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The Smartsediment tool: a QGIS plug-in for evaluating ecosystem services in estuarine and delta systems

Smartsediment WP4 Ecosystem services (Report 4.6)

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1 Introduction: the Smartsediment project

The Scheldt delta has been shaped by the numerous human activities that are taking place in the area. Since the construction of a storm surge barrier in 1986 covering the whole mouth of the Eastern Scheldt, as part of the Delta Works, the tidal dynamics decreased severely and the sediment balance in the area was disrupted. The natural sedimentation of intertidal area decreased, while the erosion rate remained the same. If this process, referred to as **sand starvation**, continues and no measures are taken, most of the intertidal area will disappear (Louters et al., 1998; Van Zanten & Adriaanse, 2008). As a consequence of the sand starvation **valuable foraging habitat for waders is threatened**.

On the other hand, the **Scheldt estuary**, formed by the Western Scheldt (The Netherlands) and Sea Scheldt (Flanders, Belgium) is characterised by high hydrodynamics and fast changing sedimentation and erosion patterns. To ensure a navigable fairway towards the ports in these circumstances, frequent dredging is necessary. Because of a history of river engineering and sand extraction in the Scheldt estuary**, nature compensation and reinforcement** are needed to achieve the goals that are imposed by the European Habitat- and Bird directives.

To address these problems in the Scheldt delta, **various sediment strategies and measures** are developed within the Eastern Scheldt, Western Scheldt and Sea Scheldt. They mostly aim to conserve and extend the intertidal area and improve and restore natural habitat through the (re)use of dredged sediment. In the Eastern Scheldt, measures are focussed to mitigate the effects of sand starvation by applying sediment nourishments on intertidal flats sometimes combined with artificial oyster reefs or dams to protect the nourishment against erosion. In the Western and Sea Scheldt the measures aim to reuse dredged sediment with a focus on both morphological and ecological benefits. The measures include subtidal placement of dredged sediment at the edges of intertidal shoals.

These sediment measures are not only possibly beneficial for nature, they also have the potential to provide benefits for society, such as the creation of new recreational area, the provision of spawning grounds for fish and crustacea, which benefits the food industry, the safeguarding of the fairway, flood prevention and contributions to climate change mitigation by carbon sequestration. These are the so-called **ecosystem services**.

Within the **Interreg project Smartsediment**, eight different measures throughout the Scheldt delta are performed and evaluated by a cooperation of several Dutch and Flemish project partners to address the above described problems and add to the knowledge about sediment management and the provision of ecosystem services.

During the project, also **a spatially explicit tool was created** to support the evaluation of ecosystem services provision related to sediment management within the Scheldt delta and similar estuarine systems.

In this report, the background, structure, use and purpose of the Ecosystem Services tool (ES-tool) are explained and two case studies are presented.

2 Background: sediment management and ecosystem services (ES)

2.1 Sediment management for ecosystem services

Sediments form an essential, integral and dynamic part of our river, estuarine and coastal systems, where they determine both patterns (habitats) and processes (e.g. erosion and sedimentation). Human interventions such as dredging, disposal and sand mining, but also alterations in the hydrodynamics, influence the sediment household of water bodies. This can benefit certain targets (e.g. navigation) but also affect patterns and processes, positively and negatively, in the natural system at hand. A shift can be observed to sediment management strategies that are more integrated with the needs of other user functions, e.g. disposal of dredged material to create valuable habitat. The benefits of these strategies on ecological objectives (habitat and species) are studied during design and legally required evaluation procedures. However, the creation of habitat also benefits other objectives than biodiversity. In this paper we try to explore and unravel with which relations between sediment management and ecosystem services (ES) an evaluation of all benefits for society can be made.

ES are the benefits that humans derive from nature (MEA, 2005, TEEB, 2010). There are different types of ES with different benefits for human wellbeing. The Common International Classification of Ecosystem Services (CICES) defined three categories (CICES 2020): provisioning (e.g. reared aquatic animals for nutrition, surface water used for energy), regulating and maintenance (e.g. regulation of soil quality, regulation of baseline flows and extreme events), and cultural (e.g. physical and experiential interactions with natural (a)biotic components of the environment).

The ES cascade framework illustrates the link between the ecological system and the socio-economic system (Figure 1). The ecological system exists of biophysical structures that form an ecosystem (properties, EP) and any change or reaction which occurs in an ecosystem (functions, EF). Due to the functioning of the ecosystem, ecosystem services (to humans) are being delivered ('ES supply') and hence contributes to human wellbeing (benefits, B). This change in wellbeing brings with it certain (non-)economic value for society (V).

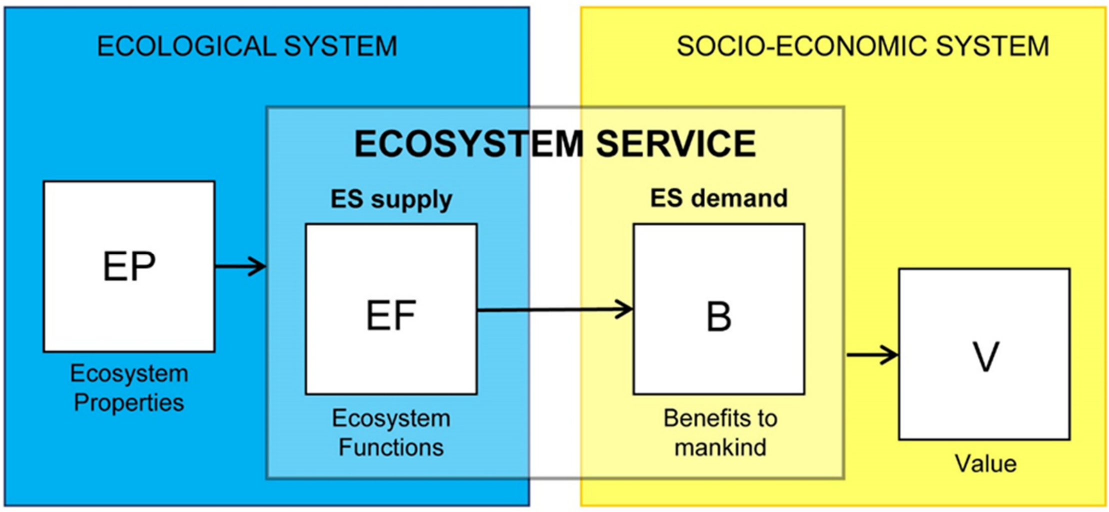


Figure 1: Ecosystem services (ES) cascade framework, showing ES as the link between the ecological system (consisting of ecosystem properties with certain ecosystem functions) and socio-economic system (with needs and benefits for society with a certain value) (Boerema et al. 2017).

At a global level, the concept of ES is finding its way in important programmes. It is recognised that healthy and sustainable ecosystems are critical for the Millennium Development Goals since they are the ultimate source of natural resources which represent the essential ingredients for human survival, and the 'fuel' and building blocks for human wellbeing and economic development (MEA, 2005, UNEP, 2009). Some key messages in the Blue Planet synthesis paper from the Millennium Alliance for Humanity and Biosphere (MAHB) are also related to ES (Brundtland et al., 2012):

> *"Biodiversity has essential social, economic, cultural, spiritual and scientific values and its protection is hugely important for human survival. […] Measures to conserve biodiversity and make a sustainable society possible need to be greatly enhanced and integrated with social, political and economic concerns. There is a need to value biodiversity and ecosystem services and create markets that can appropriate the value for these services as a basis for a 'green' economy."*

Furthermore, the use and restoration of ES is being recognised by the UN-Water to be an effective and cost-saving alternative to conventional infrastructure (e.g. wastewater treatment plant, dikes for flood prevention) (UN-Water, 2014).

Since 2012, the independent Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) takes an important role globally to strengthen the science-policy interface for biodiversity and ES for the conservation and sustainable use of biodiversity, long-term human well-being and sustainable development (IPBES 2012). IPBES currently works on the rolling work program up to 2030 to advance the achievement of the overall objective of IPBES. This 2030 work program corresponds to the 2030 Agenda for Sustainable Development, including the Sustainable Development Goals, the biodiversity-related conventions and other biodiversity and ES processes (IPBES 2012).

2.2 Challenges to develop ES-based sediment management

For the specific context of dredging and marine constructions, the application of the ES concept is acknowledged to be able to demonstrate benefits of such projects to human welfare and the environment (CEDA, 2013, PIANC, 2016). Yet, ES are often not considered in project related cost-benefit analysis, probably due to a lack of applicable tools and practical guidance. We address three major challenges that should contribute to a better uptake of ES in project development: (1) indicators to quantify ES based on state-of-the-art system understanding, (2) spatially explicit assessment to account for local and system-wide effects, and (3) the temporal context of effects.

Sediment management, including dredging, sand extraction, sediment disposal and nourishments, is an important tool for management of estuaries and coastal areas. Changes are induced in the water-sediment system on both short temporal and small spatial scales (e.g. sand bar nourishment) as well as on long temporal and large spatial scales (such as influencing the tidal range). The resulting geomorphological changes, on all scales, affect a variety of coastal and estuarine ES.

In order to come to an evaluation of the changes that are expected in ES, a procedure to calculate the effects of sediment management strategies on ES is needed. To date, there is low consensus on how to quantify ES. A recent literature study demonstrated that current indicators and methods are not able to grasp the complexity of ES (Boerema et al., 2017). This can give an explanation why many effects of estuarine management measures on ES are described in qualitative terms rather than in quantitative terms (Boerema and Meire, 2017). What is needed are indicators for ES that will allow for a more precise evaluation of the biophysical effects of interventions in terms of ES for the specific context of estuaries.

Secondly, it should be possible to analyse how the effects are spatially distributed in the system. To calculate local effects at the project location rather straightforward methods are sufficient because these effects are usually rather straightforward. However, local changes can result in ecosystem-wide effects. Although these effects may be small at a greater distance from the project location, they are often not negligible due to the large spatial context in which they occur. What is needed is a spatially explicit tool to calculate effects on ES at the ecosystem scale with a distinction between local and system-wide effects. The appropriate ecosystem scale depends on the management strategy scale and characteristics of the affected ecosystem.

Thirdly, also the temporal scale of effects on ES should be considered. After a project, it can take several years for the system to develop towards a new 'stable' situation. During such successional evolution, also the capacity of the ecosystem to deliver ES will evolve (Boerema et al., 2016a). What is needed is an instrument that can assess the temporal evolution of these effects.

These are three important aspects for a sound ES assessment, which can be used as input for an environmental impact assessment, societal cost-benefit analysis and cost-effectiveness analysis. GIS tools can enable decision makers and executives to make a first evaluation of the ES delivery of the estuarine or coastal system they are interested in. Furthermore, with such tools a comparison can be made of different strategies or project designs, also spatially (using maps). It should be possible to use local knowledge and data as much as possible. In this paper, we present the development of the Smartsediment tool, that tries to addresses all three aforementioned aspects. The tool is based on a conceptual model to unravel impact-effect pathways and builds on ECOPLAN-SE, a spatial decision support system to assess a wide range of ecosystem functions and services on land (Vrebos et al., 2020).

3 Development of the Smartsediment tool: a QGIS tool to evaluate ecosystem services

We present here four steps that are needed to develop an instrument that addresses the three outlined challenges. The aim is to develop a spatially explicit tool to calculate effects of sediment management strategies on ES. The tool is developed and tested for the transboundary Scheldt delta in the frame of the EU Interreg regional Flemish-Dutch project Smartsediment (www.smartsediment.eu/english).

3.1 Step 1: Selection of relevant ecosystem services

When evaluating the ES within a management context, considering all possible ES is difficult, time consuming and unnecessarily expensive. Therefore, a selection of the most relevant ES should be made. However, it is important to include a broad range of ES covering provisioning, regulating and cultural ES. Therefore, a structured procedure to select the relevant ES is required.

Starting from a long list of ES based on the Millennium Ecosystem Assessment (MEA, 2005), The Economics of Ecosystems and Biodiversity (TEEB, 2010) and the Common International Classification of Ecosystem Services CICES (Haines-Young and Potschin, 2013), ES that are identified specifically for estuaries and the marine environment were added to this list (Barbier et al., 2011, Liquete et al., 2013, Turner and Schaafsma, 2015, Böhnke-Henrichs et al., 2013, Jacobs et al., 2015).

Next, this list of ES was screened by experts to select those that depend in some way on sediment and that can potentially be affected by sediment management. Previous work on ES in the context of sediment management, dredging and port activities was also consulted (Apitz, 2012, Brils et al., 2014, van der Meulen et al., 2016, Boerema et al., 2016b, PIANC, 2016).

The following ES were selected (see Table 1): aquatic animals for nutrition (crustacean, shellfish, fish), substances used for materials (sand), mediation of wastes (regulation of water quality), regulation of baseline flows and extreme events, physical and experiential interactions with natural environment (shoreline recreation, swimming, recreational navigation), and habitat protection (seals, birds). Additionally, also effects on the navigation potential of the river were considered.

The first three ecosystem services included in the tool are related to **food resources for human consumption: shellfish, crustacea and fish productivity**. The Eastern Scheldt basin is a very important area for shellfish farming, with around 40 km² and 15 km² of bottom culture plots for mussels and oysters respectively (Taal et al., 2010). In the Western Scheldt, commercial fishing on crustacea and fish (mainly sole and eel) takes place. Sediment nourishments in the tidal basin could negatively affect shellfish productivity by for example burying the plots or increasing suspended matter concentrations. Increasing suspended matter concentrations also affect fish and crustacea productivity. Additionally, sediment measures may change the area of habitat (mainly superficial low dynamic ecotopes, mud flats and high marsh) that is important as feeding and/or spawning grounds (Boerema et al., 2018a).

Table 1: List of ecosystem services included in the ES-tool

Ecosystem services	
1.	Food resources for human consumption
	1.1 Shellfish productivity
	1.2 Crustacea productivity
	1.3 Fish productivity
2.	Shipping space
3.	Mining resources
4.	Regulation of water quality
5.	Regulation of flooding
6.	Climate regulation
7.	Recreation and tourism
	7.1 Coastbound recreation
	7.2 Swimming
	7.3 Recreational shipping
Habitat types	
1.	Seal habitat
2.	Bird habitat

Provisioning services such as the **provision of shipping space and mining resources** are also included in the tool. The Western and Sea Scheldt connect several ports, among which the Port of Antwerp, to the sea. Since sediment measures affect bathymetry and current velocities, they will inadvertently impact shipping when applied at or close to the fairways. The area also has a long history of dredging activities to deepen the fairway. The availability of mining resources (sediment) can increase or decrease when sediment is taken out or put into the system.

Intertidal area has an important role in the regulation of water and soil quality through the dilution and fixation of pollutants. The ES-tool includes the **regulation of water quality** by looking at the amount of denitrification, nitrogen fixation, phosphorus fixation and silica release. By creating or harming intertidal area and high marsh, sediment measures can enhance or disturb this regulating function. Through fixation of CO_2, mostly in vegetation and silt, vegetated high marshes and mudflats can also contribute to **climate regulation**. On the opposite, mudflats can also be a source of methane by releasing it to the air.

Another regulating service that can be impacted by sediment measures is the **regulation of flooding**. Intertidal areas and high marshes serve as buffers that brake waves. In that way, sediment measures can decrease the impact on the dikes and increase their lifetime. This improves safety and reduces the costs of flood protection.

Sediment management can also affect **recreation and tourism** by creating or damaging low dynamic areas suitable for swimming or foraging and resting area for birds and seals in the near of walking and cycling paths. Similar to the impact on commercial shipping space, sediment management can also affect recreational shipping. This is mainly due to a change in turbidity and water depth.

Next to the impact on ES, sediment management could also affect **habitat for birds and seals**. A big part of the Scheldt delta is designated as Natura 2000 area and as such protected under the European Birds and Habitat directives. The intertidal area in the Scheldt delta is also designated as a key site of international importance for migratory birds under the international Ramsar Convention. By changing emersion time of intertidal area, foraging grounds and resting area for birds and seals is affected. Additionally, all macrobenthic species die of by burying an area with sediment in the case of for example intertidal sand nourishments. To allow the area to still serve as foraging grounds, first recolonization by benthos has to take place.

3.2 Step 2: Conceptual model to unravel impact-effect pathways

How do specific sediment management strategies affect the functioning of the coastal zone (natural system) and hence on the delivery of ES? Different impact-effect pathways can exist between the management strategy, the functioning of the coastal zone and ES. To unravel these pathways, a conceptual model representing the relationships 'how does the world work' was developed. This conceptual model provides an analytical framework to give insight in the effects of sediment strategies on ecosystem functioning and on the selected ES (Figure 2). The estuarine ecosystem is divided in the soil, water and air components. The interaction between hydrodynamic and morphodynamic processes (water flow, sedimentation and erosion) forms the basis of the system structure (a-biotic structure). In addition to that, soil and water quality aspects such as nutrients, oxygen, organic material, primary production and detritus, form the basic food cycle in the system. On top of that, the food web can develop with higher trophic levels.

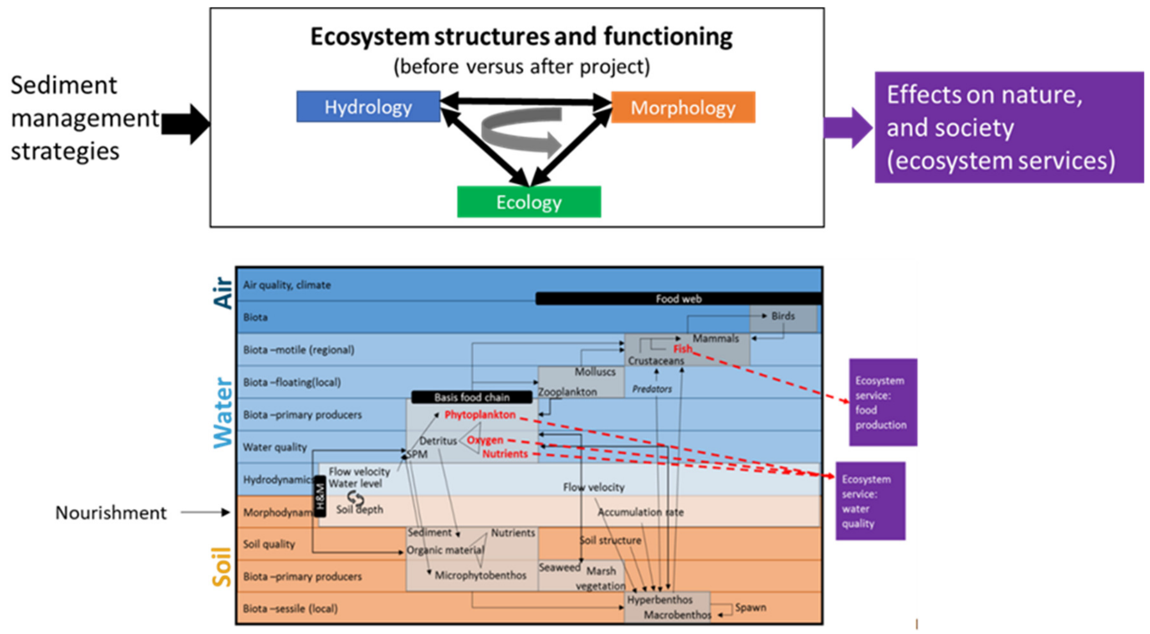


Figure 2: Smartsediment conceptual model, which is used to unravel impact-effect pathways. The top row shows the global concept: sediment management strategies intervene in the overall ecosystem structures and functions (hydrology, morphology and ecology) which results in effects on nature and society (ecosystem services). The bottom zooms in on the complex relationships that are taking place within the ecosystem. Consequently, one intervention (e.g. sediment nourishment) results in a direct effect on the morphodynamics of the ecosystem, but through the processes between hydrology, morphology and ecology many indirect impact-effect relationships occur with effects on e.g. food production because of changing fish feeding habitat, and water quality regulation because of changing water turbidity.

This conceptual model is used to depict impact-effect pathways. First, the main direct and indirect effects of sediment management strategies on the functioning of the system are identified. Next, the functions of the system should be linked to the different ES. The latter step requires insight in the underlying ecosystem processes that form the basis for the delivery of the ES.

Direct effects are related to (i) changing the local morphodynamics by dredging or disposing sediments, (ii) changing the local sediment characteristics (disposal of new material can add different sediment composition and grain size), (iii) changing the water quality (dredging and disposal can cause more turbidity when fine sediment ends up in the water column), and (iv) temporal visual or auditory disturbance during the project which can affect higher biota such as seals, porpoise and fish.

Direct effects could be linked to ecotopes. Ecotopes are a classification system based on the smallest ecologically distinct landscape units with relatively homogeneous, spatially explicit abiotic landscape characteristics such as a typical depth and water velocity (e.g. channels versus intertidal areas). Ecotopes have distinct characteristics and can therefore be considered representative for other functions and for the delivery of particular ES. It provides a practical solution for a rapid assessment which might be needed in an early project phase when one is interested in a high-level comparison of different scenarios. In a later stage, for more detailed assessments of different designs, more detailed local information is required, which goes beyond the simple ecotope approach. This is similar with the habitat approach which is often used in ES studies, but ecotopes are limited to units based on abiotic parameters only. Biotic parameters should be considered in addition (more local specific, not less straightforward to be considered representative).

Besides the more obvious direct effects, also indirect effects should be considered (**Fout! Verwijzingsbron niet gevonden.**). Potential indirect effects are very diverse and linked to the entire ecosystem functioning. Hydrodynamic conditions can change due to morphodynamic changes because of their strong interactions. Changes in hydrodynamic and morphodynamic conditions can result in changes in the presence and characteristics of ecotopes. Changes in hydrodynamic and morphodynamic conditions can also affect water quality (suspended matter). Due to changes in water velocity, flow direction and sediment characteristics, more sediment can get in suspension or suspended matter can decrease in case more sediment is trapped under the new situation. Furthermore, changes in hydrodynamic and morphodynamic conditions and soil and water quality affect biotic conditions (e.g. benthos, birds, fish and shellfish, seals).

3.3 Step 3: Calculation methods

The most challenging part is the quantification of the impact of sediment management on ES. The tool translates changes in the ecosystem, e.g. flow velocity, sediment type, access for recreation, into changes in the delivery of particular ES. The calculation methods per ES are based on ecosystem knowledge of coastal systems (from the Scheldt delta and similar North West European deltas) and specific studies that investigate management effects. To develop the calculation methods for each ES, a balance had to be found between representing the complex reality and ease of use. Aspects such as the necessity of input parameters and ease of implementation in the QGIS tool had to be considered. Therefore, for some ES two quantification rules are foreseen, one more advanced and one more simple. Obviously, the simpler method, based on less parameters, is less precise. All calculation rules and necessary input data is described in detail in the user manual (De Swerdt et al., 2020).

An example is the ES 'climate regulation'. This ES expresses (within the context of sediment management) the storage of carbon due to sedimentation and primary production at mudflats and marshes. Two calculation methods are available in the Smartsediment tool.

The first method is simple and uses the mean value for carbon storage for different ecotopes based on expert knowledge and literature (Boerema et al. 2016b). Based on the different ecotopes and their average carbon storage values, a total amount of carbon storage for the area of interest is calculated. Also, the salinity (in three categories: salt, brackish, fresh) is taken into account. For the

Scheldt estuary, a salinity map is already added to the underlying model and should thus not be added by the user.

The second method is more advanced and foresees a calculation of carbon storage based on sediment storage, soil density and emissions. The total carbon storage (ton C/year) is the change in carbon storage via sedimentation corrected for greenhouse gas emissions from sediment (Boerema et al. 2016a). The change in carbon storage via sedimentation is calculated from the change in area mudflat and marshes (ha), sediment accumulation per year (cm/year), soil density (kg/m²), suspended particulate matter (mg/l) and particulate organic carbon (mg/l). For both methods, the output map shows the amount of carbon storage per year for the area of interest in ton C/year.

3.4 Step 4: Development of the Smartsediment tool

The quantification rules from step 3 were integrated in a QGIS plug-in to make them easily available. The Smartsediment tool enables the user to calculate the impact of different sediment management strategies on the delivery of the ES and compare them with each other over a longer period of time. It has three functionalities: (1) preparation of data layers, (2) calculation of each of the selected ES separately, and (3) analysis of the results (Figure 3).

As QGIS is an open source software, others can easily use our tool without licence. This considerably increases the applicability of the Smartsediment tool in the future. The tool exists of two parts, the actual plug-in and as a GIS database. The first part, the QGIS plug-in, consists of the scripts that build the interface and integrates the quantification rules in a range of ES modules. The second part, the GIS database, consists of several folders needed to run the plugin. These folders contain ES specific information and a location to store intermediate data during the calculations.

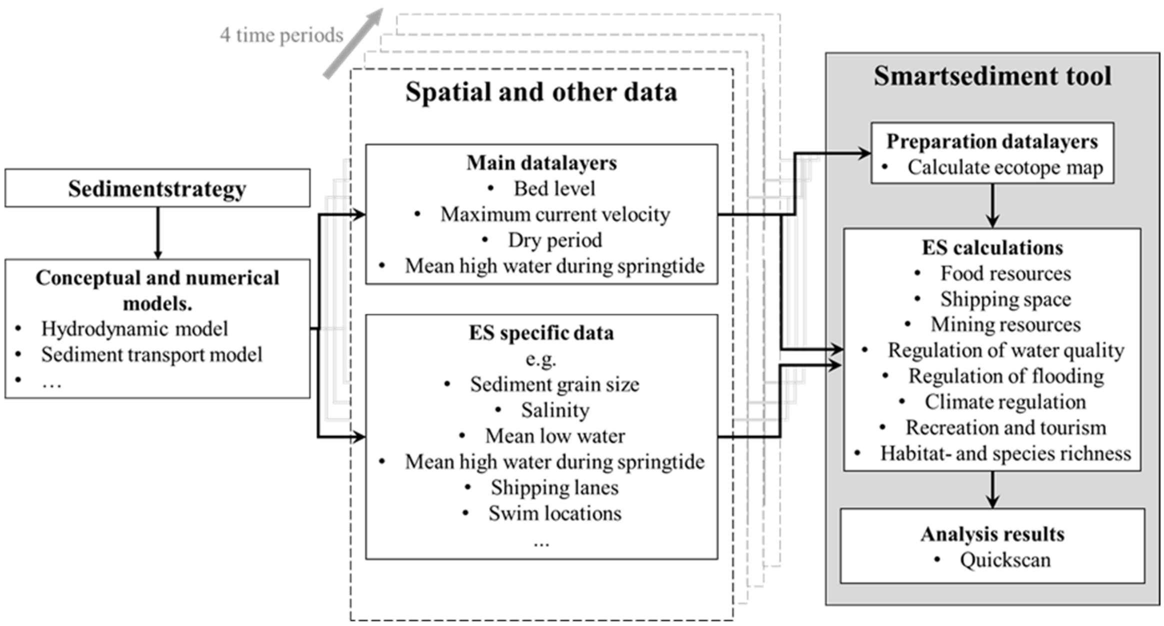


Figure 3: Overview of the analysis.

To run the ES calculations in the Smartsediment tool, information on a wide range of parameters is required. These parameters can be spatial maps or values which are consistent for the entire research area. This information can be derived from other conceptual and numerical models which can evaluate the impact of sediment management strategies on different estuarine characteristics such as hydrology, sediment behaviour, etc. An important parameter, which is used in different ES calculations, is a spatial description of the ecotopes. However, models or methods to calculate the ecotope map are not widely available. Therefore, a module is provided to calculate this map through other, usually more accessible, model derived, datasets.

Ecosystem services often have complex relationships with many parameters. To accurately predict the impact of sediment management interventions on these ES, the impact on these parameters can only be evaluated with specialized, numerical models. However, this type of models is often not available to the user, making it difficult to provide many of these parameters in detailed maps. To address this shortcoming, the ecotope map and other ES specific data are used to calculate a range of ecosystem services. Wherever possible, the Smartsediment tool provides a multi-level approach.

For some ES both a simple and more complex calculation method is provided, allowing the user to choose the more appropriate method depending on data availability. When only one method is available, a minimum set of parameters is required. But, if available, additional data can be used to improve the outcome of the ES calculation. Additionally, spatial data are not always available for all parameters. If only one value is available for the entire area, this value can be provided to the module instead of a spatial dataset. As such the Smartsediment tool offers flexibility to users, giving a first screening of effects with the available data and knowledge. This thereby creates the disadvantage that the quality of the prediction is highly dependent on the quality and detail of the given input data.

The delivery of ES is not static, especially in dynamic systems such as estuaries. To understand how ES delivery evolves during the successional evolution of an estuary, the user can evaluate each ES for four time periods in one calculation run. The outcome of each calculation is a map which gives a spatial representation of the ES delivery. However, maps are often difficult to compare, especially over a range of time periods and different ES. Therefore, a specific tool (created with Microsoft Excel) is made available to aggregate the spatial data in total values and mean values per ha and present them in different tables. These tables allow the user to better compare changes between different sediment management strategies and how these strategies will impact the delivery of ES in time. By aggregating the data for only the project area or the larger estuary, comparisons can also be made between local and estuarine effects.

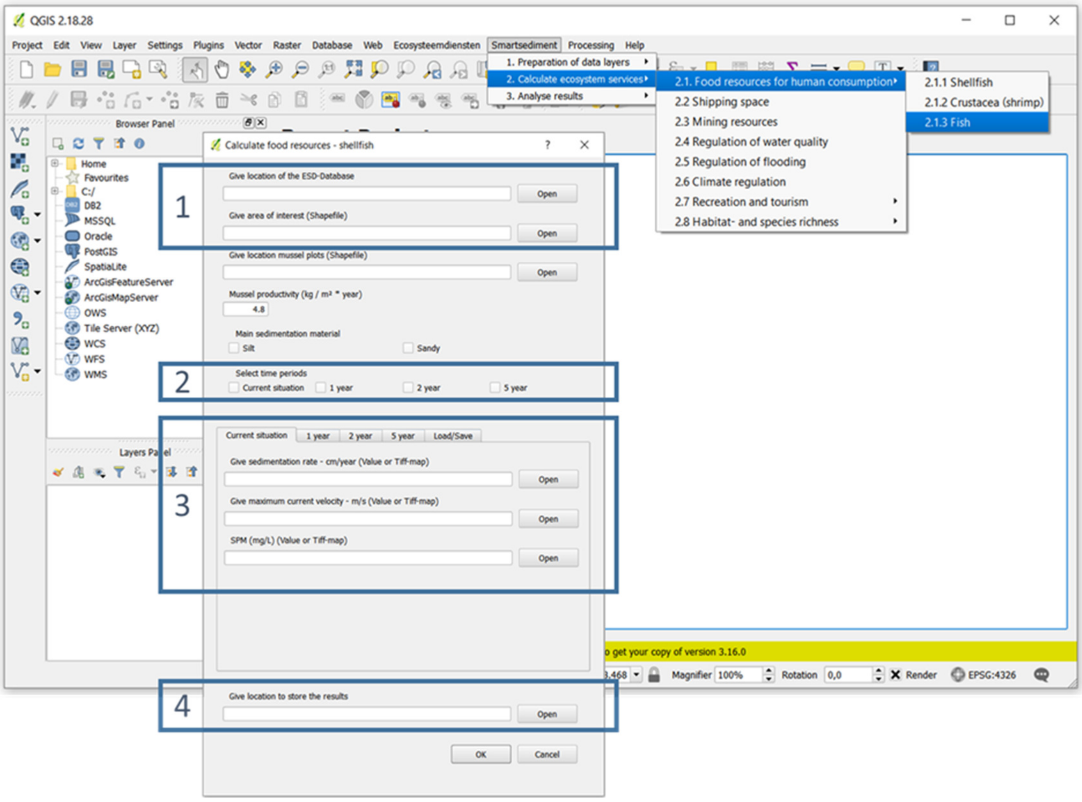


Figure 4: Example of an ES calculator interface with the four types of information that are asked. Here the calculator interface for ES food resources from shellfish is shown: 1) The location of the ES-Database and the area of interest for which the calculation should be done. 2) The timestep(s) for which the calculation has to be performed. 3) Data needed for the ES calculation for the different timesteps. 4) The location where the results should be stored.

4 Towards a spatially explicit evaluation of ecosystem services in QGIS

With the **Smartsediment ES-tool**, the user can calculate the provisioning of a selection of ecosystem services in an estuary or coastal system and compare scenario's with different sediment measures or developments. The end result gives an indication of how much (quantitatively, by calculations based on expert knowledge) and where (spatially explicit presentation in GIS maps) certain ecosystem services are provided.

The tool has three modules. In a first module, **ecotope maps** of the area of interest can be calculated within QGIS following a simplified version of the methodology for the salt ecotope system used for the ecotope maps of the Western and Eastern Scheldt (Bouma et al., 2005). With the second module, the user can calculate maps that represent the **delivery of ecosystem services** and the suitability as bird and seal habitat. For these calculations the ecotope maps are used together with other environmental characteristics given by the user. In the third module (called **Quickscan**) an excel-sheet can be created with overall numbers of ecotopes and ecosystem service delivery within a specified area. The excel sheet also enables the user to compare different scenario's.

The values given for the provision of ecosystem services are **no exact representation of reality**. They are meant to give an insight and an overall view of the areas added value in terms of ecosystem services. They are also meant to make it more easy to compare different scenario's. The reliability of the results represented by the maps and Quickscan is highly dependent on the reliability and precision of the input data. Therefor the results should always be interpreted by an expert with knowledge about the area of interest. It should also be noted that the effect of different ecosystem services on each other is not taken into account. Here, also **expert knowledge is recommended**. When for example recreation is favoured, this can raise disturbance, thereby negatively affecting suitability as habitat for birds and seals.

The ES-tool wants to **enable decision makers and executives to make a first evaluation** of the ecosystem service delivery of the estuarine or coastal system they are interested in. Furthermore, with the tool a comparison can be made of different strategies or project designs. Because of the generation of maps, results can also be compared spatially. The consultant IMDC performed a usability study of the ES-tool. In this study it was concluded that the ES-tool can be a useful instrument to use during the decision making between designs of sediment nourishments. They also emphasise the need for expert knowledge when using the ES-tool and interpreting its results (Van Holland, 2020).

To give an insight in the ES-tool's abilities two cases that were worked out in two previous (Dutch) reports are given below (Mestdagh et al., 2020; De Swerdt et al., 2020).

4.1 Case 1 - Roggenplaat intertidal sand nourishment

The Roggenplaat is a large intertidal flat near the storm surge barrier at the mouth of the Eastern Scheldt. The flat is prone to erosion through sand starvation. As a consequence, the Roggenplaat is expected to disappear in the future, which would lead to a loss of habitat and foraging area for waders (de Ronde et al., 2013). The disappearance of the Roggenplaat would also entail a safety risk, as it currently serves as a natural buffer against storms near the southern cost of Schouwen. To counteract these problems, a project to raise the bed level of the Roggeplaat by means of six individual nourishments was developed (Figure 5). The goal of these nourishments is to retain the original size of the foraging area and to safeguard the Schouwen coastal area (Ysebaert et al., 2017). Since the nourishment was performed by the end of 2019, the bathymetry of the nourishment and the course of the sedimentation and erosion processes are yet to be described. Therefore, this report is based on the original design (Figure 5) and assumptions on the future developments.

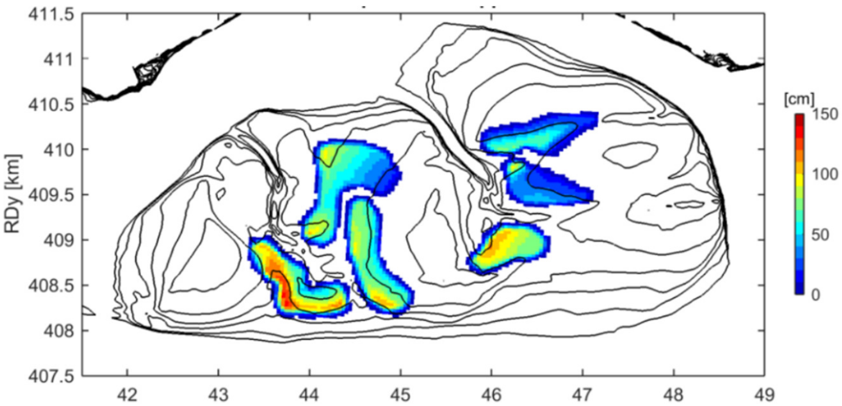


Figure 5: Location and height (cm) of the six planned nourishments on the Roggenplaat, by van der Werf et al., 2016.

Simulation with the ESD-tool: scenarios and input data

We calculated the impact on the delivery of ecosystem services of four different scenarios, from which two with and two without nourishments. For each, one current 'Current (2016)' and one future 'Future (2030)'was calculated based on following data:

- **Bathymetry maps** of the Eastern Scheldt are available for 2016 and 2030 (Simulation ANT-study from de Ronde et al., 2013). For 2030 the bathymetry map only comprises data of the intertidal. For the subtidal area, the data was complemented with the map of 2016. Because the Roggenplaat nourishment was only completed at the endo of 2019 and no maps were available yet of the situation after the project's completion, maps for the scenarios with nourishments were similated based on the existing bathymetry maps, the design and the expected erosion rate.
- **Maps of emersion time** of the Eastern Scheldt are available for 2016 and 2030 (Simulation ANT-study from de Ronde et al., 2013). The emersion time maps for the other scenarios were simulated based on the respective bathymetry maps and the bathymetry - emersion time relation from 2016.
- A map of the **maximum current velocity** of the Eastern Scheldt is only available for 2016. Since this data is based on complex modelling, it was unfeasible to make a new map and we were forced to use the 2016 data for all scenarios. This will of course have an impact on the ESD-tool results.

Calculation of ecotope distribution

With the ES-tool ecotope maps were calculated for each scenario using the bathymetry-, emersion- and current velocity maps (maps in Appendix A). Next, the distribution of ecotopes at the Roggenplaat and its immediate surroundings were calculated using the 'Quickscan' function of the ES-tool (Figure 2; Appendix A).

Given the distribution ecotopes over the different scenarios (Figure 6), the effect of the nourishment on the distribution of ecotopes appears to be limited. The expected scenario for 2030 predicts an increase of the shallow low dynamic sublittoral area with respect to 2016, both with and without the addition of the nourishment. This area would originate from eroded low dynamic middlehigh litoral areas. Do note that the low dynamic middlehigh litoral area is predicted to be larger in the scenario 'Future (2030)' in case the nourishment is added. As such, the effect of the nourishment on the distribution of the ecotopes seems to be more pronounced in the long term.

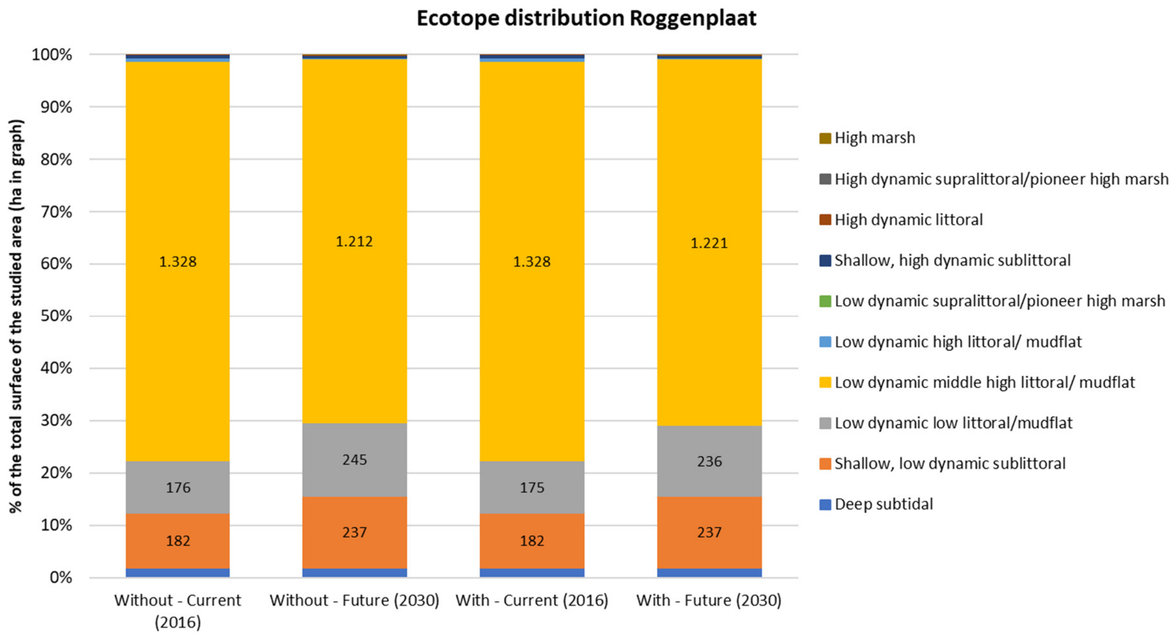


Figure 6: Ecotope distribution for the four different scenarios at the Roggenplaat and its immediate surroundings.

Ecosystem services

Most ecosystem services may be calculated for the Roggenplaat. It is not realistic to assume an impact of the nourishments on recreation (i.e. swimming and shoreline recreation), as the flat is located relatively far away from the shore. The following ecosystem services may be calculated:

- Food provision (shellfish, crustacea, fish)
- Flood risk prevention
- Regulation of water quality
- Climate regulation
- Recreation and tourism (recreational shipping)
- Habitat- and species richness (seals, waders)

For each of the four scenarios, the ES-tool was used to calculate the effect of the Roggenplaat nourishment on the different relevant ecosystem services (Table 3). In addition to the maps that were discussed in the previous paragraph, several numerical values were adopted for grain size, water level, productivity of fish, shellfish and crustacea, … The adopted values, per ecosystem services and per scenario, are given in Appendix A.

Table 3: Calculated ecosystem services in the direct surroundings of the Roggenplaat nourishment for four scenarios

ES Roggenplaat and its surroundings	**Without nourishment**		**With nourishment**	
	Present (2016)	**Future (2030)**	**Present (2016)**	**Future (2030)**
Food provision				
Shellfish (kg/j)	176	=	=	=
Crustacea (kg/j)	5225	++	=	++
Fish (number x1000)	120	++	=	++
Regulation of flood risk	Ref.	=	=	=
Regulation of water quality				
Denitrification (tonN/jaar)	303	=	=	=
Nitrogen uptake (tonN/jaar)	161	=	=	=
Phosphorus uptake (tonP/jaar)	45	=	=	=
Silica release (tonSi/jaar)	303	=	=	=
Climate regulation (tonC/j)	1420	=	=	=
Recreational shipping (passages/year)	8	--	=	--
Habitat & biodiversity				
Seals (m^2)	179	=	=	=
Waders (m^2)	671	-	-	=

- Food provision – shellfish

According to the ES-tool, the nourishment measure has no impact on the production of shellfish. These results, however, may be unreliable, as the provided input was insufficiently detailed. The ES-tool requires the sedimentation rate at the mussel beds, the maximal current velocity and the concentration of suspended particular matter (SPM) as input. Given the limited available data, a uniform sedimentation rate was assumed. The only available data for the maximal current velocity was obtained in 2016; as such, these data were used in all four scenarios. SPM is measured continuously in the monitoring station near the Roggenplaat (Roompot binnen). As such, SPM is measured only on a single location, that is relatively far away from the Roggenplaat. If we test the effect of SPM by increasing (260 mg/l) or decreasing (6 mg/l) this value in the tool, we only observe a local difference. As such, more detailed information on the SPM in the area of the nourishment is essential to faithfully asses the effect of SPM on the nearby mussel beds. Given the current results, higher SPM values are associated with lower primary production, as expected.

- Food provision – crustacea

The nourishment has almost no effect on the production of crustacea. From the resulting map (Figure 7), we observe that the production of crustacea is not expected in any of the four scenarios.

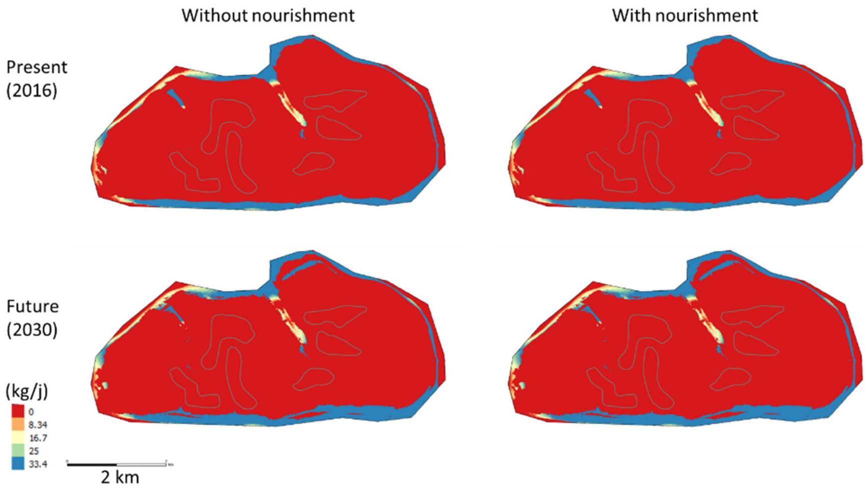


Figure 7: Output of the ES-tool for the production of crustacea (kg/year) for the Roggenplaat, before and after nourishment in the current and future scenarios. The nourishment is indicated by the grey contours.

- Food provision – fish

The ES-tool predicts only a limited negative impact of the nourishment on the productivity of fish. Initially, a minor decrease (2000 individuals) in fish is predicted, even though it is assumed that the macrobenthos do not recover in scenario 'Current (2016) with nourishment' and the area low dynamic low litoral/mudflat decreases under the nourishment measure. In both future scenarios, the productivity of fish increases with respect to the current scenarios by approximately one third. The increase is slightly lower in the scenario without nourishment.

- Regulation of flood risk

To calculate the efforts for flood risk, the only required input is the average high water and the maximal wave height. Based on this input, the ESD-tool is used to calculate the change in required efforts for limiting flood risk between the reference scenario 'Current (2016) without nourishment' and the three remaining scenarios. Due to a lack of data, we were forced to make assumptions regarding the maximum expected wave height, with higher wave heights in future scenarios and lower heights in the scenarios with nourishment (Appendix A). In both future scenarios, the ES-tool expects that more measures will have to be taken to mitigate flood risk compared to the current reference scenario. In the current scenario with nourishment no additional measures are needed (Table 3).

- Regulation of water quality

From the results we can conclude that the nourishment has no effect on the regulation of water quality. The amount of denitrification, nitrogen & phosphorus uptake and silica release all stay the same with the implementation of the nourishment. By 2030, also no difference appears between the scenario with and without nourishment. In Figure 4, the maps for silica release are given.

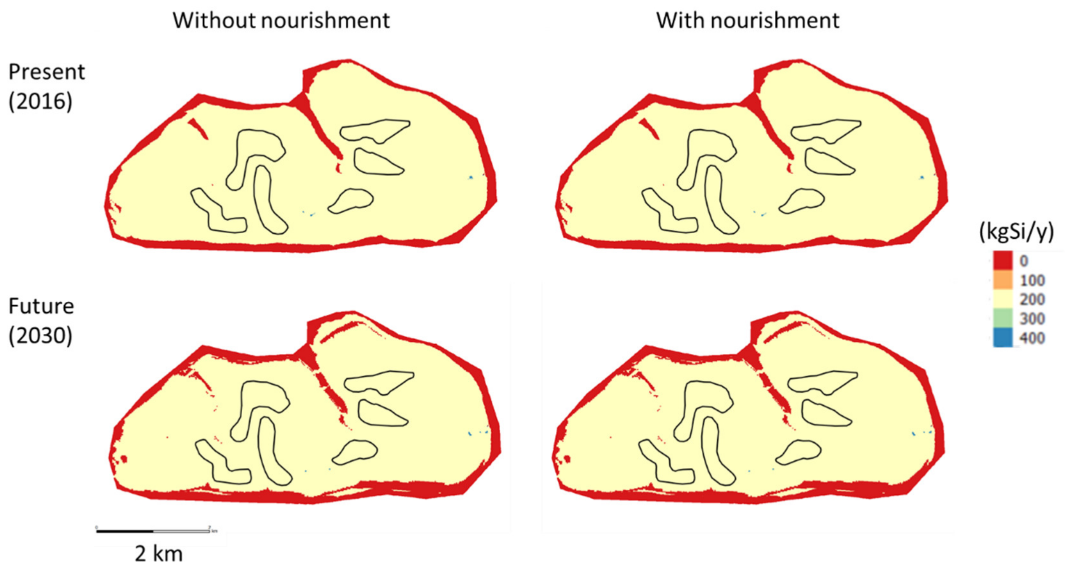


Figure 8: Silica release at the Roggenplaat for fourr scenarios: with and without nourishment at present and in the future. Maps are calculated with the ES-tool. The nourishment is indicated by the black contours.

- Climate regulation

From the results we can conclude that the nourishment has no effect on CO_2 uptake. By 2030, the amount of uptake will in both scenario's decrease at the same rate compared to the current scenario. The calculations were done with the first, simple method that involves only an ecotope map. The second, more extensive method needed too much detailed data.

- Recreational shipping

The nourishment does not seem to have an effect on recreational shipping in the surroundings of the flat. If more detailed data would be available about SPM, this result could be different due to changes in water transparency.

- Habitat- and species richness – seals

The ES-tool expects no effect of the Roggenplaat nourishment on the habitat suited for resting seals. Because the nourishment is carefully designed to not have an effect on seal habitat, this outcome is as expected. In the future, the habitat it is expected to slightly increase (several m^2) both with and without nourishment.

- Habitat- and species richness – waders

With the implementation of the nourishment, habitat for waders will initially disappear. This is due to the burial of the macrobenthos community. In the future, benthos will recover, leading to an increased foraging habitat compared to the future scenario without nourishment (Figure 5). This is as expected and can be explained by the increased emersion time because of the nourishment (van der Werf et al., 2016).

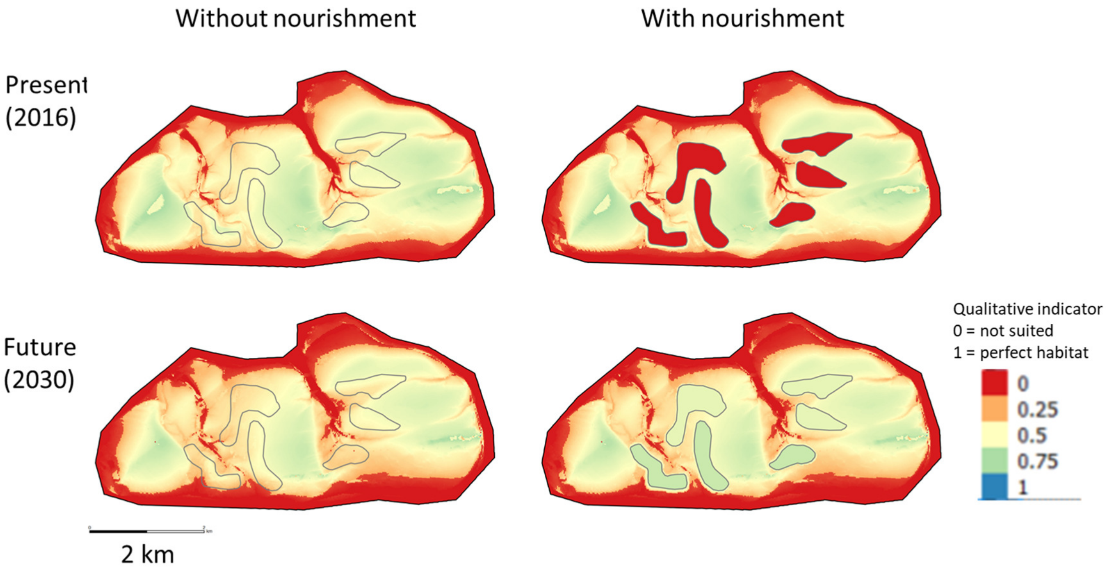


Figure 5: Suitability of the Roggenplaat as foraging habitat for waders (0, red = not suited; 1, darkblue = perfect habitat) for four scenarios: with and without nourishment, at present and in the future. Maps are calculated with the ES-tool. The nourishment is indicated by the grey contours.

4.2 Case 2 - Nourishment of all intertidal area in the Eastern Scheldt

In 2013, de Ronde et al. (2013) performed a study (ANT-study) on the long-term developments (until 2100) of the intertidal area in the Eastern Scheldt tidal basin and the effects of the eroding trend on foraging area for waders and wave impact on the dikes. Based on this study, several measures were proposed. One of this researched measures, the nourishment of all intertidal area, was taken as a case to apply the ES-tool. Within this case we look at the relations between ecosystem services and different characteristics of sediment measures.

Used data and simulation

For six different scenarios, ecotope maps and the delivery of different ecosystem services were calculated using the ES-tool. The first three scenarios involve the predicted developments of the Eastern Scheldt by the ANT-study in 2020, 2060 and 2100. For the three other scenarios, the bed level was increased with 0.60 m sandy sediment in 2020. To account for erosion of the nourished area, the 2060 bathymetry map was increased with only 0.50 m and the 2100 bed level with 0.40 m sediment. This is only a fictional case and involves multiple assumptions. The future current velocity data was not available. Because this can only be calculated through extensive modelling, for all scenarios the most recent current velocity data was taken from 2016. The current velocity is therefore constant through all six scenarios. The bathymetry maps from the ANT-study from 2060 and 2100 only comprise the intertidal area and do not involve subtidal channels. These maps were therefore complemented with data form 2020. For the water level, a sea level rise of 4.17 cm/year was taken into account. All constants and used data can be found in Appendix B. Because this case involves timesteps of 40 years, it is assumed that the benthos communities are fully recovered. Also SPM concentrations are kept constant over all scenarios since this variable highly fluctuates and is difficult to predict.

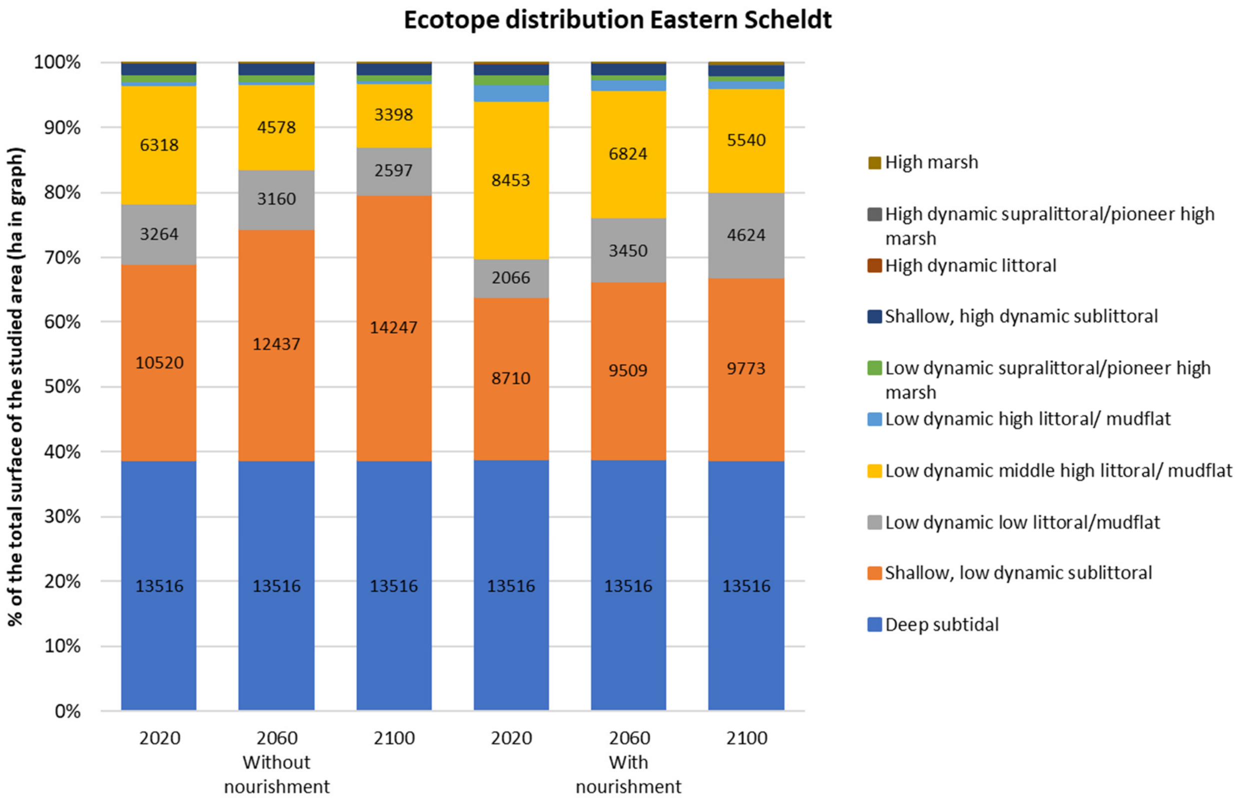


Figure 6: Ecotope distribution in the Eastern Scheldt for the six different scenarios

Results

Table 4 gives the distribution of ecotopes for the six different scenarios. The deep subtidal area is the same in all scenarios. This is because only the intertidal was raised and for the channels of 2060 and 2100 the bed level of 2020 was used. The decreasing trend is visible in all scenarios; the area sublittoral increases and middle high, high and supralittoral decrease. There is also a strong decrease of low dynamic supralittoral in the scenarios with nourishment compared to the scenarios without. In 2020 more area low dynamic supralittoral is present in the scenario with nourishment and by 2100 more of this same ecotope is present in the scenario without nourishment.

Table 5 presents the results for the calculated ecosystem services. Because current velocity, SPM and the bed level in the channels are the same over all scenarios, the ecosystem services that only depend on these variables (productivity of shellfish, shipping space and recreational shipping) are not calculated.

Table 5: Delivery of ES in the Eastern Scheldt in 2020, 2060 and 2100 with and without nourishment.

	With nourishment			**Without nourishment**		
ES Eastern Scheldt	**2020**	**2060**	**2100**	**2020**	**2060**	**2100**
Food provision						
Crustacea (kg/j)	314239	+	++	-	-	=
Fish (number x1000)	4605	+	++	--	=	=
Regulation of water quality						
Denitrification (tonN/jaar)	2041	-	--	+	=	=
Nitrogen uptake (tonN/jaar)	1458	-	--	++	=	=
Phosphorus uptake (tonP/jaar)	306	-	--	+	=	=
Silica release (tonSi/jaar)	2123	-	--	+	=	=
Climate regulation (tonC/j)	9571	-	--	+	=	=
Recreation						
Swimming (visitors/year)	4960	=	=	-	=	=
Habitat- & species richness						
Seals (m²)	169	--	--	=	-	+
Waders (m²)	3290	--	--	++	+	=

Discussion

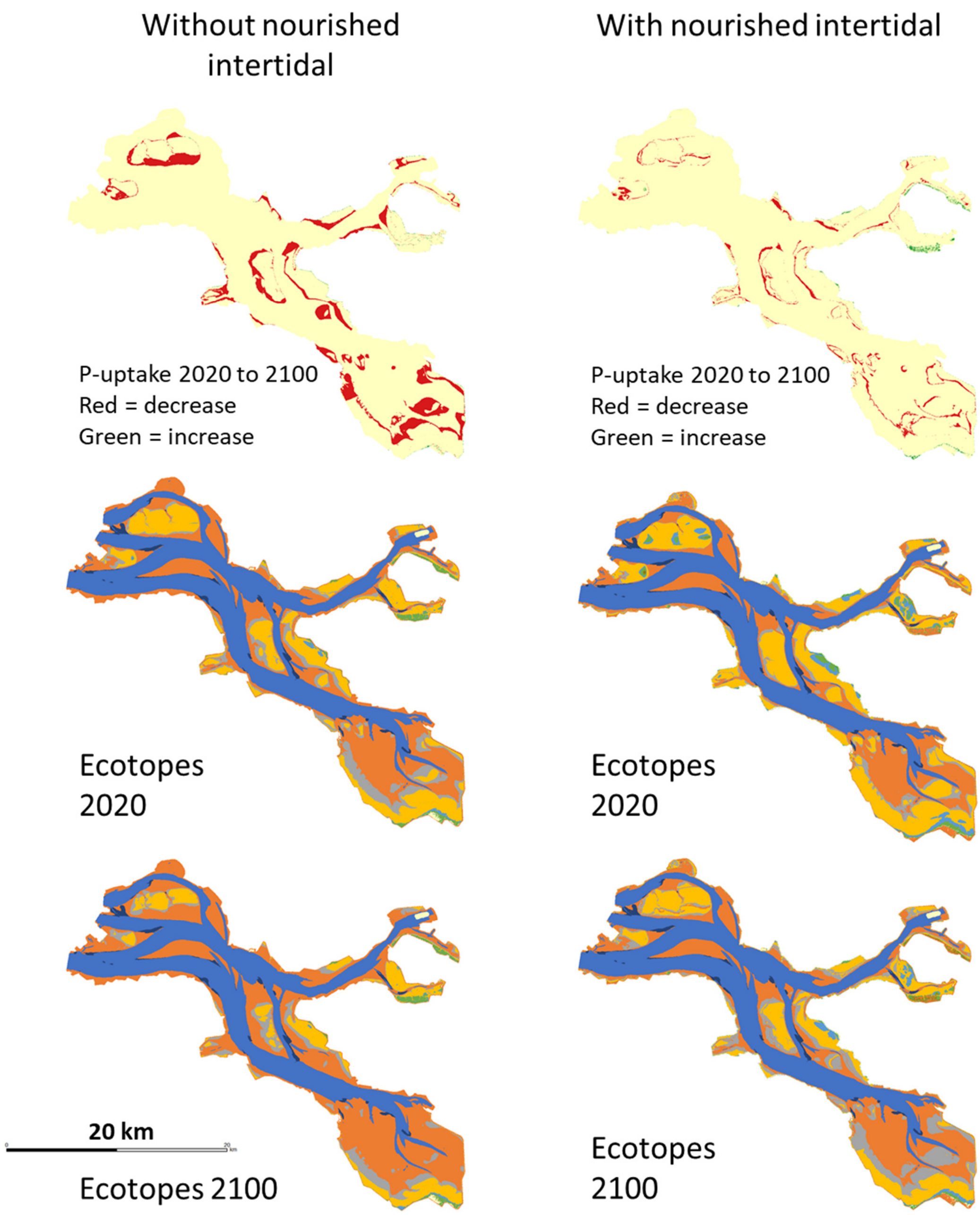
The evolution of the delivery of ecosystem services in the Eastern Scheldt between the different scenarios follows the patterns that are expected based on previously derived relations and calculation rules. Over the years, the total area of littoral decreases with a consequent increase in sublittoral area in all scenarios with and without nourishment of the intertidal area. In these areas, this implies a decrease in water regulating capacities and carbon storage. Also the area of suitable habitat for waders decreases. The total area of low dynamic littoral is, because of the increased bed level, bigger in the scenarios with nourishment than in the corresponding years without nourishment. This is also shown by the ecosystem services delivery with more denitrification, nitrogen & phosphorus uptake, silica release and carbon uptake in the scenarios with nourishment. Also the suitable area for waders is bigger in the scenarios with nourishments. In Figure 5, this is shown by the calculated maps of phosphorus uptake.

For fish and crustacea productivity, we see the inverse. The productivity increased over time and is lower in the scenarios with nourishment. This corresponds to the area shallow, low dynamic sublittoral (Figure 6). Improving the productivity of fish and crustacea cannot go together with improving water and climate regulation and habitat for waders (Figure 7). In Figure 7 it also gets clear that there are some places in the Eastern Scheldt were a conflict occurs between the ecosystem services swimming and the function as foraging area for waders due to disturbance of the waders by swimming individuals. De ES-tool does not take these relations into account. By combining both ecosystem services results, as is done in Figure 7, more insight can be gained.

The development of the ES habitat for seals and swimming are less clear. The resting area for seals was only calculated in the surroundings of the Roggenplaat since seals do not appear in the rest of the Eastern Scheldt due to disturbance. The ES-tool does not include this factor. In the scenarios without nourishing of the intertidal area, the suitable area for seals decreases over time. This goes together with a decreasing low water line and less area low dynamic low- and middle high littoral with an emerging time above 16 %. In the scenario with nourishment, the suitable area decreases between 2020 and 2060 and increases again between 2060 and 2100 up to a higher area than in 2020. This can be explained by a more rugged and thereby longer low water line in 2100 that serves as the basis for the calculations (Figure 8).

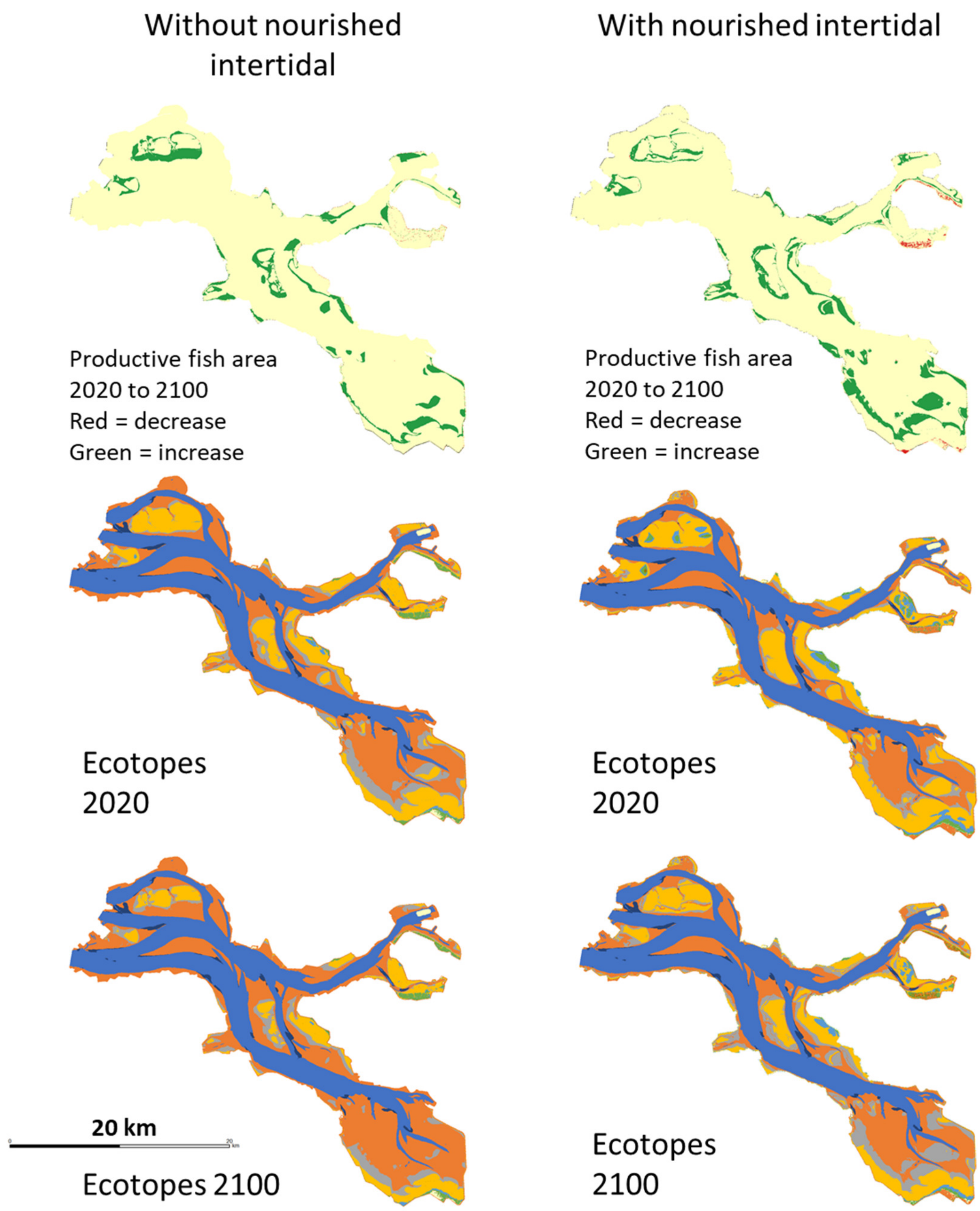
Swimming in the scenarios without nourishment firs increases between 2020 and 2060 and afterwards decreases between 2060 and 2100. With the increase of bed level of the intertidal, the delivery of ES swimming highly decreases. Over the years, the estimated amount of visitors increases again, but does not reach the level of 2020 without nourishment. This is due to a combination of changing ecotopes, bed level and slope.

This case clearly shows that it is difficult to conclude which scenario is best for in the light of ecosystem services delivery. The need for ecosystem services delivery and thus the priority that would be designated differs greatly between regions and has to be evaluated for each case individually. Because in the Eastern Scheldt strict Natura 2000 regulations are in place and compliance will be hampered by the ongoing erosion, the fictive scenario with nourishments seems more favourable since it increases the suitable habitat for waders and seals.



1	Deep subtidal
2	Shallow, low dynamic sublittoral
3	Low dynamic low littoral/mudflat
4	Low dynamic middle high littoral/ mudflat
5	Low dynamic high littoral/ mudflat
6	Low dynamic supralittoral/pioneer high marsh
7	Shallow, high dynamic sublittoral
8	High dynamic littoral
9	High dynamic supralittoral/pioneer high marsh
10	High marsh

Figure 9: Relation between area of ecotopes and phosphorus uptake for 2020 and 2100 with (left) and without (right) nourishment of the intertidal area. The area where phosphorus uptake takes place (for 2020 white+grey area, for 2100 grey area) overlap with the low dynamic littoral (yellow-orange, ecotopes 3-5) that decreases over time and is bigger in the scenarios with nourishment.



	1	Deep subtidal
	2	Shallow, low dynamic sublittoral
	3	Low dynamic low littoral/mudflat
	4	Low dynamic middle high littoral/ mudflat
	5	Low dynamic high littoral/ mudflat
	6	Low dynamic supralittoral/pioneer high marsh
	7	Shallow, high dynamic sublittoral
	8	High dynamic littoral
	9	High dynamic supralittoral/pioneer high marsh
	10	High marsh

Figure 10: Relation between area of ecotopes and productive area for fish for 2020 and 2100 with (left) and without (right) nourishment of the intertidal area. The productive area (for 2020 white+grey area, for 2100 grey area) overlaps with the low dynamic sublittoral (dark orange, ecotope 2) that increases over time and is smaller in the scenarios with nourishment.

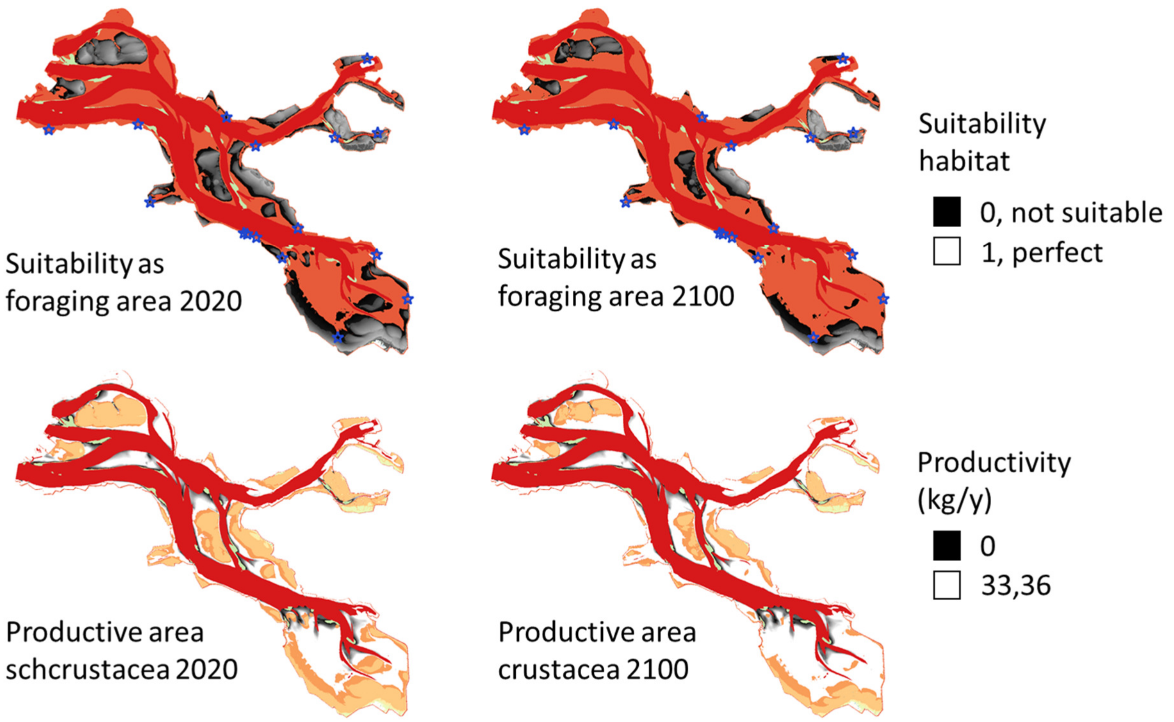


Figure 11: Difference in suitable area between two ecosystem services, foraging area for waders (top) and productive area for crustacea (bottom, in kg/y), in 2020 and 2100 for the scenario without nourishments. The locations where the productive area for crustacea increases between 2020 an 2100, the foraging area for waders decreases. The underlying maps show the ecotopes for the corresponding years. The blue stars point out the swimming locations. Here, a conflict can emerge between the ES swimming and the function of the area as foraging ground for waders due to disturbance.

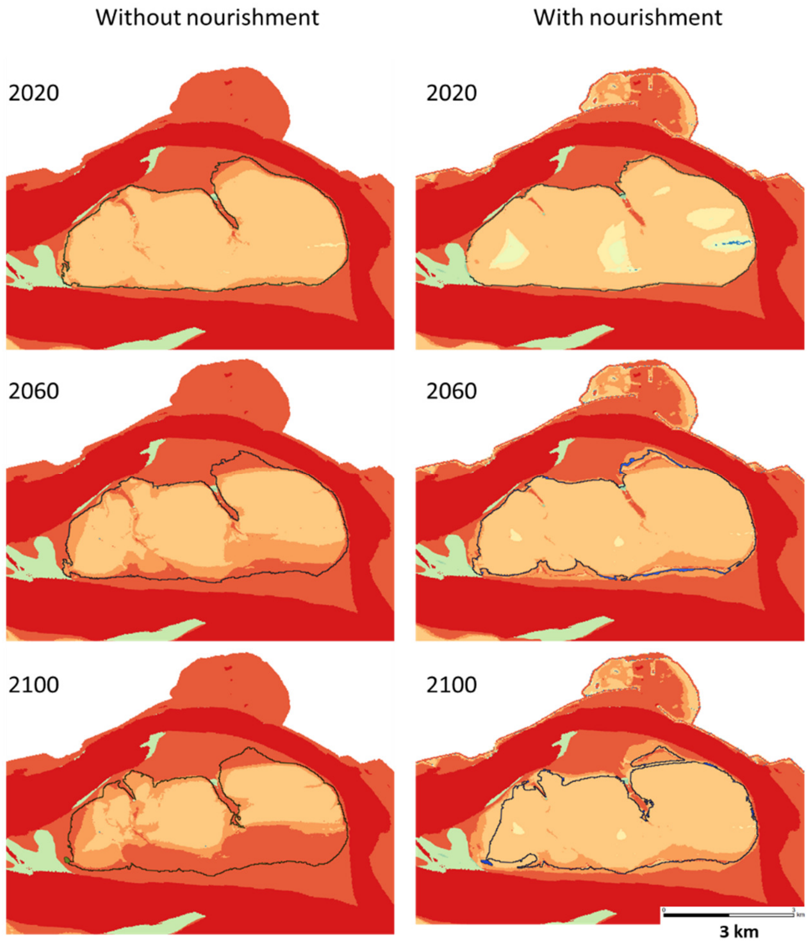


Figure 12: Low water line calculated with the ES-tool as a basis for the calculation of the area resting habitat for seals. The underlying maps show the ecotopes for the corresponding years.

5 Reflections on the applicability of the Smartsediment tool

The Smartsediment tool is innovative because it is one of the first instruments that combines knowledge on ecosystem functioning (for coastal zones) and the impact on the socio-economic context. A group of scientific experts evaluated the methodology for both its content and applicability for management. The Smartsediment tool is developed and tested for the transboundary Scheldt delta, but the conceptual model is generally applicable for estuaries and coastal areas with similar characteristics elsewhere. The relationships between ecosystem parameters and ES can be applied on other estuaries (although adaptations for local conditions might be required). The calculation rules should be specified for the characteristics of the studied coastal zone (morphological conditions, discharge, nutrient load, species types, etc.). Furthermore, the applicability of the Smartsediment tool is not limited to the evaluation of sediment-related measures. The effect evaluation methodology can also be used to assess other measures in estuaries such as changes in fresh water management or changes in local discharges (e.g. cooling water).

The Smartsediment tool can offer added value in several areas (Verheyen, 2020). First, it can help expand the cost-benefit analysis to include broad societal costs and benefits, where ES can also be viewed spatially. The tool is also useful for stakeholder's dialogue. On the one hand, it makes it possible to illustrate the purpose of a project, as well as possible positive and negative side effects. This provides a communication tool to discuss certain possible concerns, which can be useful in dialogue with stakeholders. The tool can be used to estimate the effects of different scenarios to facilitate an objective comparison of scenarios in terms of ES delivery. As such, this is a valuable tool for developing future sediment strategies for coastal zones. In case of large-scale interventions that can create initial concerns due to their visual impact, the tool also allows to focus on both the possible negative and positive impacts a project is expected to have.

However, it is necessary to be aware of the limitations of the tool. This tool is a screening tool, not a numerical model. Since the tool pursues a broad scope of applications, both large and small project areas as well as detailed and less detailed inputs, the level of detail of output cannot be limited in advance. Furthermore, it is important to note that the result of the simulation with the Smartsediment tool is largely determined by the assumptions made for the ecotope maps. A change in the ecotope distribution between the scenarios used, is also noticeable in the result of the simulation with the Smartsediment tool (demonstrated for the Roggenplaat case). The user should be aware that the reliability of the output highly depends on the reliability and precision of the input data. One should be aware of the different levels of uncertainty linked to the input data as well as the provided calculation methods in the tool.The methods foreseen in the tool for individual ES are rather simple to ensure that data input requirements are not too high but leading to less precise outcomes.

Furthermore, the effects of different ES on each other are not considered (e.g. recreation activities that might disturb bird habitat). The tool can be used for a high-level comparison of scenarios with only high-level estimates as input, but then off course the output should also be considered as a high-level screening. In case the tool is used to assess future situations, without extensive modelling beforehand, it is difficult to predict exact realistic values, leading to an uncertain outcome of the calculations.

The output values given for the ES are not exact values but must be considered in a relative way to compare between sites and scenarios. Therefore, the results should always be interpreted by an expert with knowledge about the area of interest. As demonstrated for the Roggenplaat case (Table 1), the output can be translated into positive or negative trends/impact to prevent that the exact number outputs are given too much attention. This puts the output more in line with the status of a screening tool, giving an indication of the impact of sediment measures, to support decisions for further research and/or communication.

6 Overall conclusions

The Smartsediment tool can be used to investigate how different sediment strategies affect a range of ecosystem services in both the short and long term in a fairly simple way and with a limited data set. The tool is developed as QGIS plug-in to make a spatially explicit quantitative evaluation tool and is based on a conceptual model that allows to identify all impact-effect pathways from sediment strategies on the functioning of the coastal zone including ecosystem knowledge, and to translate this into effects onto the selected ES. However, the simplicity of the tool is not only a strength. The results need to be handled with care. Although these provide useful trends and can serve as a basis for communication or decisions for further research, they do not accurately reflect all details of the much more complex reality.

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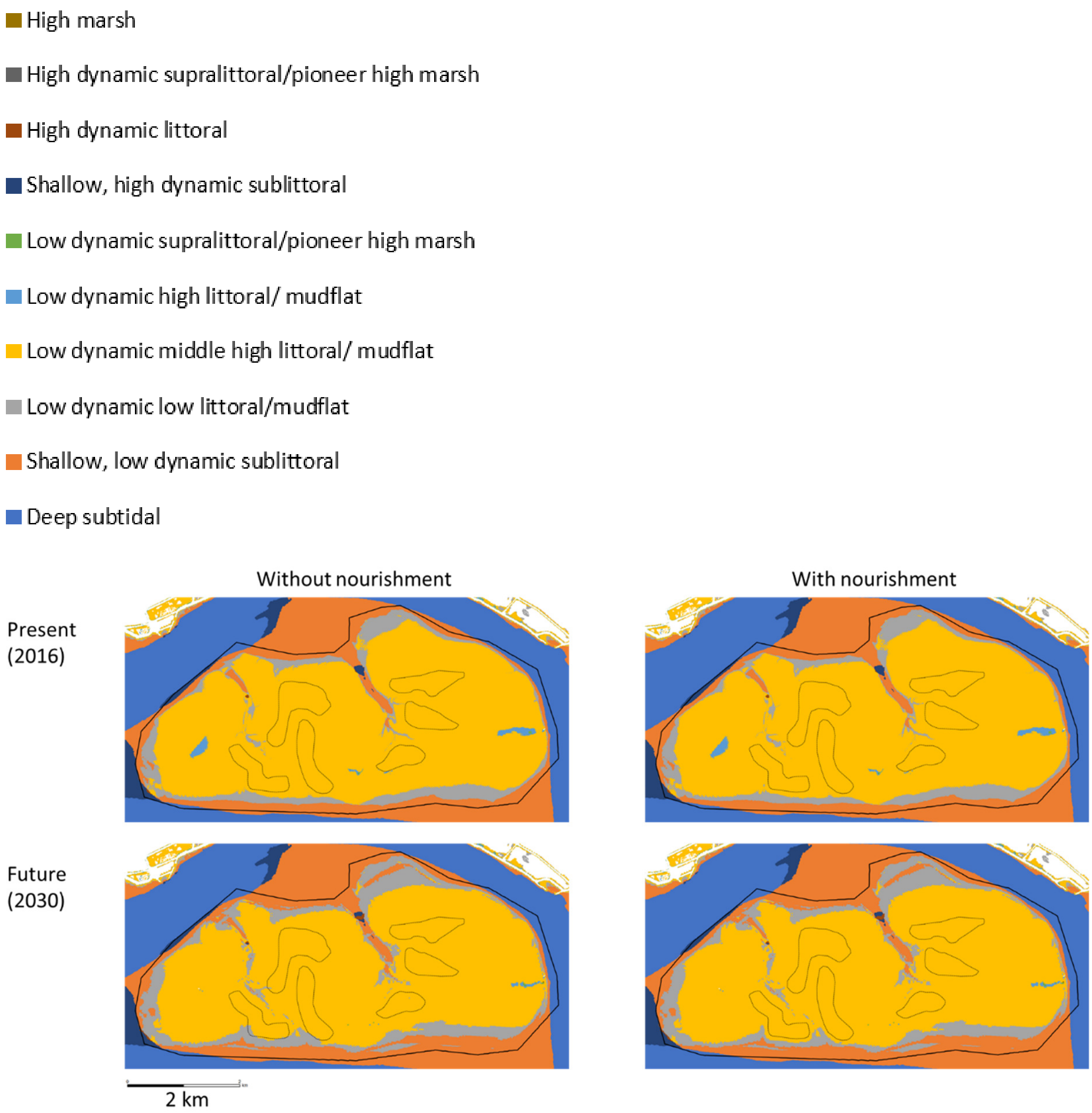
Appendices

Appendix A – Ecotopes case 1: Roggenplaat

Table A1: Distribution of ecotopes in the direct surroundings of the Roggenplaat nourishment for four scenarios.

	Without nourishment		**With nourishment**	
Ecotopes Roggenplaat and its surroundings (ha)	**Current (2016)**	**Future (2030)**	**Current (2016)**	**Future (2030)**
Deep subtidal	33,705	33,705	33,705	33,705
Shallow, low dynamic sublittoral	181,6825	237,4475	181,6825	237,4475
Low dynamic low littoral/mudflat	175,78	244,5475	175,4625	235,985
Low dynamic middle high littoral/ mudflat	1328,015	1212,393	1328,412	1220,955
Low dynamic high littoral/ mudflat	11,1075	2,135	11,0275	2,135
Low dynamic supralittoral/pioneer high marsh	0,435	0,4175	0,435	0,4175
Shallow, high dynamic sublittoral	10,55	9,6275	10,55	9,6275
High dynamic littoral	0,6275	1,55	0,6275	1,55
High dynamic supralittoral/pioneer high marsh	0	0	0	0
High marsh	0	0,0425	0	0,0425


High marsh
High dynamic supralittoral/pioneer high marsh
High dynamic littoral
Shallow, high dynamic sublittoral
Low dynamic supralittoral/pioneer high marsh
Low dynamic high littoral/ mudflat
Low dynamic middle high littoral/ mudflat
Low dynamic low littoral/mudflat
Shallow, low dynamic sublittoral
Deep subtidal
Without nourishment
With nourishment
Present
(2016)
Future
(2030)
2 km

Appendix B – Ecotopes case 2: Eastern Scheldt

Table A2: Distribution of ecotopes in the Eastern Scheldt in 2020, 2060 and 2100 with and without nourishment.

	With nourishment			**Without nourishment**		
Ecotopes Eastern Scheldt (ha)	**2020**	**2060**	**2100**	**2020**	**2060**	**2100**
Deep subtidal	13516	13516	13516	13516	13516	13516
Shallow, low dynamic sublittoral	10520	12437	14247	8710	9509	9773
Low dynamic low littoral/mudflat	3264	3160	2597	2066	3450	4624
Low dynamic middle high littoral/ mudflat	6318	4578	3398	8453	6824	5540
Low dynamic high littoral/ mudflat	210	169	127	889	571	415
Low dynamic supralittoral/pioneer high marsh	400	372	348	521	288	261
Shallow, high dynamic sublittoral	583	585	586	576	578	579
High dynamic littoral	5,3	3,2	2,7	12,1	10,0	9,3
High dynamic supralittoral/pioneer high marsh	0	0	0	0,1	0,1	0,1
High marsh	9,7	10,0	14,3	14,6	8	83,4

High marsh

High dynamic supralittoral/pioneer high marsh

High dynamic littoral

Shallow, high dynamic sublittoral

Low dynamic supralittoral/pioneer high marsh

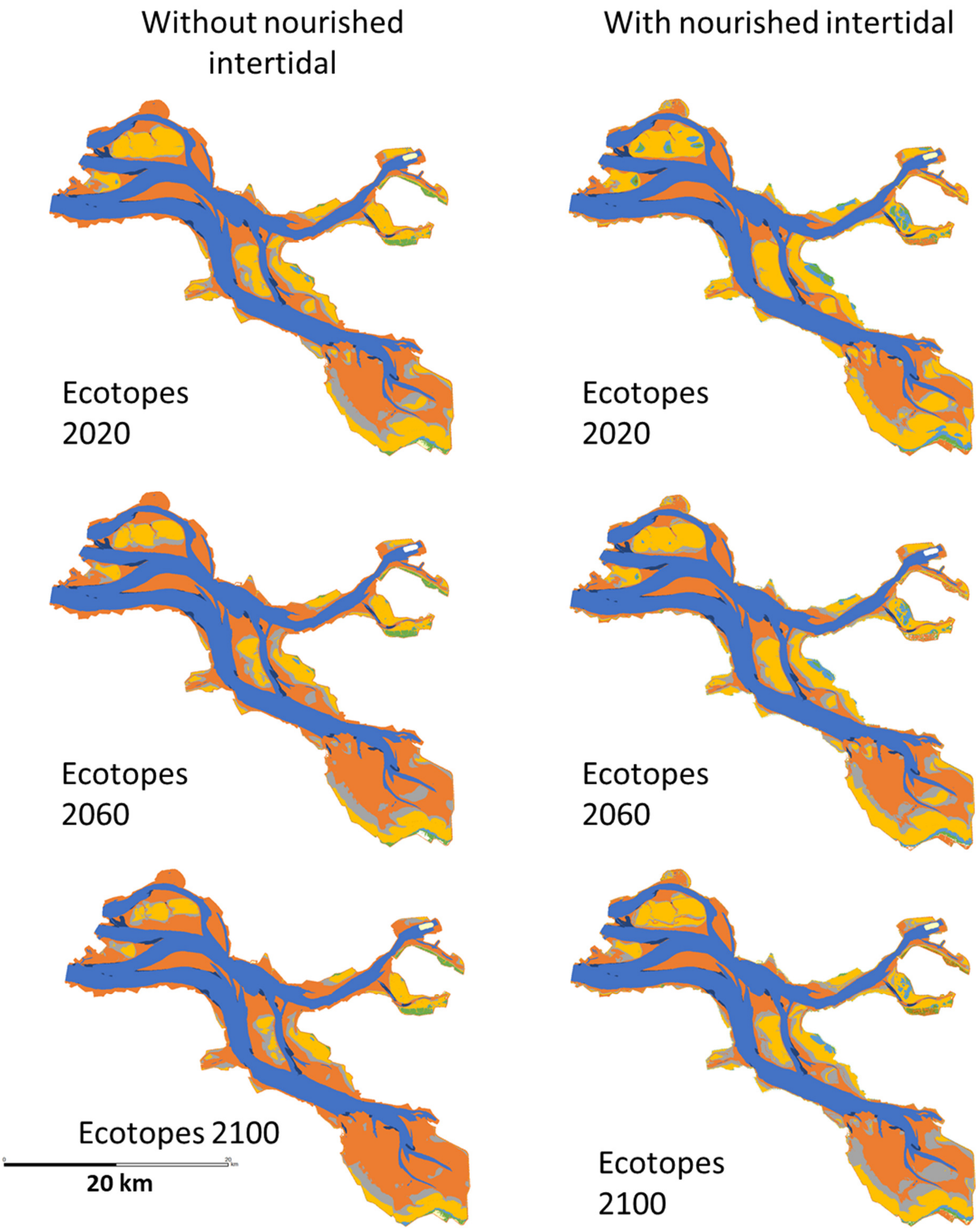
Low dynamic high littoral/ mudflat

Low dynamic middle high littoral/ mudflat

Low dynamic low littoral/mudflat

Shallow, low dynamic sublittoral

Deep subtidal


Without nourished intertidal
With nourished intertidal
Ecotopes 2020
Ecotopes 2020
Ecotopes 2060
Ecotopes 2060
Ecotopes 2100
20 km
Ecotopes 2100