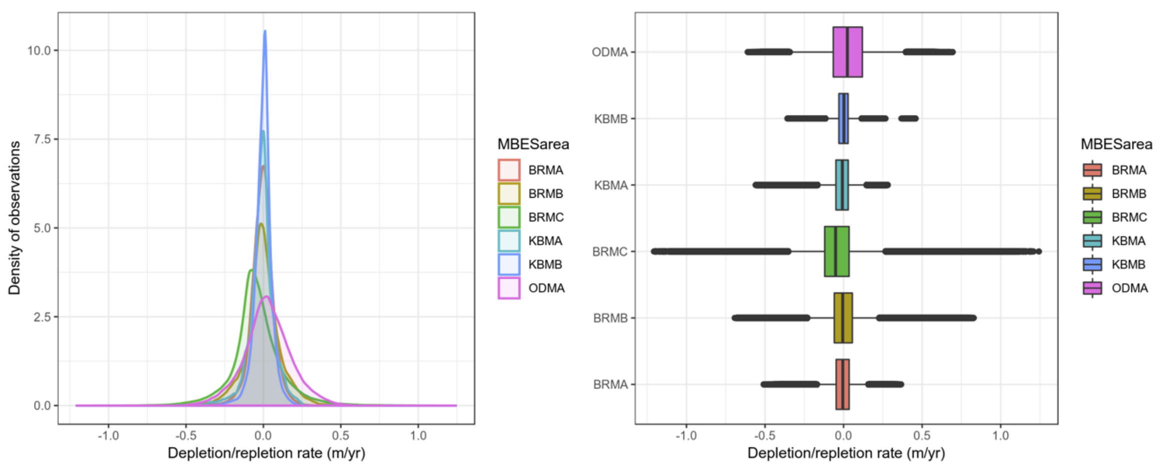


Figure 29 (a-b). Density plots and boxplots (right) of the depletion/regeneration rates for each area.

Across the six areas, the depletion/regeneration rates vary from -1.21 to 1.24 m yr^{-1} (in BRMC), but 90% of the surface within these areas experience a depletion/regeneration rate between -0.21 and 0.12 m yr^{-1}. Table VII shows the percentile 10 and 90 for each area: given that each value represent one pixel from Figure 29 (corresponding to 1 m²), these values encompass 80 % of the surface of each area.

Table VII. Percentile 10 (p10) and 90 (p90) of the depletion/repletion rates for each area.

Area	**p10 (m yr-1)**	**p90 (m yr-1)**
BRMA	-0.090	0.079
BRMB	-0.14	0.13
BRMC	-0.21	0.15
KBMA	-0.11	0.082
KBMB	-0.066	0.061
ODMA	-0.16	0.22

The median depletion/repletion rate is close to 0 m yr^{-1} (no bathymetric change), but is more negative for BRMC. This area has a skewed distribution towards negative bathymetric changes (Figure 30). Interestingly, the distribution of locations experiencing erosion or deposition in BRMC shows a clear spatial pattern (Terseleer et al., 2016): erosional areas are concentrated on the crests of the very large dunes covering the sandbank (mostly at the northern corner of the area; Figure 29c), and accretion marks the extraction pit (along an axis perpendicular to the sand-wave crests, in the southeastern part of the area). Figure 30 shows the relationship between the depletion/repletion rate and the extraction rate: in areas experiencing a non-negligible extraction (> 0.1 m yr^{-1}, i.e. BRMA, BRMC, KBMB, and ODMA), a positive relationship exists between the depletion/repletion rate and the extraction rate. In other words, and as more clearly visible for BRMC (which experienced the largest extraction), the locally most heavily extracted locations tend to experience residual accretion.

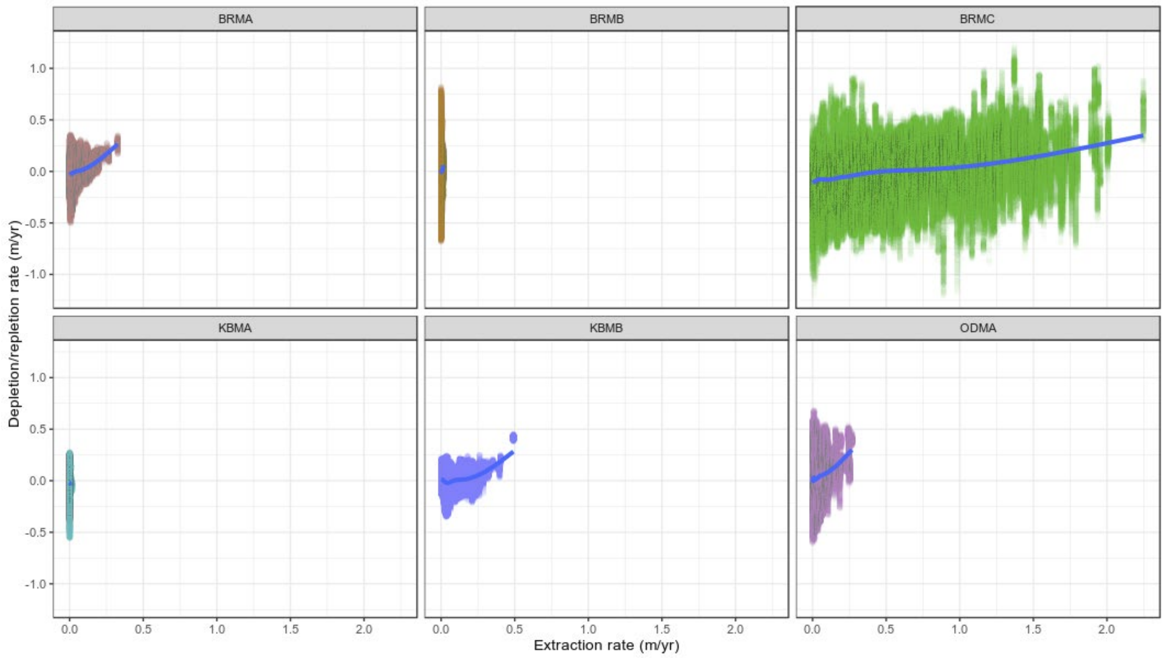


Figure 30. Depletion/regeneration rates vs extraction rates in the six investigated areas. The smoothing curves illustrate the global trend of the relationship (they are produced with a generalized additive model using cubic regression splines).

Two observations are made here: first, the regeneration rate is reduced compared to the extraction rate (on average, about one order of magnitude lower); second, the positive regeneration rates in some locations are accompanied by negative depletion rates elsewhere, leading to a global balance in bathymetric change within each area which is close to zero (or slightly negative in the case of the most heavily extracted area, BRMC). Altogether, these observations seems to indicate that the large-scale regeneration potential after human extraction is very limited. Moreover, these regeneration vs depletion dynamics suggest a possible flattening of the seabed, driven by local sediment redistribution. This can negatively affect the longer-term diversity in these areas: while a local biodiversity increase has been observed at a small scale after disturbance by human extraction (De Backer et al., 2014), a longer-term and larger-scale seabed homogenization would negatively affect the habitat potential and biodiversity in areas of marine aggregate extraction.

These observations can be exploited in decision making about the management of exploited areas and deserve further investigation: in the next step, the analysis is to be generalized to all monitored areas and actualized with the most recent data in order to further investigate the processes governing the seabed dynamics.

Long-term sediment transport patterns steering extraction location

Results on the long-term modelling need further upgrading into probability maps of long-term natural erosion and deposition magnitudes and rates. This would allow favouring extraction in depositional areas, and avoiding naturally erosive areas, hence minimising environmental impacts.

4.4. Resource decision support and knowledge base

Multi-criteria decision support tool

The TILES DSS, available at http://www.bmdc.be/tiles-dss/, allows resource qualities and quantities to be visualised within set uncertainty ranges that are deemed acceptable. Information can be retrieved for any location (user-defined polygon as in Figure 31), but also within predefined areas such as those designated in the Belgian marine spatial plan. A user can make a series of tailor-made suitability maps that assist in resource assessments. Cross-sections are an extra functionality, allowing easy exploration of sandbank architectures. They are also invaluable for outreach and educational purposes. Figure 31 illustrates the sandbank architecture of the Middelkerke Bank, probably being the best-studied sandbank in the world. Figure 31 shows the most likely lithological class with associated volumes, supplemented with the location of the boreholes used to create the subsurface model. A lacquer peel shows an excellent correspondence with the modelled lithoclasses for the corresponding location. The alternation of different qualities of sand, clay and shell is illustrative of how complex a sandbank body can be. The cross-section, as derived via the TILES DSS, reflects this complexity and additionally provides insight into the spatial distribution of the lithological units.

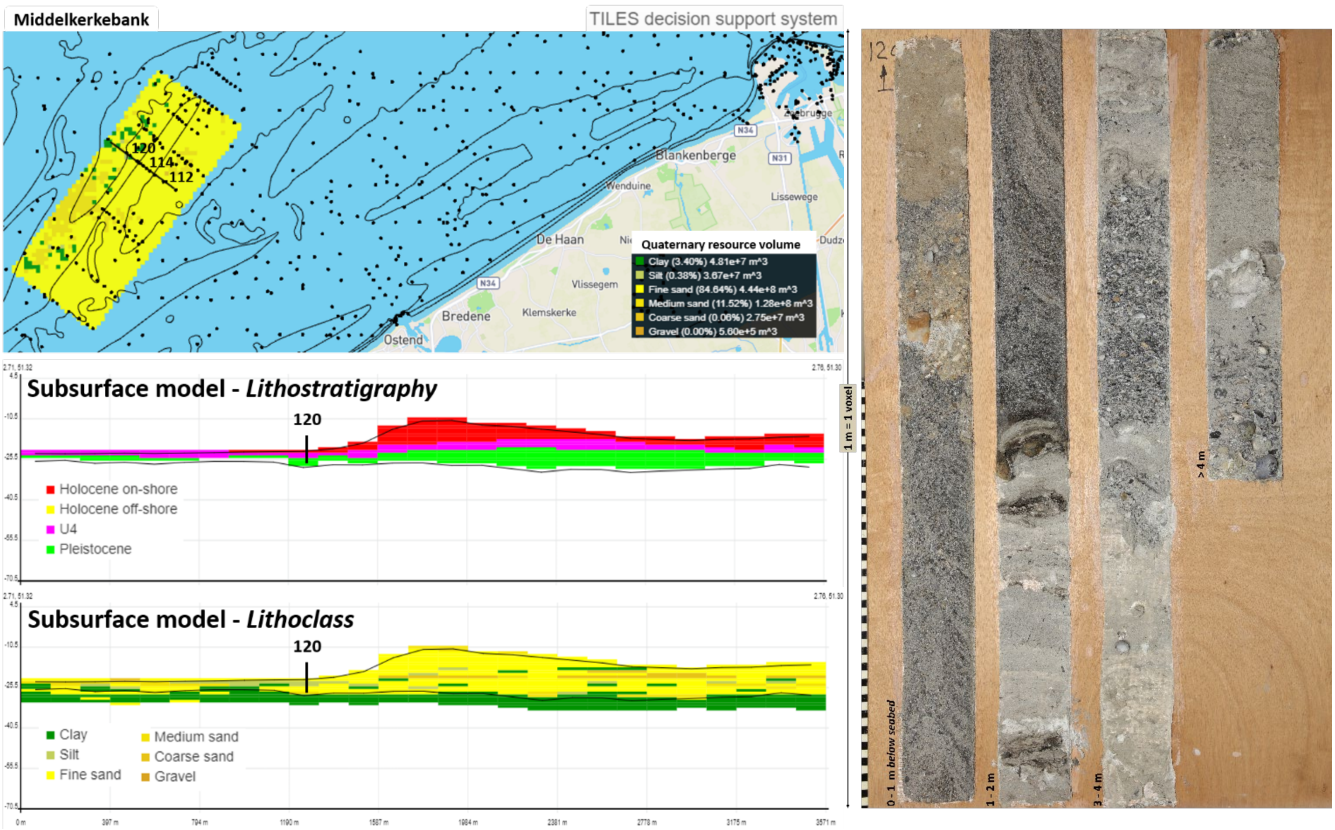


Figure 31. TILES DSS extract of the Middelkerke sandbank (BPNS), lithological classes with volumes, and lithostratigraphy. A cross-section is made along some vibrocore locations. Right: picture of core 120 showing the heterogeneity of the Quaternary layers.

More information can be found in section 5.2 and on the TILES DSS portal itself.

Future DSSs ideally have variable voxel sizes determined by user-defined criteria, e.g. core density and uncertainty. The colour would be indicative of the suitability of a defined aggregate quality (Figure 32).

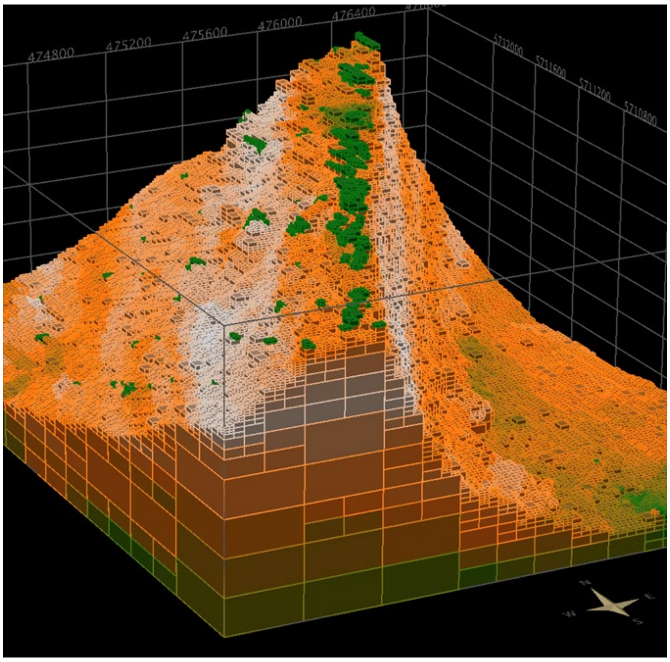


Figure 32. Prototype of a variable-size voxel model, here of a sandbank. The colour indicates suitability for extraction of medium sands (greyish: highest suitability; green: lowest suitability). Voxel size provides a broad indication of data uncertainty. Small voxel sizes at the surface are indicative of the highly detailed bathymetrical data layer and of samples describing the active layer; increasing voxel size in the subsurface is a function of decreasing borehole density with depth.

Long-term strategies for adaptive management

Geological knowledge bases are inherently uncertain. As long as extraction practice is not subject to significant change, management actions are uncomplicated. However, anticipating on the higher diversification and increasing need of well-specified resource qualities and quantities in Belgium and the Netherlands on the medium to long term, management practices need adaptation. Such adaptation is necessary at various levels: (1) with increasing competing sea-based activities there is an urgency to reserve areas with thickest and most valuable resources for aggregate extraction; (2) knowledge on the most optimal locations for extraction from geological, economic and environmental perspectives will become ever more important; (3) with vastly increasing quantities expected to be extracted, large-scale environmental changes will need better prediction and thresholds need to be set on allowable impacts. When these are exceeded, plans need to be adapted even when there is a socio-economic cost.

Overall, **adaptive management implies better system knowledge** and monitoring to close the gap between what we know and what we should know. As knowledge and experience grow when new observations and experiences become available during extraction monitoring and resource exploitation, there must be a mechanism for adaptation of monitoring and extraction plans. On a data level, new data and information should feed into the TILES DSS, ideally from multiple sources and research disciplines, matching **resource supplies and needs** that **should** also **be regularly updated**.

Reserve areas with most voluminous suitable geological deposits for aggregate extraction

Marine Spatial Planning (MSP) is the tool of choice for reserving seabed space for marine aggregate exploitation where the geological resource is thickest. The TILES DSS provides this information and the present concession zones can be evaluated in terms of resource quantities and qualities. Since MSP is a cyclical process, adaptations to the present concession zones are conceivably possible.

The TILES DSS was consulted and used in the **revision of the current MSP**, which will be applied in 2020. Through FPS Economy, the aggregate sector was provided with geological information to propose among others a new concession zone in the northern area of the BPNS.

Define more resource-efficient extraction practices

The TILES DSS is the first tool for estimating resource quality and quantity, and their uncertainties, consistently at user-defined locations. Well constrained estimates with confidence assessments are particularly valuable in 'sediment-starved' systems, such as the BPNS. In such areas, careful considerations on **where, when and for which purpose** to extract sand are the key to sustainability. Extraction is most favourable in geological layers that are most homogeneous in resource quality. Therefore, only extraction in the upper-Holocene layers is recommended. It should be limited to the sandbanks not subject to overall natural erosion. All upper-Holocene layers formed under open-marine conditions similar to the present-day hydrodynamic regime, hence no major sediment-related habitat changes are expected during exploitation that is limited to these layers. Highly certain volumes of medium sand are small and localized within the 12 nm zone. They are more continuous farther offshore, but distance to shore adds to transport costs.

Fragmentation and patchiness of the Quaternary cover imply more heterogeneity in the geological layers, calling for **targeted extraction to minimise undesired admixtures**. Adaptive management should assist in this process by providing best available knowledge. These can be queried in the TILES DSS, but require validation and user-feedback.

Better predict large-scale environmental changes and define thresholds of allowable impacts

Predicting large-scale environmental impacts and changes is prone to large uncertainties because of the many poorly constrained variables. It requires ecosystem-wide knowledge on the status of the seabed and its biodiversity, which is highly dependent on it, as well as on the water column and its pelagic habitat. Locally and externally driven responses to a set of pressures, including the resilience and carrying capacity of the area, need to be quantified. This is a long-term endeavour requiring adaptive monitoring with updatable objectives that need periodic evaluation and cyclical adjustments to better meet objectives. To avoid exploitation into heterogeneous geological layers, that are prone to unwanted admixtures and causing habitat change, built-in safety margins should allow for threshold-related uncertainty.

The TILES DSS provides an **adaptable framework** to incorporate data of various time periods and disciplines. Coupled to environmental impact suites, it facilitates the evaluation of seabed and water-column changes as the seabed is steadily lowered and deeper geological layers are being extracted. Ideally, the TILES DSS is further **modularly coupled to other modelling suites**, e.g. to better capture changing ecosystem responses and altering (fish)habitat connectivity under extraction. Using generous safety margins, **thresholds of allowable impacts need to be redefined** and evaluated periodically, whenever the scale of extraction increases or monitoring data give good cause.

New legally binding measures for sand exploitation

Anticipating on reserving areas with the most voluminous economically valuable aggregate resources, whilst preventing major negative environmental changes, FPS Economy, Continental Shelf Service, performed a study on defining a new lower limit for extraction. The TILES results were used intensively during the evaluation of the impact of this new reference level on the evolution of available resources.

Legally, the present limit for aggregate extraction is set at a maximum of 5 m below a reference surface defined by FPS Economy, Continental Shelf Service (Law of 13 June 1969 on exploration and exploitation of the non-living resources of the Territorial Sea and the Continental Shelf, amended by the laws of 20 January 1999 and 22 April 1999). To date, this is a detailed seabed terrain model of the extraction areas, as obtained from extensive multibeam surveying in the first half of the previous decade. On the basis of this limit, three areas in the aggregate concession zones with a deepening exceeding 5 m were closed. Currently, this limit is also approached in other areas, potentially leading to additional closures.

To anticipate on increasing resource needs FPS Economy, Continental Shelf Service redefined the lower limit of extraction making use of best available scientific and legal criteria (Degrendele et al., 2017). The purpose is to **limit the impact of extraction in the most sensitive habitat areas and to increase economic sustainability** by considering the available volumes and quality of sand (TILES input). A proposal is in preparation to make this new limit legally binding. Once in place, extraction will need to be evaluated against this new reference surface. As the new limit is no longer tied to the bathymetry alone, it requires a more thorough control on the sector's activities and more in-depth exchange of information between government, science and industry.

Long-term resource use, Belgian part of the North Sea

FPS Economy, Continental Shelf Service made first predictions of how long sand resources will be exploitable given current rates of extraction. Referring to the same study of Degrendele et al. (2017) adoption of the new reference level for extraction would lead to an exploitable aggregate quantity of $260x10^6$ m^3 (medium to coarse sand) in the present-day concession zones, or **roughly 80 years of extraction** at the present rate ($3x10^6 m^3 yr^{-1}$).

This exhaustion prognosis does not account for increasing needs for existing purposes or for extra sand volumes needed in special projects (e.g. coastal defence or offshore construction). It must be emphasised that these estimations are very rough and do not account for the uncertainty on the geological data, i.e. aggregate qualities and quantities are unevenly spread and sometimes very patchy and thin. Additionally, neither cumulative impacts from different human activities nor longer term human-nature interactions that may halt exploitation are considered,. Predicting impacts of aggregate extraction well beyond today's relatively modest extraction practices is still prone to major speculation.

In contrast to the relative scarcity of medium to coarse sand, **fine sands are abundantly available**. Clearly, the sustainability debate re-opens once these resources would become of more interest to the user community. Technological advancement is needed to upgrade finer fractions for use in the building industry.

4.5. Conclusions and Recommendations

Conclusions

TILES resulted in the creation of a **transnational, harmonized geological voxel model** covering the Belgian and southern Netherlands part of the North Sea. The voxels are filled with geological data, as well as associated data quality/uncertainty and are **open to incorporate any additional data**. As such, a knowledge base has been created that can function as a **critical platform for the exchange of data, information and increasing specialist expertise**. Beneficiaries include a wide range of seabed users, hence supporting Europe's Maritime Policy, as well as its environmental pillar the Marine Strategy Framework Directive. The latter contributes to the integrated management of the marine environment, pivotal to achieving Agenda 2030's sustainable development goals.

TILES reaffirms that sustainability is a principle with a time and a space horizon. Even at its modest present rate, the **Belgian medium to coarse sands will be exhausted** within 80-100 years, or three to four generations, if extraction remains limited to the present-day concession zones. As such, **alternatives** need consideration and **marine resource management adapted accordingly**.

We propose to:

1. **Integrate** thickest geological resources for extraction in marine spatial plans, and make them central in **decision support** on competing use of the marine space;
2. Optimize **long-term** availability of resource quality by increasing **resource efficiency**, e.g. medium to coarse sand most useful in construction; fine sand sufficient for levelling and where possible also for coastline maintenance; minimize unwanted admixtures or waste;
3. Govern sustainable resource **exploitation** in a **transnational** context, given the unequal distribution of sands, i.e. scarcity to abundance in a same region. Tracking and accounting for material flows is hence important in trading;
4. Invest in technological development for physically upgrading the abundantly available fine **marine** sands, e.g., for construction purposes.

In generating these and other follow-up questions, TILES opens up new lines of research. The recommendations formulated below are the main pathways along which further developments are proposed.

Recommendations

From an overall resource use perspective, the UN Resource Panel puts forward that "*In the mid-term, except in specific cases, resource shortage will not be the core limiting factor of our (economic) development, but the environmental and health consequences caused by excessive and irresponsible use of resources".* For a significant part of the southern North Sea we now have, with TILES, a quantitative basis to account our aggregate resources. However, it remains critical that the effects of aggregate extraction remain monitored and studied on a regular basis (as mandated by Law) and build a dynamically growing knowledge base on human-nature interactions.

> To meet future resource needs, increasing quantities of sand will be extracted. The large time and spatial scales involved, call for environmental sustainability assessments to reach the **UN Sustainable Development Goals** (SDG). Improved insights into socio-economic demands and their management are critical.

Towards holistic environmental assessments

> To fully address resource sustainability on the longer term, there is a **need to more systematically comprehend connections and feedbacks within a coupled human-natural system**.

In TILES, coupling resource-related 3D voxel models with a suite of numerical environmental-impact models is major step forward. However, at present, the focus is still very much on geological attributes. Biological parameters can also be added to voxels, but is not yet included. It should be an integral part of future valorisation efforts. It is clear that marine aggregate extraction affects the whole ecosystem and in particular its living organisms (e.g. benthic or fish populations; Cooper et al., 2008; Stelzenmüller et al., 2010; De Backer et al., 2014). The resilience of marine ecosystems to human stressors (such as aggregate extraction) remains poorly quantified (Elliott et al., 2007), and 4D modelling frameworks able to incorporate temporal change can contribute to filling this gap in knowledge. Whilst model studies of the effect of extraction on living organisms (e.g. Barry et al., 2010) are increasing in number, a full suite of numerical models coupling physical drivers (e.g. hydrodynamic conditions, human disturbance through dredging) and biological components (e.g. benthic assemblages) remains to be established. The quantitative biotic-abiotic links established through such an integrated approach will allow more targeted monitoring of the environmental consequences of sand and gravel exploitation and will help the decision maker or other end users to select the most informative attributes and associated value ranges for visualisation. A holistic approach linking sand and gravel extraction to natural systems' behaviour and specified future human needs (e.g. Elliott et al., 2007; Atkins et al., 2011), and thus improving knowledge-based decision making, is possible only when data and models are shared freely (Sutherland et al., 2014). TILES data products are open and free for further use. Modular expansions of the TILES DSS are needed to further explore the human-natural system.

Developing a socio-economic resource framework and accounting of resource supplies and needs

In view of attaining the SDGs, there is a need to better comprehend the socio-economical, technological and uncertainty aspects of resources and to classify those into a comprehensive management framework. Under the umbrella of UNECE (United Nations Economic Commission for Europe, www.unece.org) a universally acceptable and internationally applicable scheme for the sustainable management of all energy and mineral resources has been developed: **United Nations Framework Classification for Resources (UNFC,** UNECE 2013**).** UNFC is a tool for harmonizing the policy framework, government oversight, industry business process and efficient capital allocation, whilst contributing to a variety of SDGs.

The geological knowledgebase and associated uncertainty, as the core product in TILES, is a pillar of further **socio-economic classifications that are more universally applicable** such as UNFC. Upcoming geological projects intend to test the applicability of UNFC in various environments, including the marine environment. Applying UNFC would allow us to assess the costs and benefits associated with vastly increasing human activities, planned, in progress and finalized, in terms of socio-economic return, environmental considerations, and technological readiness.

Resource supplies and needs are ideally accounted using **material flow analysis (MFA)** techniques and preferably include land-sea, cross-border interactions or even global evaluations. MFA would provide a systematic assessment of resource flows and stocks in a system that is defined in space and time without borders (Brunner and Rechberger 2004). UNFC could be the basis of MFA, with MFA allowing more effective scenario development, leading to indicators and strategy, as well as decision support.

Towards more intelligent decision support for sustainable development

Achieving the SDGs is also a stimulus for further innovation in the development of intelligent decision support systems (I)DSSs. Whilst UNFC and MFA already assist in decision support, IDSSs provide processing technology to seamlessly and rapidly interoperate data on environmental, economic, and social considerations, along with their inherent uncertainties.

Rapid and easy computation of multiple resource scenarios allows **efficiently and jointly weighting of geological, environmental and socio-economic parameters**, leading to a collective understanding of what is at stake, and providing a means for comparing the consequences of choices made during planning. It cannot be done without additional multi-disciplinary and cross-sector research as well as technological advancement.

Towards a more efficient and circular approach in marine aggregate extraction

TILES provides useful static insight into how to extract sand efficiently, i.e. targeting the right quality for the desired purpose and avoiding undesired admixtures (minimizing waste). More can be gained, however, if the dynamics of the marine system are considered and areas with net long-term deposition rather than net erosion are prioritized for extraction.

Acknowledging that **sand resources are finite**, behavioural changes are needed. In the longer term, extraction will need to align as much as possible with the needs of a **circular economy**.

An obvious example, and already applied is the beneficial use of dredged material from harbours and access channels. Its sandy part can be extracted, and employed for beach nourishments or for construction if the quality is fit for purpose. If needed, the finer-grained fraction may even be upgraded. Presently, considerable amounts of sand dredged for offshore works (e.g., windmills, cable laying, infrastructure works *s.l.*) is not fully utilized. Registration of these anthropogenically-induced sand flows would allow evaluating their usefulness and potential contribution to other purposes. In the long term, alternatives for sand resources need to be investigated. Recycling will become increasingly common, but upgrading the quality of sediments too fine for immediate use is even more important. Technological advancement is key in this process. Nevertheless, reducing the consumption of sand resources is perceived as imperative (Gavrilitea, 2017).

Roadmap for resource sustainability: Code of Sand

To valorize the TILES results from the perspective of a more sustainable use of aggregate resources in the long term, its main results and further research pathways are synthesized into a roadmap composed of 17 messages. These were presented at the final conference, and are available as a message 'fan'; each message is accompanied by a picture highlighting a sand type and associated quality in the TILES area.

The **Code of Sand** brings **awareness** on the nature of sand and its dynamics, its use as a resource, its management, and the way its associated data should be made available, all in view of a better **comprehension** of the marine system.

5. DISSEMINATION AND VALORISATION

5.1. Interaction with steering committee

Stakeholders from various governmental and industry organisations participated in three workshops and *ad-hoc* meetings were organized with selected stakeholders. These interactions were pivotal for data input and for the optimisation of the TILES products. They stimulated new developments such as variable-size voxel modelling.

Data exchange with government and industry
Considerable data and information exchange took place with **FPS Economy** being the major stakeholder of the TILES project. Borehole data were also received from **Flemish Authorities**, Maritime Entrance. From industry, data were received from the **marine aggregate sector**, as well as from the **NEMO** project. An '*ad hoc*' arrangement was made with the **main windmill operators**, resulting in significant extra borehole data for the creation of the subsurface voxel model. All data were standardized, and their quality was assessed. Upon request data were only used in the geomodelling; these data are flagged 'confidential' in the database.

From all interactions, from the overall enthusiasm of stakeholders at national and international conferences and workshops, and from the fact that the TILES voxel model and DSS are actively adopted by stakeholders, it is clear that the project is leading ahead in the way marine resource management is and should be approached.

5.2. New resource-management tools

A first Belgian marine geological data portal
Compiled historical data on surface and subsurface lithology of the BPNS and SNPNS are now available in data portals. For Belgian offshore data this is new, hence a portal needed development (see http://www.bmdc.be/tiles-dataportal). Newly collected data from the sNPNS have been added to the DINO data portal (https://www.dinoloket.nl/) hosted by TNO.

The data portal allows the user to navigate on a map by dragging to pan and scrolling to zoom whilst displaying locations for which lithological descriptions are available. After executing queries, the following information is downloadable in a zip file:

- Archived pdf of the original core or sample description
- Archived pdf with grain-size information if available (presently for cores only)
- Archived pdf of pictures if available (presently for cores only)
- Standardized excel sheet of the lithological information
- Standardized excel sheet of the grain-size information (in progress)

An extended suite of numerical modelling
To our knowledge, it is the first time that the initialization and parameterization of hydrodynamic-sediment transport-seabed morphology models make use of a geological knowledge base, i.e. coupling geological information to numerical models. Section 4.2 illustrated how adequate

qualitative information about the seabed is important in such tools. Altogether, this resulting modelling suite can be used to test scenarios and hypotheses, and to estimate the evolution of the geological resource (the seabed) in the future at an unprecedented level of detail and accuracy. The coupling between the voxel model and the numerical suite is fully operational. It does not have to be modified when the voxel model is updated following the addition of new data or the expansion of territorial coverage) and will thus be able to produce ever more accurate and useful simulations. This is considered as a significant contribution by the TILES project to the development of robust tools addressing long-term management of our geological resources and of our natural habitats.

The modelling suite is currently under validation and will be published and disseminated to the scientific community afterwards. Thanks to the modular nature of the numerical model COHERENS, further developments can be considered to simulate additional parts of the system. One such development could typically be the introduction of biological modules (benthic or plankton ecosystem models) to COHERENS which could benefit from and respond to prospective additional biological information within the voxel model. In such situation, the link between geology, habitat and ecology would be even more directly done, which constitutes an exciting perspective.

Resource decision support system

The web-based decision support tool developed in TILES is available at: http://www.bmdc.be/tiles-dss/. The DSS allow s the visual exploration of the voxel model, and has following functionalities:

- Filters menu option to define which filters are applied to the model. Only voxels that satisfy the filters are visualized.
- Download menu option to download the voxels that satisfy your query. A history of all filter combinations that were tried is also downloadable in JSON format.
- Advanced mode to build any query in JSON. A previous-history file downloaded in JSON can be pasted.
- Displaying numerous overlays showing the locations of the original cores, contour lines, areas of interest...
- Drawing a cross-section to generate a profile view of the voxel model.

5.3. Optimizing stakeholder interaction and outreach at large using Virtual Reality

As a demonstration, an application was built to experience the TILES models in virtual reality (VR). Walking through the model in three dimensions whilst querying the information contained in the voxels (similar to the TILES DSS) is a fun and educational experience. Several information layers can be combined, e.g. a typical nautical chart as the top surface, a detailed digital terrain model (based on multibeam bathymetry), and a less detailed subsurface model. As such, the seabed can be experienced in high detail. Diving deeper into the subsurface one can appreciate the complex geological substratum and its resource potential. From an information point of view future developments could include pictures and video movies of the seabed, as well as biodiversity elements (e.g., linking biodiversity hotspots to substrate types).

5.4. Conference on 'Marine Sands as a Precious Resource'

On June 1st 2018, final results of the TILES project were presented to 125 participants coming from government, NGOs, academia and industry. Five countries were represented: Belgium, The Netherlands, France, UK and Denmark.

Main aim of the conference was to bring awareness on marine sand resources, their exploitation and management. In a logical flow 17 oral presentations were given, conveying key messages that should be known and understood by all involved in the exploitation of the seabed. Key messages about where the sand comes from, how it behaves, where it is, what impacts its quality, how its extraction impacts the marine environment, if it could become scarce, and indeed how to monitor and manage this precious resource. Together our key messages form a Code of Sand, providing perspectives on the long-term and responsible exploitation of our precious sand reserves. The Code of Sand was provided to the audience in the form of a unique portfolio ('fan') with pictures of different sand types and qualities on the front and the key messages at the back of each photo. This was very well appreciated and the fan is now further distributed nationally and internationally.

As keynote speaker we invited Prof. dr. Ester van der Voet, an industrial ecologist from Leiden University and member of the UNEP Resource Panel. She provided a view on global sustainability challenges and gave some perspectives on how to deal with resources in the long term, including concepts on circular economy.
Throughout the conference, interactive demonstrations were held, starring the newly developed tools: volumetric 3D pixel ('voxel') models, numerical impact models accounting for geological boundary conditions, a geological data portal and the resource decision support module. EMODnet-Geology data products were promoted at a booth, and data sharing was discussed at a side event. All participants were invited to experience the newly developed models in Virtual Reality. Overall, the conference was very well appreciated.

Conference output was further promoted via (social)media. Two press articles and one interview appeared in the Walloon media (see publications). On Twitter-LinkedIn our results got more than 6000 views.

5.5. Valorisation and follow-up (international) projects and initiatives

From its conception to its completion, the TILES project has raised considerable interest, both nationally and internationally. (1) the TILES products are valorised within **EMODnet-Geology** (**DG MARE**) targeting harmonized geological mapping across European seas. (2) A close synergy was realized between the research activities of TILES and the **SBO IWT project Se-Arch**. (3) The **Flemish Government**, Maritime Entrance, incorporated the voxel modelling approach in their geotechnical study around Zeebrugge Harbour and Knokke-Heist. (4) In the **Netherlands** a new geological mapping programme is being set-up, and government/industry partnerships are sought for the further development and refinement of the offshore voxel modelling, including a resource information model (DIS). (5) As part of Geo-ERA (**H2020 Eranet** on the development of a Geological Service for Europe), a project was submitted on a better classification and more harmonized geomodelling of aggregate resources. (6) In the framework of the **Marie Skłodowska-Curie** innovative Training Networks, it is attempted to expand the TILES legacy and develop more intelligent decision support systems addressing the many sustainability challenges faced by society. (7) A follow-up **Belspo valorization action** has been proposed focusing on raising community awareness on the use and management of finite aggregate resources, and on securing their long-term use.

6. PUBLICATIONS

Internationally reviewed papers and book chapters

2018

De Tré, G., R. De Mol, S. van Heteren, J. Stafleu, V. Hademenos, T. Missiaen, L. Kint, N. Terseleer, V. Van Lancker (2018). Data Quality Assessment in Volunteered Geographic Decision Support. In: 'Mobile Information Systems Leveraging Volunteered Geographic Information for Earth Observation', G. Bordogna, G. and P. Carrara, (eds.), 173-192, Springer, Cham, Switzerland.

Hademenos, V., Stafleu, J., Missiaen, T., Kint, L. & Van Lancker, V. (in press). 3D subsurface characterisation of the Belgian Continental Shelf: A new voxel modelling approach. Netherlands Journal of Geosciences.

2017

Van Lancker, V., Francken, F., Kint, L., Terseleer, N., Van den Eynde, D., De Mol, L., De Tré, G., De Mol, R., Missiaen, T., Chademenos, V., Bakker, M., Maljers, D., Stafleu, J., van Heteren, S.: Building a 4D voxel-based decision support system for a sustainable management of marine geological resources. In: Diviacco, P., Leadbetter, A., Glaves, H. (eds.) *Oceanographic and Marine Cross-Domain Data Management for Sustainable Development*, pp. 224–252. IGI Global, Hershey (2017)

2016

De Clercq, M., Chademenos, V., Van Lancker, V., Missiaen, T., 2016. A high-resolution DEM for the Top-Palaeogene surface of the Belgian Continental Shelf. *Journal of Maps 12(5)*: 1047-1054. https://hdl.handle.net/10.1080/17445647.2015.1117992

Van Lancker, V. (2016). Bedforms as Benthic Habitats: Living on the Edge, Chaos, Order and Complexity, pp. 1-4. In: Guillén, J, Acosta, J, Chiocci, FL, Palanques, A (Eds). Atlas of Bedforms in the Western Mediterranean. Springer International Publishing Switzerland. ISBN: 978-3-319-33938-2. DOI 10.1007/978-3-319-33940-5_30.

2015

van Heteren, S & Van Lancker, V (2015). Chapter 8. Collaborative seabed-habitat mapping: uncertainty in sediment data as an obstacle in harmonization, pp. 154-176. In: Diviacco, P., Fox, P., Pshenichny, C. & Leadbetter, A. (eds.). Collaborative Knowledge in Scientific Research Networks. IGI Global. doi:10.4018/978-1-4666-6567-5.

Proceedings

Submitted

Terseleer, N., Degrendele, K., Kint, L., Roche, M., Van den Eynde, D. & Van Lancker, V. (submitted). Automated estimation of seabed morphodynamic parameters, pp. 1-6. In: Lefebvre, A. et al.. Marine and River Dune Dynamics – MARID VI . Bremen (GE), 1-3 April 2019.

2017

Francken, F., Van den Eynde, D., Van Lancker, V. (2017). Application of a large dataset of sediment transport parameters: variability in sediment transport in the HBMC area, ***in***: Degrendele, K. *et al.* (Ed.) *Belgian marine sand: a scarce resource? Study day, 9 June 2017, Hotel Andromeda, Ostend.* pp. 149-159.

Van Lancker, V., Francken, F., Kapel, M., Kint, L., Terseleer, N., Van den Eynde, D., Degrendele, K., Roche, M., De Tré, G., De Mol, R., Missiaen, T., Hademenos, V., Stafleu, J., Van Heteren, S., van Maanen, P.-P., van Schendel, J., 2017. Flexible querying of geological resource quantities and qualities, a sustainability perspective, *in*: Degrendele, K. *et al.* (Ed.) *Belgian marine sand: a scarce resource? Study day, 9 June 2017, Hotel Andromeda, Ostend.* pp. 121-133.

2016

Terseleer, N., K. Degrendele, M. Roche, D. Van den Eynde and V. Van Lancker (2016). Dynamics of very-large dunes in sandbank areas subdued to marine aggregate extraction, Belgian continental shelf. Marine and River Dune Dynamics, MARID V, 4-5 April, Bangor, UK, Extended abstract, 5 pp. (oral presentation)

Van Lancker, V., F. Francken, L. Kint, G. Montereale Gavazzi, N. Terseleer and D. Van den Eynde (2016). Large dunes hosting hotspots of biodiversity: testing proxies of occurrence and habitat change. Marine and River Dune Dynamics, MARID V, 4-5 April, Bangor, UK, Extended abstract, 3 pp. (oral presentation)

2015

Van Lancker, V, Francken, F., Terseleer, N. , Van den Eynde, D., De Mol, L., De Tré, G., De Mol, R., Missiaen, T., Hademenos, V., Bakker, M., Maljers, D., Stafleu, J. & van Heteren, S. (2015). Geological Knowledge Base, a digital platform for sharing and quantifying resource information, pp. 1-2. 5th EMSAGG conference: Marine sand & gravel - Finding common ground. Delft (NL), 4-5/6/2015. (oral, invited)

Evangelinos, D., Baeye, M., Bertrand S., Van den Eynde, D., & Van Lancker, V. (2015). Dispersion and deposition of sediment plumes, resulting from intensive marine aggregate extraction, pp. 1-4. Proceedings 11th Panhellenic Symposium on Oceanography and Fisheries, Mytilene, Lesvos island, Greece, 13-17/5/2015. (oral)

2014

Van Lancker, V., Francken, F., Terseleer, N., Van den Eynde, D., De Mol, L., De Tré, G., De Mol, R., Missiaen, T., Hademenos, V., Maljers, D., Stafleu, J., Van Heteren, S. (2014). Interactive management of marine resources in the southern North Sea, a long-term perspective, in: De Mol, L. et al. (Ed.) (2014). 'Which future for the sand extraction in the Belgian part of the North Sea?'. Study day, 20 October 2014, Belgium Pier - Blankenberge. pp. 89-94. (oral, invited)

Newsletters

TILES was promoted in newsletters from the European projects EMODnet-Geology, as well as the H2020 project MIN-GUIDE on establishing a coherent and innovation-friendly minerals policy framework in Europe.

Press and magazines

2018

La Libre, 2/6/2018. Pourquoi le sable, comme le pétrole, est une ressource limitée... mais de plus en plus convoitée. Sophie Devillers, with interview of N. Terseleer.

DailyScience, 4/6/2018. L'or de la mer du Nord, c'est son sable. Laetitia Theunis, with interview of N. Terseleer.

Europe1 (radio), 6/7/2018. Circuits courts - Comment échapper à la guerre du sable? Anne Le Gall et Maxime Switek, with interview (by Isabelle Ory) of N. Terseleer

Canvas Documentary "Er was eens". Fifth episode (A model of Nature) of the six series on the Royal Belgian Institute of Natural Sciences made by the production house Diplodokus. Virtual reality scenes of the TILES models were included. Interviews of V. Van Lancker, N. Terseleer.

RTBF (forthcoming)

2015

Knack. 6/5/2015. Het strand dreigt te verdwijnen. Wat moet er met de Belgische Kust gebeuren? Dirk Draulans. Artikel met interview contributies van C. Baeteman, J. Seys, en V. Van Lancker.

2014

Searching for marine sand in the Low countries (NL). Promotion of TILES in the February 2014 number of 'Geo.brief', a joint publication of the Dutch "Royal Geological and Mining Society of the Netherlands KNGMG" and "Earth and Life Sciences of the Netherlands Organisation for Scientific Research NWO-ALW".

Abstracts

2018

Hademenos V, Missiaen T, Kapel M, Kint L, Terseleer N, De Tré G, De Mol R, Stafleu J, van Maanen P-P, Rick Appleton R, Van Lancker V (2018). Mapping offshore resources of the Belgian Continental Shelf using 3D voxel modelling. RFG2018 Resources for Future Generations. Vancouver (CA), June 16-21, 2018. Session: Session: Three-Dimensional Geological Modelling for Sustainable Resource Development. (oral presentation)

Kint, L., Terseleer, N., Van den Eynde, D., Van Lancker, V., Hademenos, V., Missiaen, T., De Mol, R., De Tré, G., Stafleu, J., van Heteren, S. (2018). Challenges and pitfalls in building a marine voxel model. 3D-models and voxel-models in geology. BLUG workshop. Brussels, 19th April 2018. (oral presentation)

Kint, L., De Mol, R., Hademenos, V., Stafleu, J., van Heteren, S., Van Lancker, V. (2018). Incorporating data uncertainty in 3D voxel modelling and the importance in decision making. NCK Days, 21-23/3/2018, Haarlem (NL). (oral presentation)

Van Lancker, V., Kapel, M., Kint, L., Terseleer, N., Van den Eynde, D., Hademenos, V., Missiaen, T., De Mol, R., De Tré, G., Appleton, R., van Heteren, S., van Maanen, P-P, Stafleu, S., Degrendele, K., & Roche, M. (2018). Transnational Belgian-Dutch geological knowledge base on marine aggregates. From 3D voxel modelling to 4D cross-border environmental assessments. GeoHab2018 Marine Geological & Biological Habitat Mapping. Santa Barbara (US), 7-11/5/2018. Session Marine Minerals. (poster presentation)

Van Lancker, V., Kint, L., Terseleer, N., Hademenos, V., Missiaen, T., De Mol, R., De Tré, G., van Heteren, S., Stafleu, S., Degrendele, K., & Roche, M. (2018). Transnational Belgian-Dutch geological knowledge base on marine aggregates. From 3D voxel modelling to 4D cross-border environmental assessments. RFG2018 Resources for Future Generations. Premier conference on

Energy, Minerals, Water, The Earth. June 16-21. Vancouver (CAN). Session: Marine Geoscience and Geospatial Data Crossing Borders. (poster presentation)

Van Lancker, V., Kint, L., van Heteren, S. & the TILES Consortium. Standardisation of sediment data across transnational boundaries. CEFAS workshop on 'Particle size Sediment data standards meeting'. Peterborough (UK), 22/6/2018. (invited oral presentation)

Van Lancker, V. & TILES consortium. Integrated seabed mapping for management and industry: from 2d maps to 3d voxels to 4d evolution over time. Workshop Hydrographic Society Benelux "Bathymetry - the foundation for sustainable seas, oceans and waterways". Antwerpen (BE), 20/6/2018. (invited oral presentation)

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9. PAPERS AND REPORTS

Code of Sand: 17 messages guiding a more sustainable use of marine sands

(Van Lancker et al., 2018. Available via Belspo website)

Overall approach of the TILES project

(Van Lancker et al., 2017. Available upon request or via https://www.igi-global.com/chapter/building-a-4d-voxel-based-decision-support-system-for-a-sustainable-management-of-marine-geological-resources/166843)

Redefining the Paleogene surface

(De Clercq et al., 2016. Open access: https://doi.org/10.1080/17445647.2015.1117992)

Methodological workflow of the voxel modelling

(Hademenos et al., in press. Soon open access via https://www.cambridge.org/core/journals/netherlands-journal-of-geosciences/)

Data quality assessment

(De Tré et al., 2018. Available upon request, or via https://www.springer.com/us/book/9783319708775)

A coded lithological database of the Quaternary sediments, Belgian part of the North Sea

(Kint & Van Lancker, soon available at http://www.bmdc.be/tiles-dataportal/)

10. WEBSITES

TILES Homepage: https://odnature.naturalsciences.be/tiles/

TILES Decision Support System: http://www.bmdc.be/tiles-dss/

TILES Geological Data Portal: http://www.bmdc.be/tiles-dataportal/

11. REFERENCE TO THE DATAPRODUCTS

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