Flexible querying of geological resource quantities and qualities, a sustainability perspective

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Introduction

To anticipate on future resource supplies and needs, long-term adaptive management strategies for the exploitation of geological resources are urgently needed (cf. EU's Maritime Policy, Marine Spatial Planning, Marine Strategy Framework Directive). These are based ideally on a geological knowledge base incorporating comprehensive knowledge on the distribution, composition and dynamics of geological resources.

Such a knowledge base is being built for the Belgian and southern Netherlands part of the North Sea (Belgian Science Policy 'TILES') with the aim of providing long-term predictions of geological resource quantity and quality (Van Lancker et al., 2017, for an overview). Therefore, the lithology or sediment composition of the subsurface needs quantification which is traditionally derived from borehole point data. First these data are classified into classes, e.g., following the Wentworth scale (i.e., clay, silt, fine, medium to coarse sand and gravel), but secondly their distribution needs interpolation. Since the data are prone to a high variability, both in space and in depth, it is important to constrain the lithological interpolation within the geological unit or stratigraphy the lithoclass belongs to. This information ideally comes from seismic line data. Combining both point and line data is most efficiently done in a voxel modelling approach of which 3D volume elements are the key component. Advantages are the suite of geostatistical interpolations that can incorporate various criteria, including expert knowledge, the unlimited information that can be added to the data cube in a later phase, and the easy calculation of resource volumes per geological unit or resource quality. Importantly, the geostatistical modelling allows for probabilistic instead of static mapping providing the user with a measure of uncertainty on the lithoclass that is interpolated.

Quantifying uncertainty is indeed crucial in geological modelling and the suitability of the resource should be accompanied by a level of confidence in the data or data product. Many algorithms exist in this regard (e.g., interpolation-related uncertainty), though are mostly lacking for the geological information itself, as well as for the databases upon which the products are built. As such, uncertainty in the mapping of the lithological class and stratigraphic uncertainty are ideally incorporated. For databases comprising information over long-time spans, it is also important to quantify data-related uncertainty, e.g., to accommodate the wide range that exists in positioning techniques, vintages, as well as sampling and analytical techniques. Quantifying these uncertainties, propagating them in 3D models and combining them is not straightforward.

In a resource sustainability context, scenario analyses on resource use, but also on expected environmental impacts are important. Primarily, this includes predictions on how much the seabed can be deepened before major changes occur to the current and wave regime, but also how the seabed sediments change with implications towards biodiversity. The geological nature of the subsurface is in this respect very important, however it is hitherto never accounted for in environmental impact studies that are typically 2D and limited in time scale.

A final aspect is how bringing all of this information together in a decision support tool. From stakeholder consultation, a wide scope of needs emerged, e.g., the desire to assess local aggregate quality (incl. heterogeneity) and quantity, but also decision-making on large-scale and long-term resource use. Additionally, a flexible resource mapping and querying approach was preferred that should be most efficient and user-friendly. To accommodate these varying needs and also to provide the user with combined confidence qualifiers, a new way of dealing with the various data and modelling sources was needed.

All of the above challenges are dealt with in the TILES project, often in most innovative ways. As a result, the approach can handle small- to large-scale data and queries, making it of interest to numerous applications.

The project lasts until June 2018, hence intermediate results are presented at this stage. In the last phase, the geostatistical modelling will be refined making use of the newest data sources, as well as including sensitivity analyses on the various parametrisations that are applied to the datasets. More detailed lithological information will be added to the model, especially for the top or seabed voxel. The 4D component in the scenario analyses will be fully exploited in Autumn 2017. Challenging remains on how to demonstrate and communicate the complex information and uncertainties in a most meaningful way to the user. Continued stakeholder interaction is therefore critical.

Material and methods

On the overall methodological framework, three book chapters have been published: in van Heteren and Van Lancker (2015) on uncertainties in sediment databases; the resource context and the TILES approach in Van Lancker et al. (2017), and concepts of handling data uncertainty in decision support in De Tré et al. (in press). Papers are now prepared on the detailed methodological approaches. Status and progress are listed below.

Data to knowledge

Three main geological databases have been developed and are still further refined: (1) a database with lithological descriptions from available boreholes (Kint and Van Lancker, 2016); (2) a grain-size distribution database populated with sediment distribution curve data, incorporating recovered historical data (expanding on Van Lancker, 2009); and (3) a geophysical database containing seismic line data, as well as stratigraphical interpretation. The latter data originate primarily from Ghent University, Renard Centre of Marine Geology.

Publically available data sources were consulted, including data from neighbouring countries (mostly via national data portals). Data from industry are being incorporated as well: mostly data from non-confidential projects, or upon permission, were added through digitization from available reports. Ad-hoc arrangements can be made if the data needs to remain confidential, but usable for model improvement. All entries in the borehole database are carefully verified and metadata are maximally added for uncertainty analyses. Metadata coding followed EU guidelines (www.seadatanet.org) Main fields were positioning, timestamp (vintage), methodological and analytical techniques used. Quality flags were entered in all databases, also to the seismic lines (following www.geoseas.eu). For the latter, the discrimination potential of subsurface reflectors was accounted for, the vintage of the lines, and whether the data were digital or scanned from paper. Combining and cross-verifying all of this information significantly adds on to the geological knowledge on the marine areas under investigation.

A Belgian marine geological data portal is now under development, integrating the databases, as well as data products. As such a platform for knowledge building and knowledge management is created to serve the scientific, policy and stakeholder community, as well as the public at large.

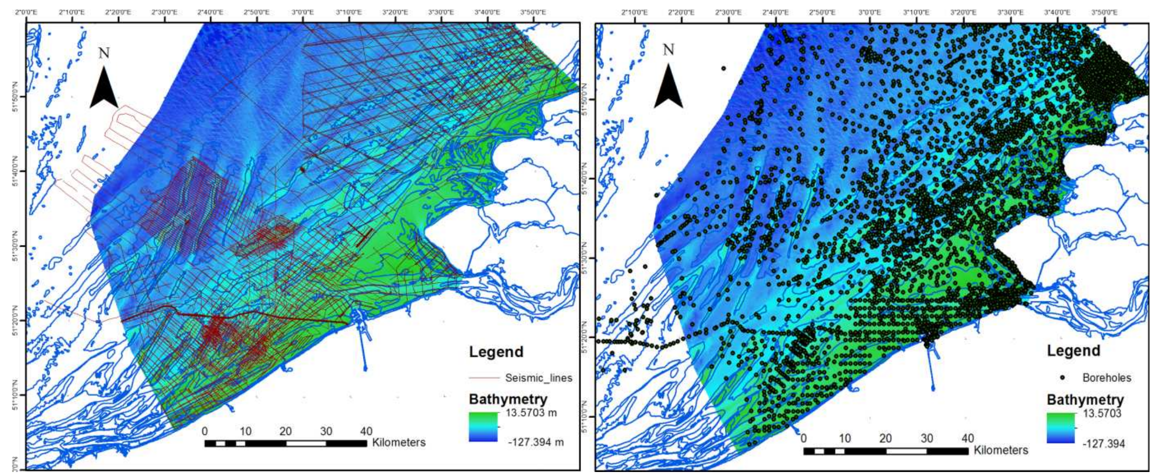

Figure 1: Available seismic data and lithological descriptions.

Geological layer models to 3D voxels

The boreholes were standardised and coded following EU guidelines on geological and geophysical data (e.g., www.geoseas.eu). These were fed into seismic interpretation software to match the boreholes with seismic data. For the Belgian part of the North Sea (BPNS) existing Top Paleogene (De Batist and Henriet, 1995) and Quaternary (Mathys 2009) layer information was extensively reviewed, and new data (newly acquired, or received from third parties) were added. Layers in the boreholes were assigned a stratigraphical and facies interpretation. This information, together with the refined 2D geological layers, was fed into geostatistical software for the voxel modelling (Figure 2).

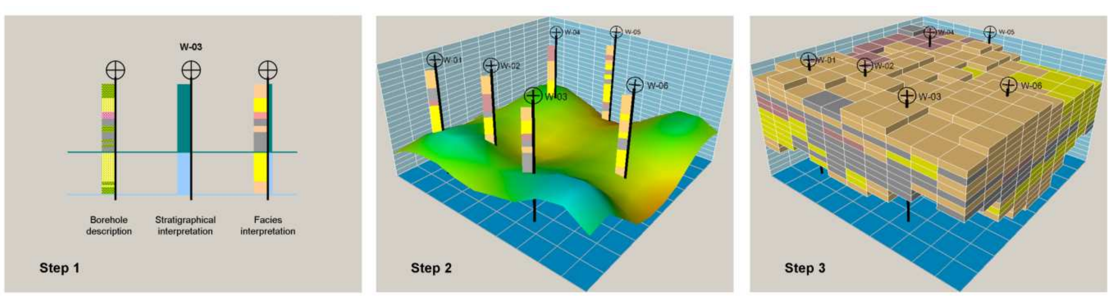

Figure 2: Basic modelling procedure. Step 1: Borehole descriptions subdivided into lithostratigraphical, lithofacies and lithological units. Step 2: 2D interpolation of the basal surface of each lithostratigraphical unit. Step 3: voxel modelling or 3D interpolation of lithofacies and lithology within each lithostratigraphical unit (Stafleu et al. 2011).

The base of the resource-relevant geological layer (Quaternary) was completely revisited, i.e., the Top-Paleogene surface and its topographical features were described in detail (e.g. valleys, flood plains, estuaries).

This research has been published in Declercq et al. (2015). Furthermore, Quaternary units were verified for lithostratigraphical relevance (i.e., in terms of aggregate quality). As a result, a four-unit geological layer model was created: upper Paleogene, Pleistocene and two units in the Holocene. Furthermore, the Holocene layer was split in two regions, on- and offshore accounting for the difference in the geology and lithological nature in both subareas (marine to estuarine environment). This was important to fine-tune the statistical parameterisation that drives the interpolation process (e.g., more clay in the Holocene layers of the nearshore). Lithoclass information was then interpolated constrained within the geological unit it belonged to. Dimensions of the main voxel model are 200 x 200 x 1 m, up to a depth of -70 m mean sea level (MSL). As a case study, the Hinder Banks concession zone was modelled at a higher resolution (100 x 100 x 0.5 m), as was suggested by stakeholders.

Once the models are developed, resource volumes are easy to compute. Sensitivity analyses are conducted on the impact of the voxel resolution, e.g., 200 x 200 x 1 m versus 100 x 100 x 0.5 m. At this stage, voxels are counted per lithological class, without accounting for the morphological complexity of an area. This will be accounted for in post-processing in the decision support module (see further). This will allow incorporating other data sources that may impact on the available resource volumes (e.g., other human activities).

Uncertainty estimation

Following the approach of Stafleu et al. (2011), estimates of the lithological class of each voxel in the model were calculated using a stochastic interpolation technique (running 100 simulations of lithoclass predictions per voxel) which allowed the construction of multiple, equally probable realisations of 3D lithological class distributions. From these realisations, probabilities of occurrence for each lithological class were calculated. In addition, the probabilities were used to compute a 'most likely' lithological class distribution using an averaging method tailored to the datasets.

For the interpretation of the probabilities in terms of likelihood of occurrence, the verbal descriptions of uncertainty, as used in the Intergovernmental Panel on Climate Change (IPCC) are suggested for use (Table 1).

Table 1: IPCC guidelines of translation of probability phrases

Phrase	**Likelihood**
Virtually certain	> 99 %
Very likely	> 90 %
Likely	> 66 %
About as likely as not	33 % - 66 %
Unlikely	< 33 %
Very unlikely	< 10 %
Exceptionally unlikely	< 1 %

Information entropy was calculated also. This is a single value ranging from 0 to 1 that can easily be calculated from each of the probabilities of lithological class. An entropy value of 0 means that there is no uncertainty, whereas a value of 1 occurs when all lithological classes had the same probability in a voxel. 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). Entropy was calculated also on the stratigraphical unit the voxel belongs to. This was based on the geological layer model, attributed with a standard deviation of the geological bounding surfaces that defined them. The probabilities for each of the stratigraphical units were then combined into an entropy value of stratigraphy.

Variation in borehole density was accounted for as well. Many users assume a one-to-one relationship between borehole density and reliability of a model. Although this relationship not always exists (for example, a homogeneous unit may be fully characterized by a single borehole), it adheres to common sense and is therefore easily understood. Borehole density was calculated for horizontal slices through the model, each at a certain vertical position with respect to MSL. Subsequently, for each of these horizontal slices, the number of boreholes available in cells of 5 by 5 km at the depth of the slice were counted. The result was then converted to the voxel model.

A new approach is being worked out on quantifying data-related uncertainty (e.g., in the lithological and grain-size database). Uncertainty caused by differences in positioning, sampling gear, analysis procedures and vintages is now represented as a percentage flag scaling. As such, integration with other uncertainties and the voxel model itself is much more flexible. Expert knowledge is systematically revisited as to avoid totally inappropriate use of the flag scaling process.

Coupling of the geological models with 4D environmental impact models

Marine resources are subject to both natural processes (bedform migration, erosion and deposition); and human influences (e.g. dredging activities, extraction) that cause their quantity and quality to change. To understand past and predict future behaviour of the resource in this 4^{th} dimension (time), it is necessary to couple the 3D voxel model to a suite of environmental impact models.

The model suite used in TILES contains a hydrodynamic model of the continental shelf (COHERENSv2; https://odnature.naturalsciences.be/coherens/, building upon Luyten et al., 1999), a sediment-transport model (simulating erosion, transport and deposition) and a seabed-morphology model (simulating changes in seabed composition and bathymetry). The model suite is coupled to a third-generation wave model in order 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 explains the static top of the 3D voxel model in terms of driving forces, and is crucial for a quantitative understanding of past as well as future resource changes resulting from natural seabed dynamics and human impact. The coupling with the voxel model offers an opportunity to initiate and parameterise the model suite with geological boundary conditions and to investigate the aggregate resource at an unprecedented level of detail and accuracy and to execute scenarios over time. The model suite is also used for detailed analyses on bedform evolution in extraction areas. Therefore, results from the multibeam monitoring are used (Roche et al., this volume) and automated procedures on quantifying bedform migration rate and direction are developed and are analysed against driving forces (natural and anthropogenic). From this, statistical models of depletion rates per substrate type are derived. As such, knowledge is gained on rates of resource depletion under present-day extraction practices, being critical for long-term predictions of resource availabilities.

A final aspect of the 4D component of the voxel modelling is the incorporation of results of a 16-yrs hindcast (1999-2015) on sediment transport parameters in the upper voxel (e.g., bottom shear stress, bed evolution, total sediment transport) (see Francken et al., this volume). In line with the methodology on geological modelling, probability maps of long-term natural erosion and deposition magnitudes and rates will be created. This information can be used to steer extraction activities towards depositional areas, and to avoid naturally erosive areas, hence minimising environmental impacts. Model results are validated with results from the multibeam monitoring (Roche et al., this volume).

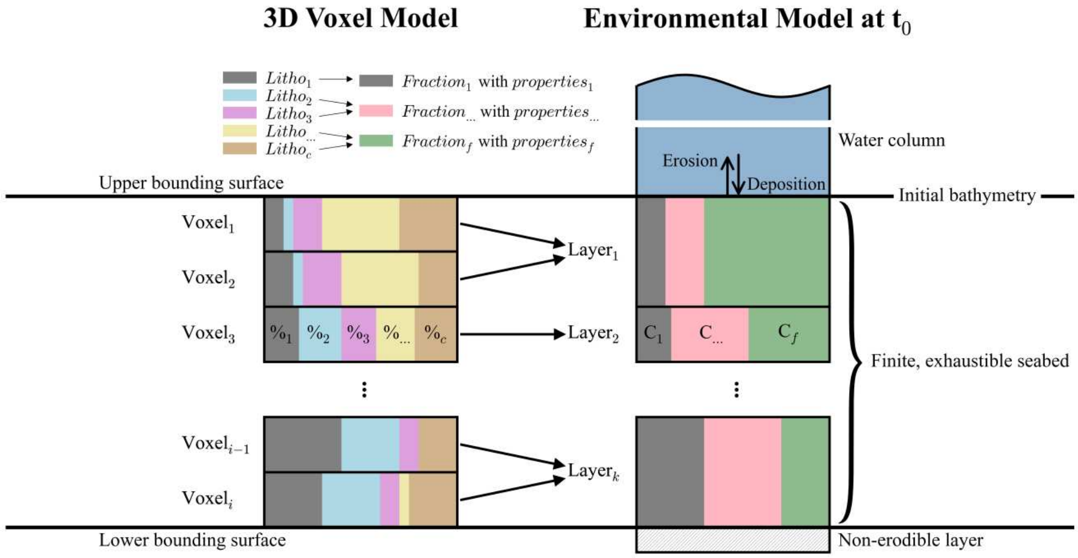

Figure 3: Coupling between the 3D voxel model (left) and the suite of environmental impact models (right). The voxel model provides percentages (%) of the different lithological classes (Litho), which are translated into concentrations (C) of the different sediment fractions to initialise the seabed of the numerical model. Properties of the sediment fractions (e.g. particle size) are provided as well to parameterise the numerical model (see Van Lancker et al., 2017 for more information).

Decision Support System (DSS)

The DSS is vital to allow easy querying of all resource-related information, as well as the accompanying model uncertainties. Furthermore, other datasets (e.g., on human activities) can be added allowing combined querying of data and information.

From fixed- to dynamically-sized voxels

To anticipate maximally on stakeholders' needs (see Introduction), a fundamental change was implemented in the way the voxel models are being used in the DSS. In the geological modelling, voxels are of equal dimension (i.e., 200 x 200 x 1 m) which proved too coarse for some detailed applications and for resource calculations in morphologically complex areas. Furthermore, most voxel attributes were filled by interpolation, implying that most of the time needed for querying the DSS went to voxels with no real data. In the current state of the DSS data from various sources (voxelized lithoclass information, surface maps (bathymetry, Top Paleogene, ...) and area maps (shipwreck locations, pipelines, windmill farms, ...), can define a 3D space which can be partitioned "on-the-fly" into new voxels of differing size. The size of these voxels is derived from the amount of information that is available in the region. As a consequence, in the DSS a voxel now reflects a box of 3D space that is considered to be homogeneous by the end-user. Research is further conducted on the most optimal form of the 3D space, hence rectangular voxels may merge into polyforms of different dimensions if this adds to a more accurate representation of an area.

Suitability mapping

Suitability scores are calculated for each voxel, reflecting how well the encapsulated area is able to satisfy a set goal. The goal needs to be entered by a set of criteria and the way they relate to each other (e.g., : "where are areas with a low amount of clay, within 5 m of the seabed, where Holocene medium sand is the dominant lithological class, not near pipelines or military training areas?"). On general terms, each voxel is then rated with a suitability score between 0 (=unacceptable) and 1 (=perfect). If a detailed querying of information is desired, a tiered approach is proposed where maps are generated to quickly discover regions of interest, which are further studied in detail afterwards, without having to generate a detailed map of the entire region.

Results and discussion

In this section only few results are shown to demonstrate the methodology and potential of the TILES workflow. The models are still in refinement and sensitivity analyses are carried out on the parameterisation of the geostatistical model. A higher resolution model of the upper seabed is in development; this one will contain more detailed sediment characteristics, as well as sediment transport parameters.

Sediment mapping of the seabed

Based on the new grain-size distribution database, seabed sediments were mapped following the Folk classification (5, 7 and 16 classes). The maps are publically available through the EMODnet-Geology data portal (www.emodnet.eu). In combination with depth zonation, tidal and wave energy data, and level of light penetration they were further translated into predominant habitats of relevance to the Marine Strategy Framework Directive (Figure 4). These habitat maps are publically available via the EMODnet-Seabed habitats data portal.

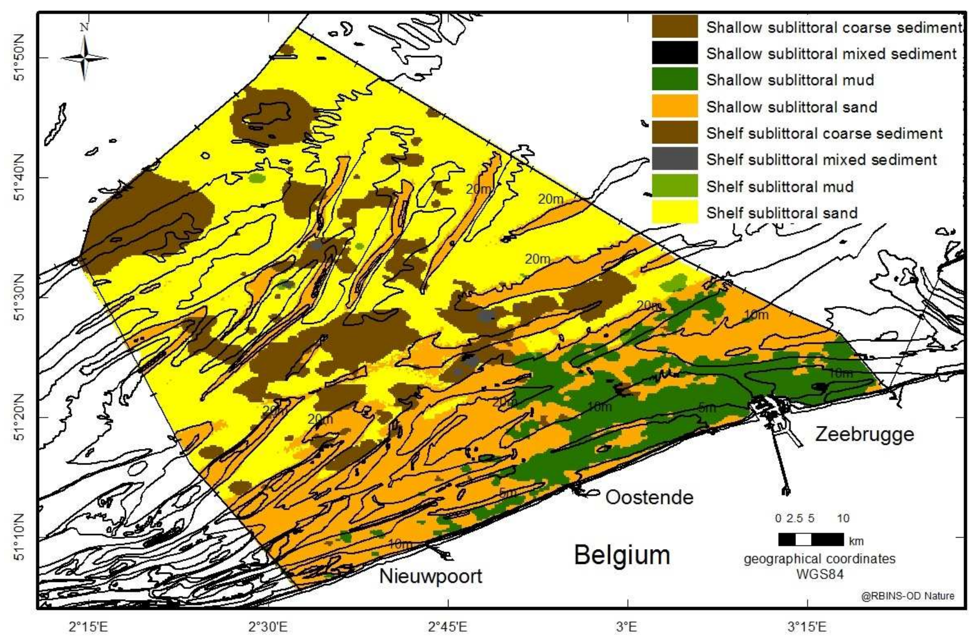

Figure 4: Most commonly occurring habitat types (EUNIS Level 3) based on a mapping of substrate type (RBINS SediCURVE@SEA_v2016 database) combined with physiographic characteristics (depth zonation and wave energy) (EMODnet Seabed Habitats project (www.emodnet-seabedhabitats.eu), funded by the European Commission's Directorate-General for Maritime Affairs and Fisheries (DG MARE)).

Geological layer modelling

A renewed Top-Paleogene surface has been published (Declercq et al., 2015). It is an important reference layer for the future extraction of marine aggregates. Within the Quaternary, three geological layers were distinguished being a proxy of the main lithostratigraphic units. All of the layers were transferred to FPS Economy for further valorization in terms of defining a new reference surface for future marine aggregate extraction (Degrendele et al., this volume).

Voxel modelling

A first portfolio of resource-distribution maps has been created for each Wentworth class (Clay to Silt; Fine, Medium to Coarse sand; Gravel), taking into account the layered model of the Quaternary. These were transferred to FPS Economy to provide first insight into the aggregate quality of the sandbank volume above a potential new reference surface (Degrendele et al., this volume). Figure 5 is an example of such a map.

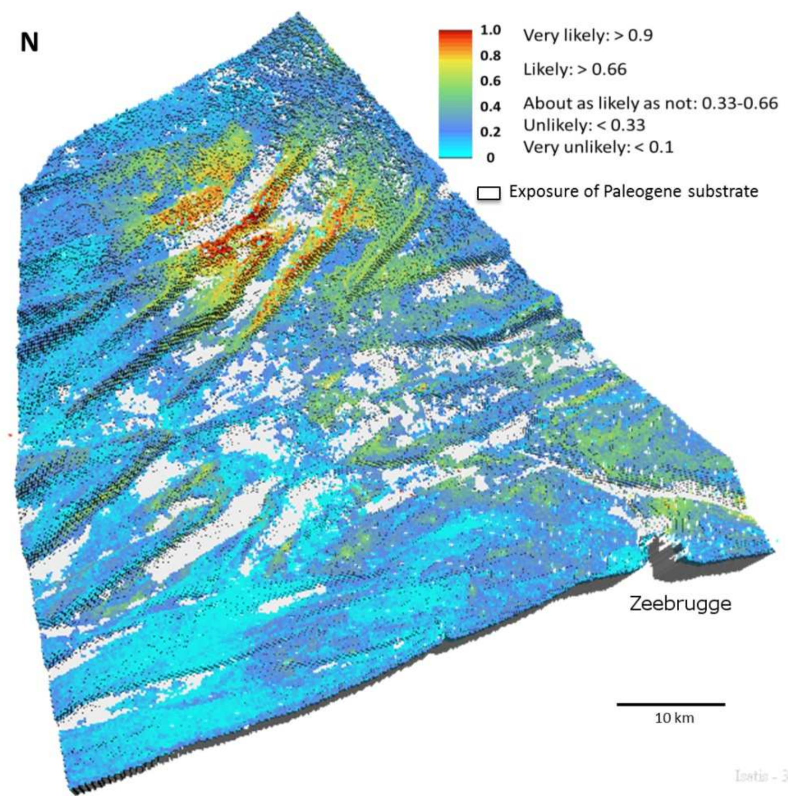

Figure 5: Probability of occurrence of medium sands in the upper Holocene layer (here seabed representation only), based on 3D interpolation of lithological descriptions within geological units (voxel dimensions of 200 x 200 x 1 m). Within the 12 nm zone, this lithoclass is only present locally; more offshore this class is more widespread available.

Figure 6 combines results from a mapping of the lithoclass occurring with highest probability, together with the entropy of the model as a measure of uncertainty when combining all probabilities of lithological classes.

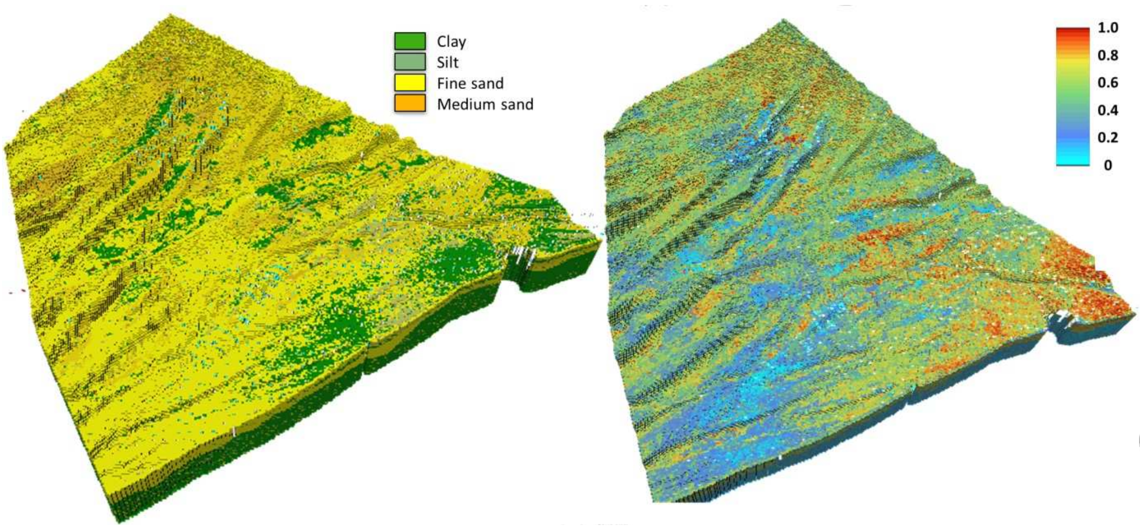

Figure 6: Left: Representation of the lithoclass occurring with the highest probability. Right: Entropy of the model. Entropy is highest, hence uncertainty in the mapping is highest in the red areas. Near Zeebrugge, and in the coastal zone, this is caused by the highly varying nature in lithoclasses at small spatial scale. To the north of the BPNS, the red colouring is merely indicative of areas with low data density.

It is important to highlight that uncertainty originates from various sources (diverse geological nature within layers, differences in data density, differences in the geostatistical interpolation), including the way the data were collected and under which circumstances (quantified from metadata).

Clearly, mapping of probabilities instead of static values of resource occurrences shows much more restrictions in where most appropriate resources for certain applications can be found. It is up to the user which uncertainty can be accepted.

First resource assessments

Figure 7 shows the volumes of the lithoclasses silt and clay, fine sand, medium sand, and coarse sand based on a query of the 200 x 200 x 1m voxel model. As mentioned, sensitivity analyses are now carried out to quantify the influence of the voxel resolution on the volumes. It is expected that the order of magnitude will be similar from a large- and long-term perspective. For detailed resource volume projections, it is likely that the voxel resolution needs up-scaling. For these, the constraints imposed by the sandbank morphology (e.g., slope areas) will also matter. However, it is clear that the majority of the available resource is fine sand. Importantly to note also is that the geological units do not have a uniform lithology. Hence, geological units, as derived from geophysical surveying, will always need ground-validation if a high certainty on a specific resource quality and quantity is desired.

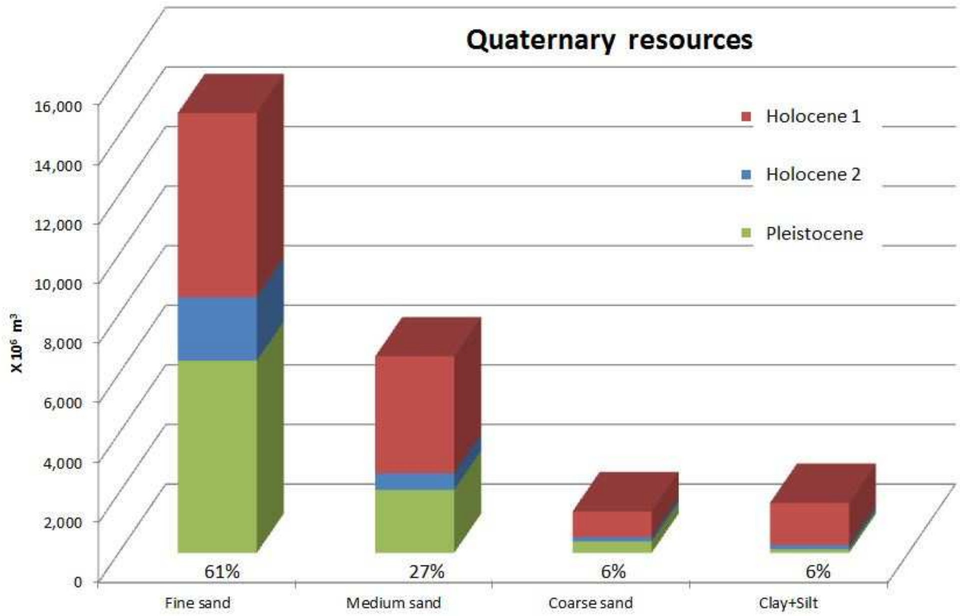

Figure 7: Volumes of the different lithoclasses in the Quaternary, and the geological unit they belong to.

Adding the 4th dimension

The coupling scheme between the 3D voxel model and the 4D environmental impact models, as presented in materials and methods, is in a testing phase. For some results on the application of 16-years hindcast of sediment transport parameters, reference is made to Francken et al. (this volume).

Decision support system

Currently, the voxel model can be queried following user-defined flexible combinations of criteria on the resource quality. In a first step the fixed-dimension geological voxel model is therefore queried. Following extra criteria from the end-user, the original voxels of 200 x 200 x 1 m are partitioned into smaller or bigger voxels. This partitioning can be based on data density as shown in Figure 8, right, but also on the other uncertainty layers that have been produced on the basis of the metadata (Figure 8, left). Experiments are now taking place on how to combine the different uncertainties into a single score that can be visualized together with the resource quality. The scoring will be fully transparent for the user.

The flexible querying of the DSS, combining resource quality with a series of uncertainties, will provide clear insight where resources can be exploited within a margin defined by the end-user. It will also become evident where existing knowledge and data are largely insufficient to support any management or exploitation advice.

Importantly, for the last phase of the project, input of end-users is critical, e.g., on improving the functionalities of the DSS, on desired qualities of resources, and exploitation strategies. For long-term predictions and management practices, it is important to gain insight into future supplies and needs. Any information on these aspects is welcome.

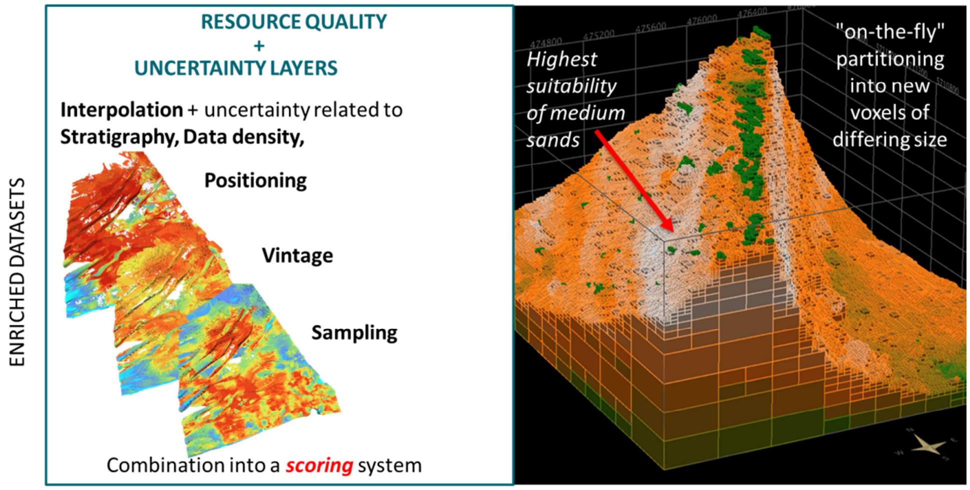

Figure 8: DSS showing a variable-size voxel model of a sandbank, based on the combination of resource suitability and an attribute of uncertainty. Here, the colour indicates suitability for medium sands (greyish: highest suitability; green: lowest suitability). Voxel size provides a broad indication of data uncertainty. Small voxel sizes at the surface are here indicative of the highly detailed bathymetrical data layer representing the seabed; voxel sizes in the subsurface are here a function of borehole density.

Conclusions

A transnational, harmonized geological knowledge base is being developed as a critical platform for the exchange of resource-related data, information and knowledge. This involves pioneering research, which is challenging in many ways: e.g., first subsurface voxel model of a marine area, accommodating voxels of varying dimensions, quantification and propagation of complex data uncertainties through the models, coupling of the voxel model with 4D numerical impact models, the development of a voxel-based decision-support system, and last but not least the many data visualization challenges. Importantly many of the developments were steered through interaction with stakeholders and their varying needs.

Sediment and borehole data have been standardised following European guidelines, allowing cross-border harmonisation in the mapping process. To facilitate this standardisation, borehole data were mapped from text-based descriptions to code. For the subsurface, a conceptual lithostratigraphic framework was set up, comparing and reconciling BE and NL subdivisions of the Neogene and Quaternary sequence.

For the BPNS, geological layer models were further refined. For the Top Paleogene a new very-high resolution digital terrain model was published. A tuned methodological workflow now exists for the creation of 3D voxel models, and is based on a four-layer voxel model distinguishing between the Top Paleogene, Pleistocene and two Holocene units. A first portfolio of resource-distribution maps for each main lithological class (Fine, Medium to Coarse sand; Clay to Silt) is created. For the BPNS, preliminary resource volume estimations of Holocene medium to coarse sands, of most interest for exploitation purposes, account for 21 % of the total available sediments in the Quaternary.

Anticipating on defining sustainable thresholds of exploitation, 4D resource modelling is performed accounting for geological boundary conditions, i.e., level of exploitation without major sediment and hydrographic changes. Additionally, an existing long-term hindcast modelling study of sediment-dynamics-related parameters was extended to 16 years, covering the time span of available monitoring data on marine sand extraction. The resulting knowledge is needed to quantify the envelope of natural and man-made variability of seabed processes. A methodological workflow is now ready for the calculation of depletion and regeneration rates.

A prototype of the decision support system is finished. It allows calculating suitability-reliability maps with scores that account for expert knowledge and data uncertainty. Results are stored in a format readable by subsurface viewers and are displayed in 2D and 3D. The result is traceable: for each voxel, it is possible to do a step-by-step analysis of how the final scores were calculated.

To conclude an efficient tool is provided to target <user-defined> suitable areas for extraction and allowing estimation of resource volume and quality. It is a flexible product of which the outcome can be coupled to other models (e.g., sediment transport, habitats, marine spatial planning).

TILES website: http://www.odnature.be/tiles/

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