D1.1

Overview of existing mechanistic ecosystem functioning models and selection of suitable models

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Acronyms

WP	**Work Package**
ES	**Ecosystem Services**
ScAB	**Scientific Advisory Board**
ERA	**Environmental Risk Assessment**
LCA	**Life Cycle Assessment**
BCS	**Belgian Continental Shelf**
OWF	**Offshore Wind Farm**

1. Executive summary

To develop a tool that quantitatively assesses ecosystem services supply based on the structures and processes of the physical system, we performed a thorough review of available models that quantify marine ecosystem functioning. The aim of this review was to understand their advantages and limitations for the purpose of quantifying ecosystem services supply based on the physical system. The review performed for all services that a) were deemed to be relevant in the Belgian Continental Shelf, b) were of interest to the SUMES project's Strategic Advisory Board, as an indication of economical and societal relevance, and c) were impacted by the presence of Offshore Wind Farms. We applied 4 criteria to the overviews of models to select the model most suited for our purposes: 1) The model can be used to quantify the effects of OWF presence. 2) The model represents relevant parts of the ecosystem for the delivery of the services of interest. 3) The model complexity is appropriate for the goals of the SUMES project. 4) The model or its outputs can be linked to other ecosystem compartments/compartments. For the relevant services, we identified the models that will be used to quantify supply in work package 3.

2. Introduction

The SUMES project aims to develop a holistic sustainability assessment tool for human activities in the marine sphere, quantitatively assessing the change in ecosystem services (ES) supply as a result of human activities. Following the rationale of the Ecosystem Services Cascade model (Haines-Young & Potschin, 2010), ES are supplied through ecosystem functioning, which is a result of the complex interactions between the biophysical structures and processes of the system (Figure 1). In order to accurately judge the state of the marine system – and the ES it supplies – it is inadequate to merely assess fixed ecosystem parameters and habitat distribution and state. It is necessary to gain an understanding of the processes underlying ecosystem functioning and ES supply and quantitatively assess these structures and processes.

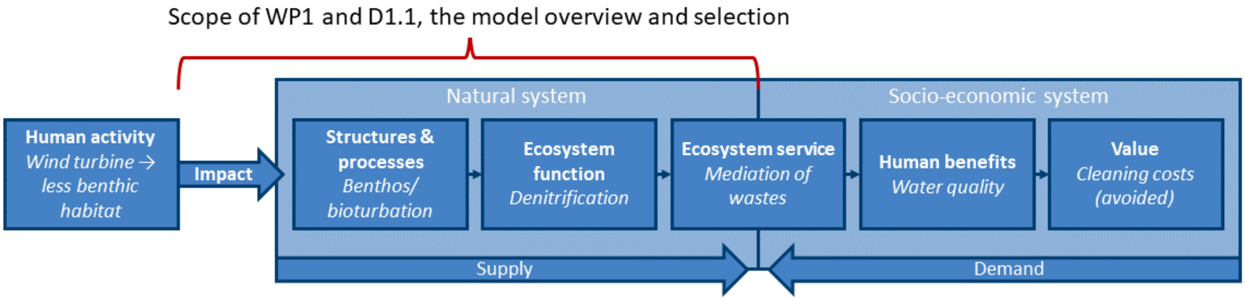

Figure 1: Ecosystem services cascade, with *mediation of wastes* as an example, showing the scope of WP1 of the SUMES project (based on Haines-Young & Potschin, 2010).

To this end, we aim to develop a quantitative modelling tool that explicitly represents the key structures and processes for the supply of ES relevant to the Belgian Continental Shelf (BCS). This modelling tool will be based on existing models of system functioning for a selection of services. To develop such a tool, a thorough review of available models was performed to understand their advantages and limitations. In this way, we can identify if the scope and complexity of the models match our criteria, before the most appropriate ones are selected.

WP1 aims to gain a mechanistic understanding of the ES supply side. To this end, we developed a conceptual model of how shallow shelf systems supply ES (D1.2 *Conceptual model of marine ecosystem functioning, supply of Ecosystem Services and interactions*), which serves as a conceptual summary of the state of the art of ecosystem functioning. In this deliverable, we adapt this conceptual model by linking the ecosystem and its services to a human activity. We specifically depict the impacts of the first SUMES case study, offshore windfarms (OWF), on ES. This is used to determine which ecosystem functions must be modelled, and which ES are the most relevant to the case study. In the following chapters, we present an overview of ecosystem functioning models that may be used to quantify the supply of ES and subsequently select those most suitable for the quantification of ES in WP3.

3. Methods

A review of mechanistic ecosystem functioning models was performed to fill in building blocks between ecosystem parameters and indicators of ecosystem functioning and ES. The available models that consider ecosystem functioning (i.e. ecological, biogeochemical, morphodynamic) that underly ES supply were screened for their capacity to analyse changes in the parameters that are likely to be affected by (socio-)economic activities (WP4) and quantify the consecutive effects in terms of changes in ecosystem functions and of ES supply and demand. For each ES, we selected the most appropriate model(s) that allow(s) us to quantify (multiple) steps in the cause-effect chain.

3.1. Adaptation of the general conceptual model

As a first step in identifying which ecosystem functions are important to include in our model review, we adapted the conceptual ES supply model from D1.2 into a conceptual cause-effect model, representing the pathways from the impacts of OWF presence to ES supply (It is important to note that we only consider the effects of OWFs in the operational phase, not the construction and/or decommissioning phases). Here, we followed the approach of Olander et al. (2018), which describes how to construct ES cause-effect conceptual models. This approach serves as the conceptual integration of Environmental Risk Assessment (ERA) and ES assessment and was done following a number of steps: first, an exploratory assessment of local and regional impacts listed which environmental changes occur as a result of the presence of an OWF. These initial changes were then connected to variables in the broader ES supply conceptual model. Following the pathways from the initial effects, through ecosystem functioning and supporting services, to final ES, we were able to give a holistic overview of the pathways in which OWF presence influences ES supply (Figure 2). In this conceptual model, other human activities that interact with OWF are also depicted. Although these activities have their own impacts on the structures and processes of the marine environment and, subsequently, on ES supply, this is not considered at this moment. We documented the evidence for the cause-effect chains in an evidence library, similar to that of the initial conceptual model (D1.2 Annex section, Table 4). For more details on what is documented in the evidence library, we refer to D1.2 and Olander et al. (2018). The evidence library is a living document and the latest version can be accessed here. This conceptual model serves as a guideline, both for which ES to include in the quantitative assessments, as well as which processes underly the supply of those services, and how these are influenced by the human activities of interest in the SUMES project.

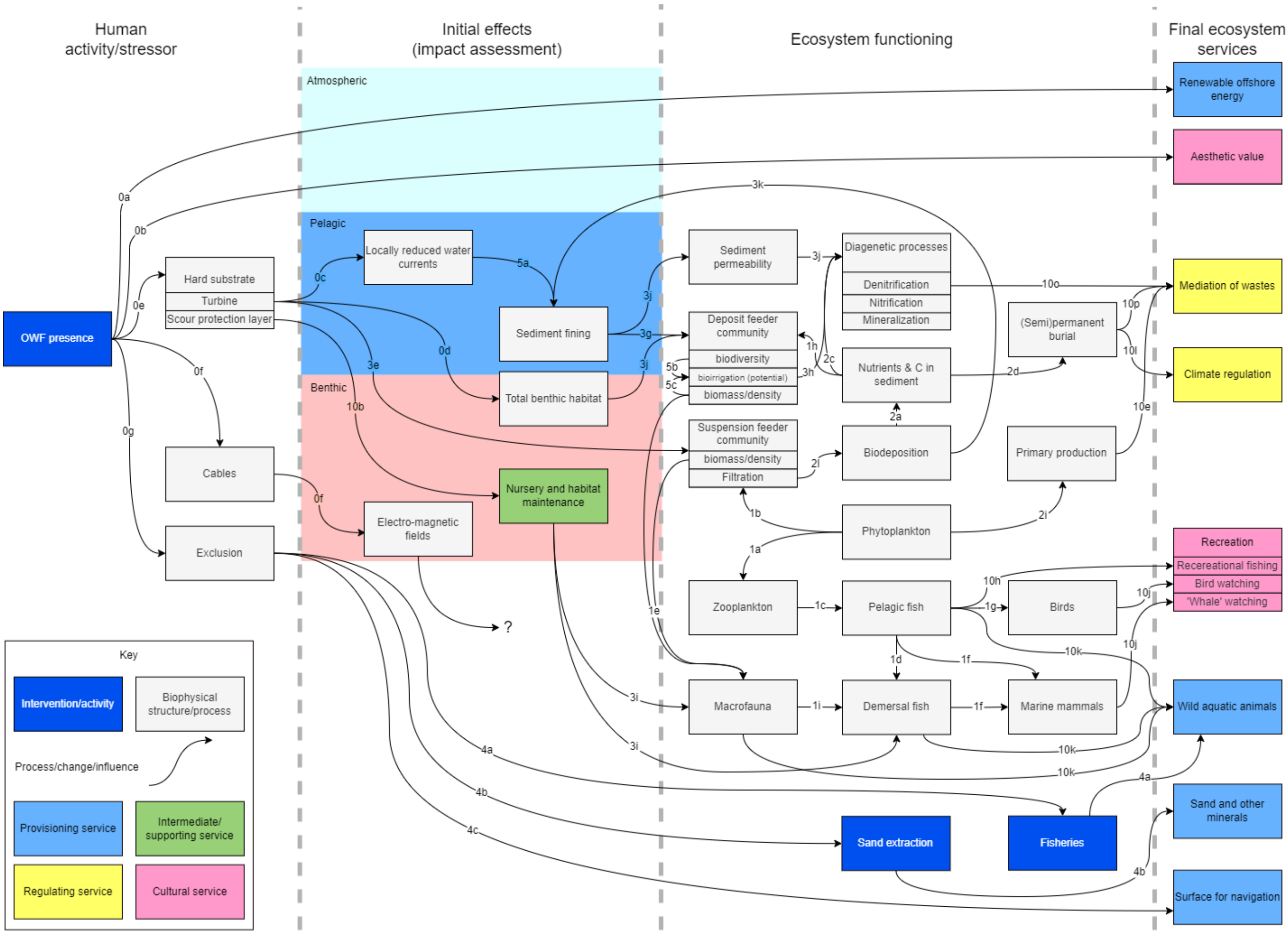

Figure 2: Conceptual cause-effect chain model of OWF presence on ES supply. The pathways are divided into the human activity/stressor of interest, the initial effects, ecosystem functioning and supporting services, and final ES. The labels of the linkages refer to the code in the evidence library.

3.2. Selection of ES

First, it is necessary to clearly define for which ES we will review and select models (Figure 3). The first step of this selection process was to identify ES which are relevant for the BCS and similar temperate, shallow shelf systems and is described in detail in D1.2, which presents a list of 15 ES. We then applied several other criteria to this list.

This selection process left us with 9 services for which models were reviewed: w*ild aquatic animals (for food material and energy)*, *sand and other minerals*, *surface for navigation*, *mediation of wastes*, *climate regulation*, *recreation* and *aesthetic value*. For some of these ES, it became clear early on during the model review process that the same models could be used for multiple services because they are supplied by the same structures and processes. Therefore, several ES were grouped together in the model review process: the supply of *mediation of wastes* and *climate regulation* is a result of similar processes taking place in the sediment, which were grouped as 'nutrient models'. Some forms of recreation, such as recreative angling, fit better with the models regarding the food web than dedicated recereation models. These models were therefore grouped under 'food web models'. The role of filter-feeding bivalves in the system is a complex one, as it can be about both aquaculture and wild (biofouling) bivalves. Because of their importance in ecosystem function, they can also supply multiple ES, which can be derived from single models. We therefore grouped *farmed aquatic animals*, *mediation of wastes* and *climate regulation* and *pest control* as 'filter feeder models'. Although *coastal protection* and *pest control* are not relevant for the OWF case, they were still included in the model review, although model selection has not been performed for these services.

Table 1 provides an overview of these criteria.

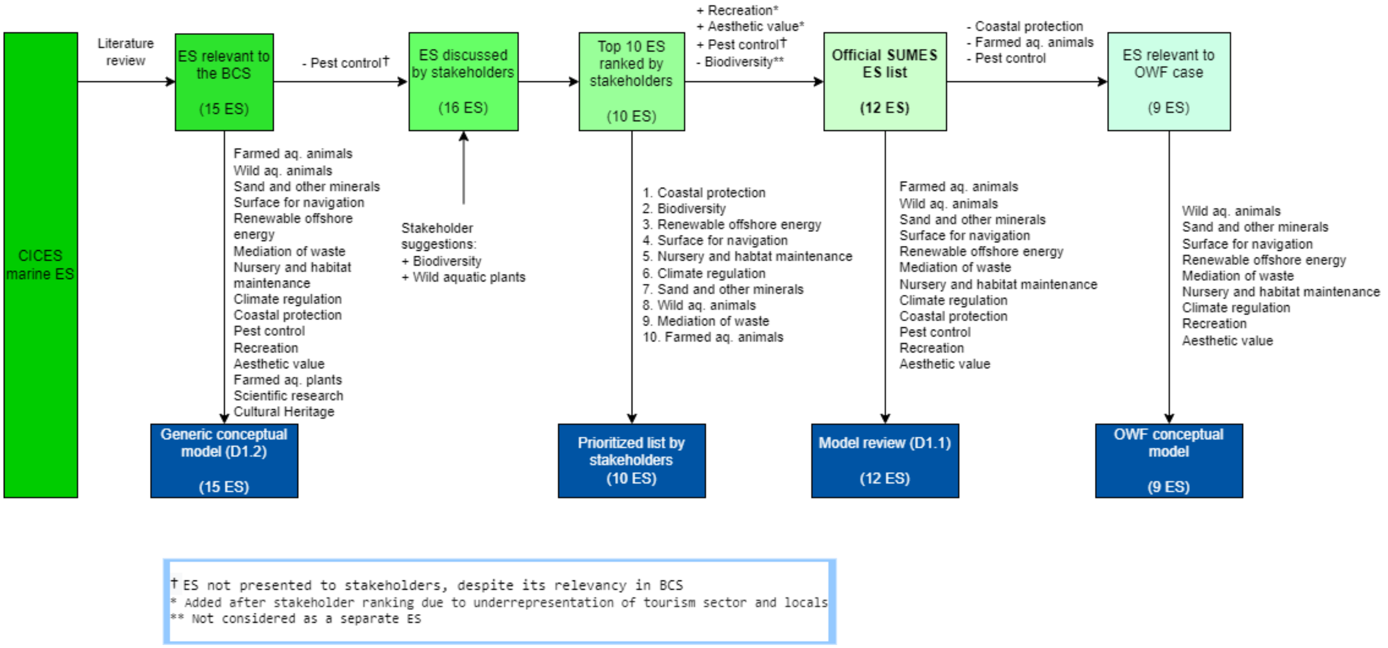

Figure 3: Figure showing the selection process of ES in the SUMES project.

As a second selection criterium, the ES had to be deemed relevant by the stakeholders. To do this, the stakeholders were questioned during the SUMES stakeholder workshop organized by VLIZ in April 2021 (D2.2 *Ecosystem Services relevant for the Belgian Continental Shelf based on multi-actor lab*) (Figure 4). Ranking of ES by the stakeholders was an important criterium to help us prioritize the selection of services for the model review. Besides the top 10 ES shown in Figure 4, we decided to also include *recreation* and *aesthetic value*, because the tourism sector and local residents, which can be expected to prioritise these ES, were not represented at the stakeholder workshop. This, despite the fact that coastal tourism is the biggest sector in the European Blue Economy in terms of both employment and economic importance (European Commission, 2021;). The list presented to the stakeholders is slightly different from the list of 15 ES presented in D1.2, as it did not contain *pest control*. The list in D1.2 also did not include *biodiversity,* which was proposed by the stakeholders themselves, but in SUMES is not considered a separate ES and *wild aquatic plants*, which was found in literature to not be relevant in the BCS.

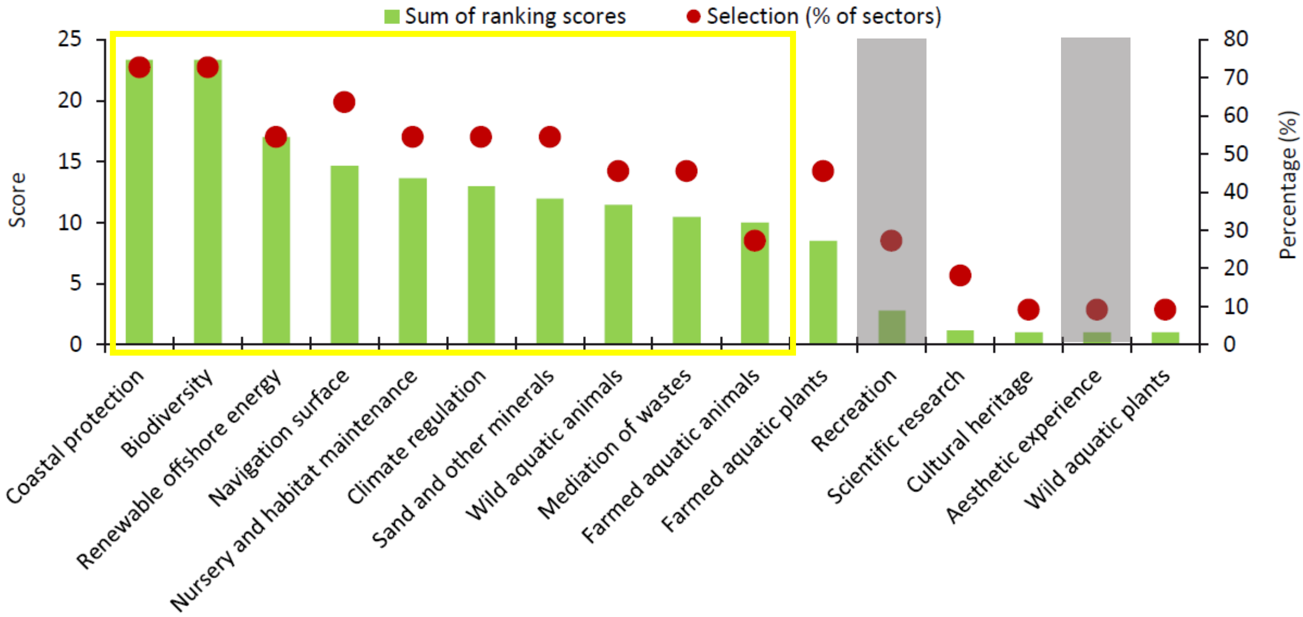

Figure 4: Overview of ES selected as relevant in the BCS by the SUMES stakeholders. The bars give the sum of ranking scores while the dots give the percentage of sectors selecting the ES as relevant. The yellow box indicates the ES deemed most relevant for inclusion in the model review. The grey boxes indicate ES that were not deemed relevant to the stakeholders, but were included in the conceptual model and model overview because the tourism sector was not represented at the workshop. Note that in SUMES biodiversity is not considered an ES in its own right and is therefore not included in the list of relevant ES.

Next, we looked at which ES are relevant for the first SUMES case study, OWFs. For this, we turned to the conceptual cause-effect chain model (Figure 2). All 9 ES represented there were deemed relevant for the case study, as these services are impacted by the presence of OWFs. Once the complex case of the SUMES project is known, this selection criterium will be applied again with a conceptual model for that case.

Lastly, some ES were not included in the list for the model review, as the quantification of these services fit better in different disciplines within the SUMES project. This was the case for two ES: (1) The generation of *offshore renewable energy* fits better in a Life Cycle Assessment (LCA) context than in the context of ecosystem functioning; (2) *Nursery and habitat maintenance* is considered a supporting service in most literature (Liquete et al., 2016). As such, it is best studied in the context of ERA, because this is where the degradation of habitat and the subsequent effects on ecosystem functioning will be investigated and quantified.

This selection process left us with 9 services for which models were reviewed: w*ild aquatic animals (for food material and energy)*, *sand and other minerals*, *surface for navigation*, *mediation of wastes*, *climate regulation*, *recreation* and *aesthetic value*. For some of these ES, it became clear early on during the model review process that the same models could be used for multiple services because they are supplied by the same structures and processes. Therefore, several ES were grouped together in the model review process: the supply of *mediation of wastes* and *climate regulation* is a result of similar processes taking place in the sediment, which were grouped as 'nutrient models'. Some forms of recreation, such as recreative angling, fit better with the models regarding the food web than dedicated recereation models. These models were therefore grouped under 'food web models'. The role of filter-feeding bivalves in the system is a complex one, as it can be about both aquaculture and wild (biofouling) bivalves. Because of their importance in ecosystem function, they can also supply multiple ES, which can be derived from single models. We therefore grouped *farmed aquatic animals*, *mediation of wastes* and *climate regulation* and *pest control* as 'filter feeder models'. Although *coastal protection* and *pest control* are not relevant for the OWF case, they were still included in the model review, although model selection has not been performed for these services.

Table 1: Overview of the 16 ES identified in D1.2 to be relevant in the BCS and similar systems. Several criteria were applied to this initial list to determine if the ES will be part of the model review: relevance for the SUMES stakeholders, relevance for the first case study (OWF), and whether the ES fits better in a different framework within the SUMES project.

Ecosystem Service	*Type*	*Relevant to stakeholders*	*Relevant for case study (OWF)*	*Relevant for complex case*	*Fits in different framework?*	*Used in model review*
Farmed aquatic animals (for food, materials and energy)	Provisioning	Yes	No		No	No
Wild aquatic animals (for food, materials and energy)	Provisioning	Yes	Yes		No	Yes
Sand and other minerals	Provisioning	Yes	Yes		No	Yes‡
Surface for navigation	Provisioning	Yes	Yes		No	Yes
Renewable offshore energy	Provisioning	Yes	Yes		Yes, LCA	No
Mediation of wastes	Regulating	Yes	Yes		No	Yes
Nursery and habitat maintenance	Regulating/ supporting	Yes	Yes		Yes, ERA	No
Climate regulation	Regulating	Yes	Yes		No	Yes
Coastal protection	Regulating	Yes	No		No	Yes†
Recreation	Cultural	No*	Yes		No	Yes
Aesthetic value	Cultural	No*	Yes		No	Yes
Pest control	Regulating	-	No		No	Yes†

***ES were not selected as relevant by the stakeholders, but this could be due to underrepresentation of the tourism sector. †Although this ES is not relevant to the OWF case, the model review had already been performed and is therefore included in this deliverable. ‡ This ES is relevant, but at present, the model review has not yet been performed. *Pest control* was not included in the list for the stakeholders and was therefore not subject to ranking.**

3.3. Model review

By reviewing literature, we assessed a range of quantitative and semi-quantitative models for each of the selected services. Our focus was on empirical models, as these describe in a detailed and specific manner the relationships between the physical structures and processes in the system. For some ecosystem components, we also broadened the scope and reviewed empirical models, like regression models or other statistical relationships, multi-criteria models and socio-ecological models such as travel cost and choice models, due to unavailability of mechanistic models or because of the complexity of available mechanistic ones. These models may be preferred in the model selection because available mechanistic models may be too complex for our aims (see Table 1

Table 2). These models do not, however, contain quantitative knowledge on the structures and processes of the system, but rather describe relationships based on real-world observations.

We identified models for the different ES and ecosystem components by performing a literature review. Besides searching for models that explicitly depict ES, our searches also included keywords related to ecosystem functioning (e.g. "nutrient cycling" rather than "mediation of wastes"). We also scrutinized the ES literature for model approaches applied specifically in ES assessments (e.g. Liquete et al. 2016; Broszeit et al. 2019). Additionally, we relied on review papers that summarized different models of the same subject (e.g. Hyder et al. (2015) for models of fisheries and the food web). For each model, we extracted information on the scope, complexity, and modelling approach. The information we identified, based on our model selection criteria, helped us select the most appropriate models for the quantitative ES supply modelling of WP3. We identified:

- General model information: which ES and ecosystem compartment is/are modelled? For what geographical area has the model been developed? What type of model is it (mechanistic/empirical, ecosystem/single-species, individual-based/biomass-based, score-based/quantitative, etc.)?
- The reference(s) on which the model review was based. For models that were identified in review articles, we also noted the article in which they were found.

Besides this, we extracted information needed to assess to what extent the models meet the 4 criteria we've established to perform the model selection:

- The model uses parameters that are relevant for the impact assessment: which variables from the initial impact assessment by UGent-GhenToxLab overlap with model components? If none can be identified, how can the model be linked to the factors from the impact assessment?
- The model represents relevant parts of the conceptual cause-effect chain model (Figure 2). For this, we extracted detailed model information: what is the specific content and scope of the model (e.g. nitrogen and phosphorus process rates, fish community dynamics, shellfish growth model, etc.)? Which processes are explicitly modelled? Specifically for each component/ES, how is it represented in the model (e.g. fishing or bivalves)?
- We extracted information on model complexity to determine whether the model has appropriate complexity for the SUMES project: what dimensions are modelled? Is it temporally and/or spatially explicit? For each model, we qualitatively assess the complexity (low/medium/high) based on these factors, as well as on how many structures and processes are represented relative to our needs. For assessing the complexity, it is important that the model only captures the structures and processes in the amount of detail needed to quantify ES supply. This can largely be derived from Figure 2**Fout! Verwijzingsbron niet gevonden.**. We then arrive at a model shortlist of about 3 models.
- Lastly, we assessed if the model or its outputs can be linked to other ES/ecosystem compartments, and in that way the model allows for the analysis of trade-offs between ES. Can we identify parameters in the model that overlap with other models/ES? Does the model already represent multiple ES? Has this model been coupled to other models before? Do we see a possibility for coupling to other models?

4. Results

4.1. Critical analysis of models

Here, we present an overview of the findings of the model review (

Table 2). For each group of models, we first show the cause-effect pathway from OWF presence to ES supply that is used to determine if the models meet the 2nd criterium, i.e. representing the same or similar structures and processes as the conceptual model. We then describe which models were selected as most appropriate to quantify ES supply within the context of SUMES and for what reasons. For the specific information gathered for each model as described in Section 3.3, we refer to this document.

Table 2: Overview of model review for the different ecosystem components. For some components, specific columns were added, because more information was needed on those topics to judge the suitability of the models.

Ecosystem component	*Ecosystem Services*	*Number of models*	*Specific columns in review*
Nutrient models	*Mediation of wastes, climate regulation*	19	-
Food web and fishing models	*Wild aquatic animals, recreation*	15	Fishing & resolution of biological community
Filter feeder models	*Mediation of wastes, farmed aquatic animals, climate regulation, pest control*	12	Processes for filter feeders
Recreation models	*Recreation*	12	
Sand resource models	*Sand and other minerals*		-
Navigation models	*Surface for navigation*	8	-
Aesthetic value models	*Aesthetic value*		
Coastal protection models	*Coastal protection*	22	-

4.1.1. Nutrient models (Mediation of wastes + climate regulation)

Nutrient cycling is a key process in the marine system which directly and indirectly supports several ES. Services directly mediated by nutrient cycling are *mediation of wastes* and *climate regulation*. *Mediation of waste* is here referred to as the removal of excessive nutrients (nitrogen N and phosphorus P) from the marine system, reducing the risk of eutrophication-related problems. *Climate regulation* is the capacity of the system to remove carbon dioxide from the atmosphere and store it for a longer period of time (sequestration), mitigating climate change. The main pathways for removal of excessive nutrients and sequestration of carbon (C) are via diagenetic and sedimentary processes taking place in sea floor sediments. N removal mainly takes place via denitrification, while C sequestration and N storage occur via the burial of organic matter in the sediment. The presence of OWF has impacts on benthic nutrient cycling via two main pathways, i.e. (1) fining of sediment through increased organic matter deposition and locally reduced water currents and (2) smothering of the bottom beneath the turbine foundation. These will result in changes in sediment permeability, organic matter content and community composition. Hence, the model review focuses on nutrient cycling models (C, N, P) that represent (the products of) benthic processes (Figure 5).

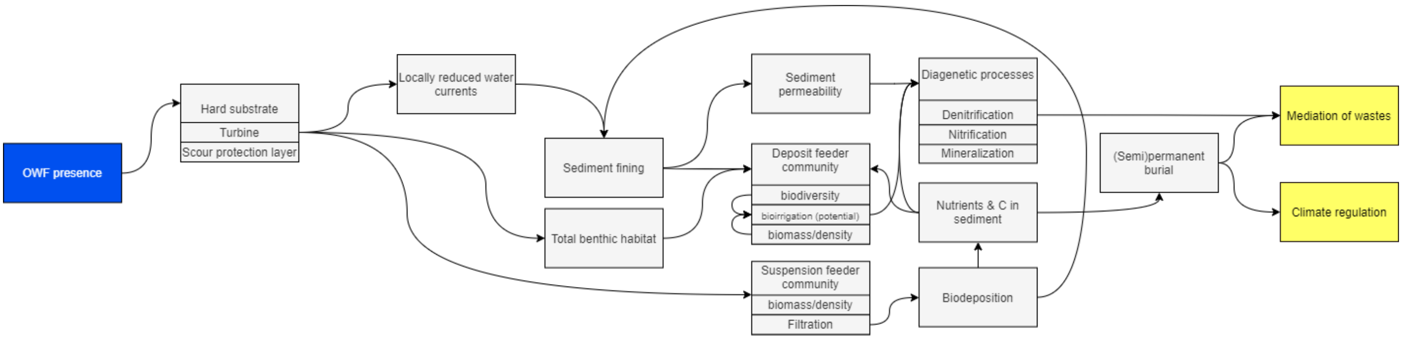

Figure 5: Part of the cause-effect chain model showing the impact of OWF presence on ES related to nutrient cycling, namely *mediation of wastes* and *climate regulation*.

Thirteen models were identified, of which some are restricted to benthic processes (e.g. OMEXDIA, Toussaint et al., 2021) and others include benthic as well as pelagic processes (coupled benthopelagic models, e.g. ERSEM). For *climate regulation*, three additional models were found that only consider C. Models that explicitly include diagenetic processes can be classified into different categories of complexity (Munhoven, 2021). The most simple benthic models ('reflective boundary conditions') assume that all material that reaches the seafloor is remineralised. They neglect the potential storage of nutrients in the sediment and are therefore not suitable for SUMES. More complex, dynamic models are the vertically integrated models (surface sediment is represented as a single box) and vertically resolved diagenetic models which consider a set of vertical layers (up to more than 100) with their own equations describing bacterial processes (Gypens et al., 2008). Simpler approaches that quantify the products of the diagenetic processes (e.g. nutrient storage, nutrient removal) without a mechanistical representation of the diagenetic processes include statistical models (e.g. Toussaint et al., 2021), non-dynamic rate equations (e.g. Middelburg, 2019) and key values (e.g. InVEST). The dynamic diagenetic models include a large number of parameters of which several can be linked to the impacts of OWF (e.g. changes in bioturbation). However, the need for supplying a large amount of parameter values makes them less suitable for use in SUMES.

For denitrification, it was found that the statistical model of Toussaint et al. (2021) provides the best balance between accuracy and complexity, while also being able to link to risks of ecosystem changes caused by the OWF. This model relates denitrification to the % of organic matter, % of fine sediment, irrigation potential of the community and bio-irrigation rate using a generalized linear model. Denitrification was estimated based on measured fluxes of O_2, DIC, NH_x and NO_x and an integrated mass balance of oxygen, carbon, nitrate and ammonium in the sediment (based on the model of Soetaert et al., 2001). The modelled values of denitrification were fitted to a set of seven sediment samples along a permeability gradient in the BPNS, including sites near wind turbine foundations and sites which are less impacted by human activities.

For C and N storage, the most suitable model in the frame of SUMES is the static rate-concentration formula of Middelburg (2019). This approach is frequently applied in ES assessments (e.g. Van der Biest et al., 2017a) and ES assessment tools (e.g. Boerema et al. 2018). The model quantifies the long-term C accumulation rate in seafloor sediments based on a limited number of parameters, i.e. sediment accumulation rate, porosity, dry density and organic C concentration at a depth at which no further degradation takes place. Although this is a computationally simple method, the availability of data for the input parameters could be a problem due to the fact that the data should be representative of sediment at depth. The amount of N stored in the sediment can be approximated based on a fixed stoichiometric C:N ratio at depth which can be derived from literature.

4.1.2. Food web and fishing models

From the conceptual model of the impacts of OWF presence on the food web and the services it supplies (Figure 6), it becomes clear that this concerns a complex interaction of biological groups that supply multiple ES, namely *wild aquatic animals* (for food, material and energy), and several forms of *recreation*. The food web is mainly influenced by the response of the benthic community both to direct and indirect effects of OWF presence. Furthermore, the exclusion of fisheries is a major effect of OWFs on the marine food web.

During the review, we identified 15 models that represent (parts of) the food web in a quantitative way. They were derived from 2 different review articles, Hyder et al. (2015) and Nielsen et al. (2017), which describe existing quantitative models, focused on the marine food web and fisheries, respectively. Out of the 15 models of the marine food web and fishing we reviewed, a food web model of the Southern North Sea in Ecopath, called EMBENS (Pint et al., 2021), was found to be the most appropriate.

Ecopath is a mass-balance food web modelling software that calculates the production and consumption of each functional group within the food web based on input on biomass, fish landings, diets and life-history traits (Polovina, 1984). Since its development, it has become one of the most used softwares for modelling marine ecosystems and has been used to address various policy questions, initially mainly regarding fishing management, but in recent years also regarding marine protected areas, climate change, and OWF presence (Pauly et al., 2000; Watson et al., 2000; Niiranen et al., 2013; Raoux et al., 2017). Ecopath, which provides a snap-shot of the food web in one year, also has a temporally explicit module, Ecosim, and a spatial module, Ecospace. Ecopath itself is not spatially and temporally explicit, but does express rates per area. For the purposes of the SUMES project, simply comparing the state of the food webs within and outside of OWFs with Ecopath is sufficient, because we are interested in quantifying the effects of a single human intervention, namely OWF presence. A temporally explicit and dynamic model would force us to take into account complex long-term processes such as changes in fishing pressure, climate, and policy. The EMBENS model consists of 38 functional groups, from phytoplankton to marine mammals, and 15 fisheries fleets, 10 commercial and 5 recreational. By changing the biomass of groups based on monitoring data and limiting fishing in the model, we can link the food web model to the impact assessment (criterium 1). It represents the entire food web and how all groups interact, which makes it cover the majority of the cause-effect chain in Figure 6 (criterium 2). Though Ecopath models can have as many functional groups as the user wishes to define, it is still a relatively complex modelling tool that requires large amounts of data to function. However, we still chose this approach, because quantitatively modelling the food web is inherently complex when we want to draw meaningful conclusions on the state of the system (criterium 3). Though the number of functional groups is relatively large, they are represented as biomass pools, which simplifies the model. Ecopath models have in the past been coupled to biochemical cycling, socio-economic drivers, climate models, etc. (criterium 4) (Niiranen et al., 2013; Cheung et al., 2008).

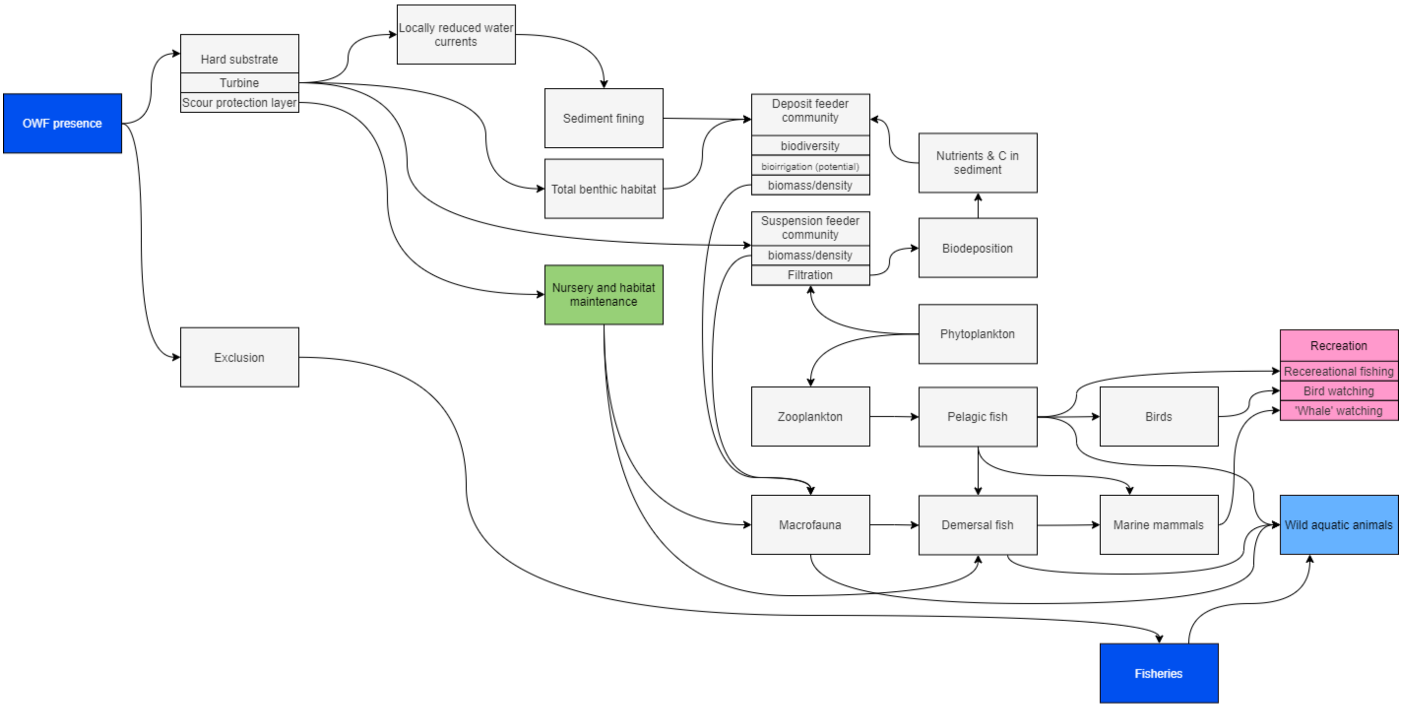

Figure 6: Part of the cause-effect chain model showing the impact of OWF presence on ES the food web, namely *wild aquatic animals*, *nursery and habitat maintenance*, and *recreation*.

The other model on our shortlist was the StrathE2E model, an end-to-end ecosystem model that simulates the fluxes of nitrogen between detritus, inorganic matter and several trophic guilds ranging from phytoplankton to marine mammals. The EMBENS model was chosen over this model for several reasons. First, its geographical range fits best with the SUMES project, whereas StrathE2E was made for the entire North Sea. Second, StrathE2E is driven by physical drivers and nutrient inputs, to which a highly simplified food web responds. This does not allow for the quantification of the effects of OWFs or other human activities.

4.1.3. Filter feeder models

As mentioned earlier, the role of filter feeders in the marine system is a complex one, which also becomes clear from Figure 7 (represented as 'suspension feeder community'). In the case of OWFs, they are ecologically relevant for the supply of the ES *mediation of wastes* and *climate regulation*. This happens in a number of ways: Firstly, they can have a significant impact on marine primary productivity, which may influence the system's ability to mediate wastes. This impact can be both positive and negative, depending on the specific nutrient concentrations and filter feeder densities (Slavik et al., 2019; Broszeit et al., 2019; Smaal et al., 2019). Filtration of phytoplankton can decrease primary productivity. However, the subsequent increase in light penetration and regeneration of inorganic nutrients can have the opposite effect (Smaal et al., 2019). Secondly, the biodeposition of organic matter and fine sediments by certain filter feeders is a major flow of nutrients from the water column to the sediment influences the deposit feeder community and diagenetic processes in multiple ways (Smaal et al., 2019; Ivanov et al., 2021; Toussaint et al., 2021). Though certain filter feeders, like mussels and oysters, can also be a source of food, *wild* and *farmed aquatic animals* were not added as an ES because the biomass of animals withing OWFs in assumed to not be available for human use and they are, therefore, not relevant for the OWF case study (though it may be investigated later on in the project when other marine activities will be integrated). Similarly, filter feeders can supply the ES *pest control*, but this was not deemed relevant for the case study, as OWFs are too far from the shore to affect areas where algae can become a nuisance.

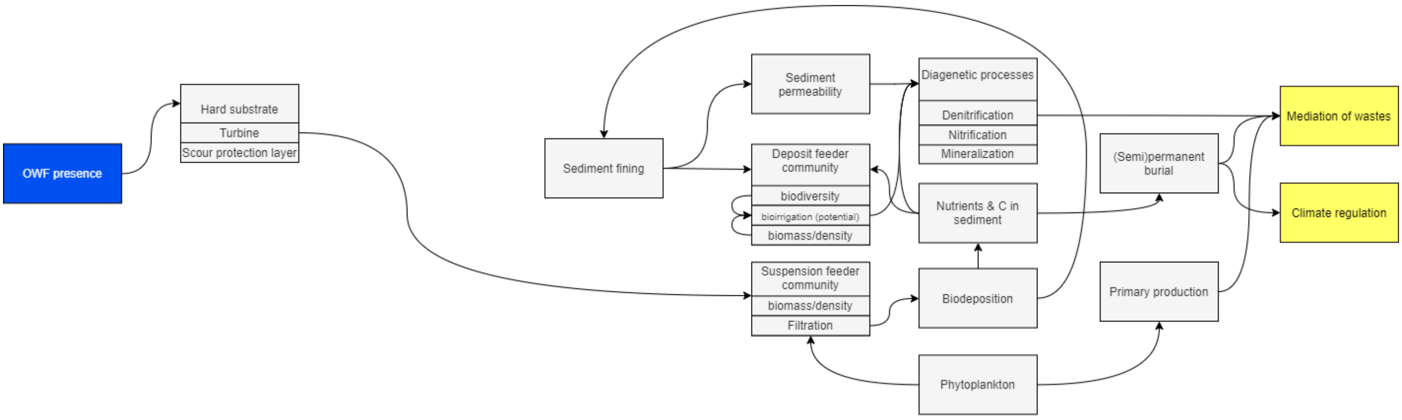

Figure 7: Part of the cause-effect chain model showing the impact of OWF presence on biofouling filter feeders and subsequently, ES related to filter feeders (*mediation of wastes* and *climate regulation*).

We reviewed 12 models that quantified the effects of filter feeders on the ecosystem. Some of these models were specifically made for cultured bivalves rather than wild (biofouling) bivalves, so these models were not relevant to this part of the SUMES project. In the end, we selected 3 modelling studies for the shortlist of relevant models, with some overlap existing between the models in terms of the research from which they derived their equations. The modelling approach by Ivanov et al. (2021), of which the filtration component is an upgraded version of Slavik et al. (2019), was found to be the most appropriate.

Ivanov et al. (2021) use a coupled hydrodynamic model, wave model, sediment model and filtration model to quantify the effects of OWFs on organic and mineral fluxes to the bottom through biodeposition induced by filter feeders. For the OWF case study, we focus on the filtration model and a simplified version of the biodeposition model component. The model is dynamic and spatially explicit, although this can be simplified to a more spatially implicit model, which would be more in line with our aims. The model resolves the rate at which carbon (phytoplankton and other organic carbon) and supsended sediment are filtered from the water column, and how much of that is deposited (compared to the reference situation without OWFs). In this way, the total flux of carbon and (fine) sediment to the benthic component can be calculated relatively easily, which can function as a driver for the nutrient model in Section 4.1.1. The filtration model can also be used to calculate the impact on phytoplankton, as is done in Slavik et al. (2019), to assess the impact of filter feeders on *mediation of wastes* through primary production. In parts, the model will have to be simplified. For example, we will not couple it to the hydrodynamic and wave models, but will use the equations in the filtration and sediment models to calculate the overall fluxes from the water column to the sediment.

This model was preferred to the other options on our shortlist. Firstly, the model by Slavik et al. (2019), on which part of Ivanov's model is based, is focused on filtration and does not include equations to quantify the flux to the sediment. Secondly, the MIRO&CO model with a module for the blue mussel (*Mythilus edulis*) resolves the water clearance and filtration of several organic matter fractions by mussel reefs in the BCS (*Martini, 2014*). The resolution of the filtered material is higher in this model than in Ivanov's, and higher than is necessary for our purposes. Although this model does explicitly calculate pseudofaeces production, it does not calculate the resulting biodeposition. Furthermore, it was developed to determine the effects of mussel reefs, rather than biofouling mussels on wind turbines (Martini, 2014).

4.1.4. Sand resource models

The supply of *sand and other minerals* is influenced by most marine activities, including OWF presence, only through the exclusion of the sand extraction necessary for the delivery of the ES (Figure 8). Otherwise, there is no interaction between OWF and ecological structures and processes that drive the availability of sand for extraction. Sand extraction itself has various effects on ecosystem functioning (Hill et al., 2011), but this is outside of the scope of this deliverable and this case study.

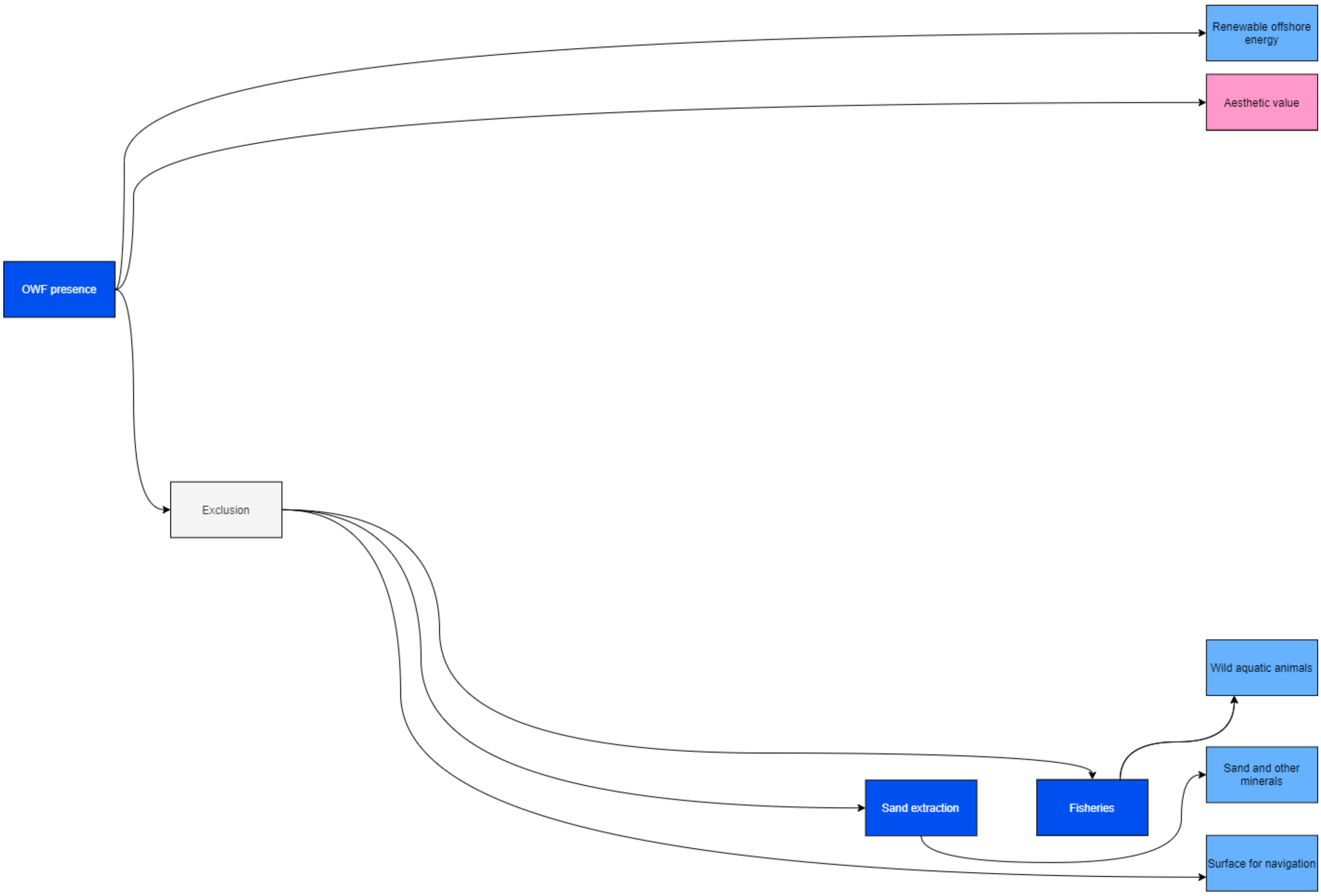

Figure 8: Part of the cause-effect chain model showing the impact of OWF presence on ES that do not interact with ecosystem functioning, namely *sand and other minerals*, *surface for navigation*, *aesthetic value*, and *renewable offshore energy*.

Because of the rather straightforward interaction between OWF presence and the supply of *sand and other minerals*, a detailed review of mechanistic models was not necessary for this ES. Rather, we aim to perform an analysis of the spatial conflict between OWF concession areas and areas dedicated to sand extraction (MSP, 2020). This spatial conflict analysis could also be performed for OWF concession areas and the potential supply of sand by exploitation of reserves that are currently not being extracted (Van Lancker et al., 2019). This would allow us to identify possible future conflicts.

4.1.5. Recreation models

Many different activities fall under the ES *recreation*, both active recreation such as swimming, angling, diving, as passive recreation (e.g. wildlife watching). Hence, *recreation* can be linked to multiple ecosystem functions and a wide variety of models are useful to model the supply side of *recreation* (Figure 9). The main recreational activities which are potentially impacted by OWF in the BPNS are recreational fishing and wildlife watching. Impacts on swimming due to changes in water quality are expected to be negligible due to the large distance of OWF from the shoreline.

Potential impacts of OWF on recreational fishing are related to a combination of changes in the food web and an exclusion of commercial fisheries. The impacts and the affected ecosystem functions are similar to those driving commercial fisheries production and therefore, the same ecosystem functioning model (i.e. Ecopath) can be used (see e.g. Montero et al. 2021). Ecopath can also be used for modelling impacts on bathing (not relevant in the case of OWF) via changes in cyanobacterial blooms, as is done by Hyytiäinen et al. 2021. Alternatively, water quality models could be used for modelling chlorophyll a as indicator of harmful algae blooms (Broszeit et al. 2019).

Other models that are frequently used for *recreation* are socio-ecological models that relate environmental properties to recreational behaviour. Such models take into account the products of ecosystem functions (e.g. water quality, habitat type), without explicitly modelling the underlying ecosystem functions. They have been applied to recreational angling (e.g. Pouso et al. 2019), boating (e.g. Viana et al. 2017) or unspecified forms of outdoor recreation (e.g. ESTIMAP). A commonly used socio-ecological modelling approach is the multi-site travel-cost method. This method assesses the amount people pay as travel costs to visit a site. These values are then statistically related to environmental attributes as predictor variables, as is done in Pouso et al. 2019 and Johnston et al. 2002. As an alternative to travel costs, the number of visitors can be used (e.g. Coombes et al. 2009, InVEST). Although these models are mathematically less complex, they may be difficult to apply in the context of SUMES as they need information on visistor numbers or individual trips made by visitors. Alternatively, social media sources such as Flickr (photographs) could be used to estimate the relative frequency of visits to a site (e.g. Van der Biest et al. 2017b). A more pragmatic approach is expert-based multi-criteria assessment (e.g. Ruskule et al. 2018), although this may be difficult to express in quantitative terms. The selection of the most suitable model for SUMES will be driven by the availability of data on visitor numbers, either visitors along the shore or visitors on boat trips. It is important to note that some of these modelling approaches are aimed at quantifying the demand, rather than the supply, for *recreation*. This is due to the fact that the supply of *recreation* and other cultural services is often determined by the demand.

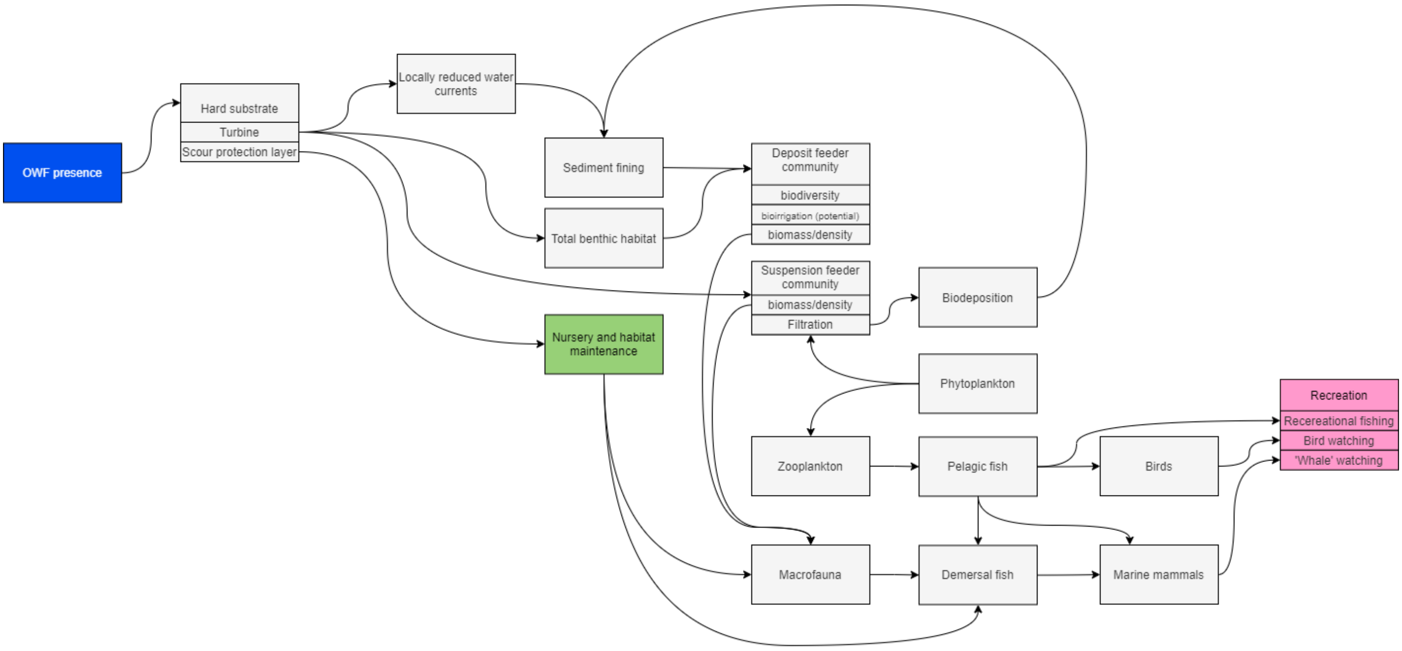

Figure 9: Part of the cause-effect chain model showing the impact of OWF presence on the ES *recreation* and related activities.

4.1.6. Navigation models

The interaction between OWF presence and *surface for navigation* is a very straightforward one: the presence of an OWF concession area excludes shipping and therefore reduces the supply of *surface for navigation* (Figure 8**Fout! Verwijzingsbron niet gevonden.**). No other interactions with the ecosystem were identified. Such a straightforward relationship is best quantified in the same way as the relationship between OWF presence and *sand and other minerals*, namely a spatial conflict analysis. This analysis aims to determine the effect of the concession areas on the length of shipping routes and consequent costs (financial or otherwise), including increased carbon emmisions due to longer shipping routes.

4.1.7. Aesthetic value models

The *aesthetic value* of the marine system is, in this case study, only directly affected by OWF presence, and does not interact with any other ecosystem function (Figure 8). For this ES, we will use the relationship between the distance of an OWF to the shore and the effect on the aesthetic perception of the system by locals/other users, as studied in Maslov et al. (2017).

4.1.8. Coastal protection models

The ES *coastal protection* refers to the capacity of the ecosystem to reduce floods of the hinterland and hence avoid damage costs and casualties. Typical coastal ecosystem structures that can reduce floods are wave dampening structures in the foreshore and shore area (e.g. submerged sand bars, bivalve reefs, beaches) and structures that constitute physical barriers to flood water (e.g. dunes).

The OWFs in the BPNS are developed at such a large distance from the coastline (>20km) that an impact on coastal protection is unlikely. Depending on the advanced case that will be selected further along in the SUMES-project, it may be needed to include coastal protection in the SDES-model of SUMES. An overview of available models for coastal protection has been made as part of this deliverable. A shortlist of the most suitable models has not been made yet as this depends partly on the case-study.

Flood damages in continental shelf seas are typically modelled using a chain of process models including: (1) a wave propagation model towards the coast, (2) a failure behaviour model of coastal defense structures, (3) a flood model of the coastal plain and (4) a socio-economic model for damages and casualties (Verwaest et al. 2009). This review focusses on marine ecosystem functioning models and therefore only the first two model types are discussed here.

A wide variety of numerical models with varying complexity (1D, 2D, 3D) exists for wave propagation towards the coast, of which 6 of the most commonly used models in Belgium and countries along the North Sea are included in this review (e.g. SWAN, Delft3D, SWASH). Additionally, some models (#3) include both a wave propagation module as well as an erosion module for the failure behaviour of the protecting ecosystem structure (e.g. GENESIS, LITPACK). For erosion modelling also a wide variety of numerical models exists, such as the highly complex 2D model XBeach (foreshore, beach and dune erosion) and the lower complexity 1D model DUROSTA (dune erosion). Models are able to mimic cross-shore erosion (occuring during storms – e.g. SBEACH), longshore erosion and sedimentation (daily occurence – e.g. DUROS), or a combination of both (e.g. LX-shore). A more practical but less accurate approach compared to numerical modelling (Wellekens 2019) is the use of a bulk transport formula that quantifies beach erosion based on wave and beach characteristics (e.g. Kamphuis 1991, Mil-Homens et al. 2013).

All of the models included in the review can be linked to risk assessment factors and to other ES via changes in seabed habitat affecting wave propagation and changes in coastal habitat structures that are able to dampen wave energy.

5. Further use in SUMES

The model review, which was now targeted at the first SUMES case study, OWFs, will also be adapted for the advanced case study. The models selected in this deliverable will be used in WP3 to construct a fully quantitative model to assess the impact of human activities on the supply of ES, specifically OWF presence. A first 'test run' of this is planned to be completed in November 2021, for *mediation of wastes* by quantifying diagenetic processes, mainly denitrification, in response to environmental changes in OWF concession areas. The other ES will be quantified in the months after with the other models selected in this deliverable. The magnitude and extent of the environmental changes due to human activities is an output of the ERA performed by UGent-GhenToxLab, which will drive the ecosystem functioning models that can be used to quantify changes in ES supply. ES supply is later on linked to potential and future demand for ES as quantified by VLIZ, to identify future pressures on the system and (mis)matches between supply and demand (WP2). This comparison is possible because the selection of indicators for supply and demand has been done iteratively to guarantee the indicators were comparable and expressed values using the same units (where posssible, in monetary terms). It will also ensure that impacts on ES supply are accounted for relative to the (future) demand for that ES. It also provides insight into potential risks of overexploitation of marine resources, allowing to improve the design of sustainable solutions to avoid this issue. In WP3, we will also attempt to transform these models into spatially explicit models to give an overview of how ES supply is distributed spatially.

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