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# Ecosystem Services Supporting Environmental Impact Assessments (EIAs): Assessments of Navigation Waterways Deepening Based on Data, Experts, and a 3D Ecosystem Model

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**Abstract:** The navigation waterways to the harbors of Rostock (Warnow Estuary), Germany, and Szczecin (Oder/Szczecin Lagoon), Poland, were recently deepened. Both activities required Environmental Impact Assessments. We conducted expert- and data-based ecosystem service assessments for both case studies. Additionally, we performed 3D-ecosystem model simulations. For the Oder Lagoon, the model results show that the waterway deepening increased the burial in sediments by 807 t N/a, 112 t P/a and 4661 T C/a. However, altogether, the impacts of the deepening to 12.5 m draught on the lagoon ecosystem are minor and a model application is not necessary, but the results improve the data basis for ecosystem service assessments. Our expert-based ecosystem service approach is adaptable to the needs of coastal engineering and hydraulic projects and is both easy and quick to apply and transferable. The assessment results highlight the relevance of cultural services and can complement EIAs. Our approach can especially support the early scoping stage of an EIA. It has the potential to enhance cooperation and communication with and between stakeholders, reduce conflicts, and save time. Additionally, it could improve the compilation and addressing of stakeholder concerns, potentially reducing costs associated with unnecessary studies.

**Keywords:** shipping channel; harbor; ecosystem service assessment; sediments; nutrient burial; Baltic Sea; stakeholder; Environmental Impact Assessment; Natura 2000; coastal waters

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## 1. Introduction

Maritime transport plays a key role in the European economy, transporting about 75% of its external trade and approximately 31% of its internal trade [1]. During the next decades, the European Union's Sustainable and Smart and Mobility Strategy aims at a significant increase in maritime transport, with required total investments until 2050 amounting to about 9.5 billion Euros [2]. This includes the deepening of existing navigation channels to enable larger ships.

The Baltic Sea hosts over 500 ports. It is one of the seas with the highest ship density and traffic volume worldwide. The 21 largest commercial Baltic sea ports belong to the trans-European transport network. In 2020, these 21 harbors recorded passenger traffic of 53.2 million persons, about one third of EU maritime passenger traffic, as well as 523.2 million tons of cargo traffic. Between 2010 and 2020, the 21 harbors showed an annual cargo growth rate of 0.4%. In parallel, between 2000 and the early 2020s, the capacity of the largest container ships increased from 8000 twenty-foot shipping container equivalent

units (TEUs) to 24,000 TEUs [3]. As a consequence, ships have increasing draughts. This causes an ongoing need for deeper navigation channels as well as increased sediment maintenance dredging.

The Baltic Sea has a surface area of 404,364 km$^2$, but with an average depth of only 53 m, it is very shallow. It is connected to the North Sea by the narrow and shallow waters of the sound and the Belt Sea and consists of a several sub-basins, which are separated by shallow sills [4]. The long and ragged Baltic Sea shoreline has a total length of about 8000 km and is characterized by numerous bays, lagoons and estuaries. The southern half of the Baltic Sea consists of soft, usually plain sandy sediments. One consequence of these special features is that storm-induced sediment erosion, re-allocation and accretion are common, and the maintenance dredging of navigational waterways has to take place frequently.

All these aspects mean that the dredging and deepening of navigational waterways play an important role in the coastal management of the Baltic Sea. These activities interfere with the natural dynamic, can cause the degradation of the marine environment and can potentially reduce the ecosystem's ability to provide ecosystem services [5].

The aims of the European Union's marine policies, such as the Water Framework Directive (WFD, 2000/60/EC) and the Marine Strategy Framework Directive (MSFD, 2008/56/EC), are to achieve and maintain a good ecological and environmental status. This includes sea-floor integrity, including the preservation of structure and functions of benthic ecosystems [6]. As a consequence, activities that potentially cause a risk for the environment require an Environmental Impact Assessment (EIA, 2011/92/EU). The EIA assesses the direct and indirect environmental impact of an activity based on a wide range of factors [7].

Ecosystem services are commonly defined as benefits that humans derive from ecosystems [8] and play an important role in European coastal and marine policies [9]. Ecosystem services take an anthropocentric perspective on ecosystems and are considered to support a comprehensive understanding of the structures and (inter-)dependencies between humans and the environment. Integrating ecosystem service assessments into Environmental Impact Assessments has received a lot of attention. In 2013, Karjalainen et al. [10] stated an experimental stage, and Baker et al., 2013 [11], named potential benefits but at the same time pointed out weaknesses and asked for pragmatic approaches. General methodologies, guidelines and case studies are available, but with a focus on terrestrial systems [12–15]. In 2013, Liquete et al. [16] pointed out the deficits with respect to marine ecosystem services assessments, and deficits are still visible, e.g., [17]. But a recent review, with focus on Marine Protected Areas (MPAs), indicates that ecosystem services in general gained importance in marine systems [18].

There are several reasons for the limited application of ecosystem service assessments in coastal waters, including weaker data availability, the highly dynamic nature of aquatic systems, and the limited transferability of existing methodologies and guidelines from land to sea. However, several case studies demonstrate the use of ecosystem service assessments in coastal waters. For instance, Inacio et al. [19] compare various Baltic estuaries, bays, and lagoons using an ecosystem service assessment tool based on compiled data, though it remains largely scientific in its approach. A more practical study compares the historical and potential future ecological states of two estuaries to support the implementation of the Water Framework Directive [20]. Since future ecosystem states are hypothetical and lack field data, an expert-based ecosystem service assessment is conducted.

Other examples include expert-driven assessments that compare different coastal protection scenarios [21] or evaluate the impacts of climate change and sea-level rise on a coastal region [22]. However, to our knowledge, there are no examples of ecosystem service assessments applied to concrete coastal or marine infrastructure projects and their associated EIAs.

Key characteristics of the EIA process include a focus on providing information, public consultations, participation, and the assessment of alternative measures [23]. Recent studies support the idea that expert-based ecosystem service assessments can be partic-

ularly valuable in coastal and marine policy implementation [24]. They help compare and prioritize various environmental measures, conservation, and restoration strategies while also raising awareness of environmental challenges, potential solutions, and their consequences [20–22]. These assessments are considered effective in capturing local perspectives, increasing awareness of the multifaceted impacts of measures, and fostering a more structured participatory dialogue with local communities and stakeholders [21,22]. Moreover, they can facilitate communication, broaden the perspectives and knowledge of stakeholders, and support social learning processes [20].

Our overarching questions is whether expert-based ecosystem service assessments can play a role in coastal and marine Environmental Impact Assessments as well as what can be learned from complementing ecosystem model applications. The objectives are to (a) compile a set of ecosystem services that enables a comprehensive assessment of the environmental and societal consequences of waterway deepening; (b) test this approach in two contrasting Baltic Sea case studies using different assessment methods and different scenarios; (c) compare the expert assessments with the results of a 3D ecosystem model to assess the reliability of expert based assessments; and (d) critically assess the results in the EIA context, as well as with respect to transferability and general applicability of the ecosystem services assessment tool for navigational waterway deepening.

Our two contrasting case studies can be regarded as representative of the southern Baltic Sea coasts, and our approach is generally transferable.

## 2. Materials and Methods

### *2.1. The Harbors Rostock, Germany, and Swinoujscie/Szczecin, Poland*

In 2016, the harbors Rostock, Germany, and Swinoujscie/Szczecin, Poland, recorded 26.9 and 24.7 million tons of cargo traffic, respectively [2]. Only a few harbors in the Baltic Sea have significantly higher cargo traffic.

For Rostock, projections for ship traffic from 2015 to 2030 suggest a slight increase from 4801 to 5094 ship movements (only tankers and cargo ships), but a substantial increase in ship capacities [25,26]. Passenger ship traffic is expected to rise from 11,994 to 17,042 passengers during this period. Notably, the number of large passenger ships (over 10,000 tons deadweight) is projected to increase from 188 in 2015 to 1322 in 2030 [25,26].

Currently, Rostock's waterway in the Warnow Estuary allows a maximum shipping depth (draught) of 13 m up to the industrial harbor. Given future projections, the port authority recognized the need to increase the shipping depth to 15 m (with waterway depths ranging from 16.1 to 16.8 m and bottom widths from 112 to 135 m) (Figure 1).

This requires dredging approximately 4.8 million cubic meters of sediment over a length of 15 km. The dredged material comprises 47% clay, glacial till, and silt and about 30% sand, gravel, and bottom mud. Approximately 0.4 million cubic meters of sediment with higher pollution levels were in advance of the project deposited in a land-based sink field, while unpolluted sediments will be deposited in a nearby offshore dumping area. It is estimated that an annual maintenance dredging of 60,000 cubic meters will be necessary to maintain the water depth over the entire length and a waterway width between 120 and 230 m [25,26]. The dredging began in the summer of 2022 and is expected to be completed by 2025 [27].

Between 2017 and 2022, the port of Szczecin-Swinoujscie experienced a significant increase in turnover, rising from 25.5 million tons to 36.8 million tons [28]. During the same period, regular passenger traffic increased slightly to 1.1 million passengers. To accommodate larger ships in the future, the 62 km waterway across the Szczecin Lagoon was deepened from 10.5 m to 12.5 m and widened to 100 m between 2018 and 2023 (Figure 1). This allowed for a doubling of ship capacity to about 20,000 tons of cargo per vessel [29]. The dredged material was deposited on two newly created islands with areas of approximately 250 hectares and 123 hectares, respectively [30]. The total project costs amounted to 337 million Euros [31].

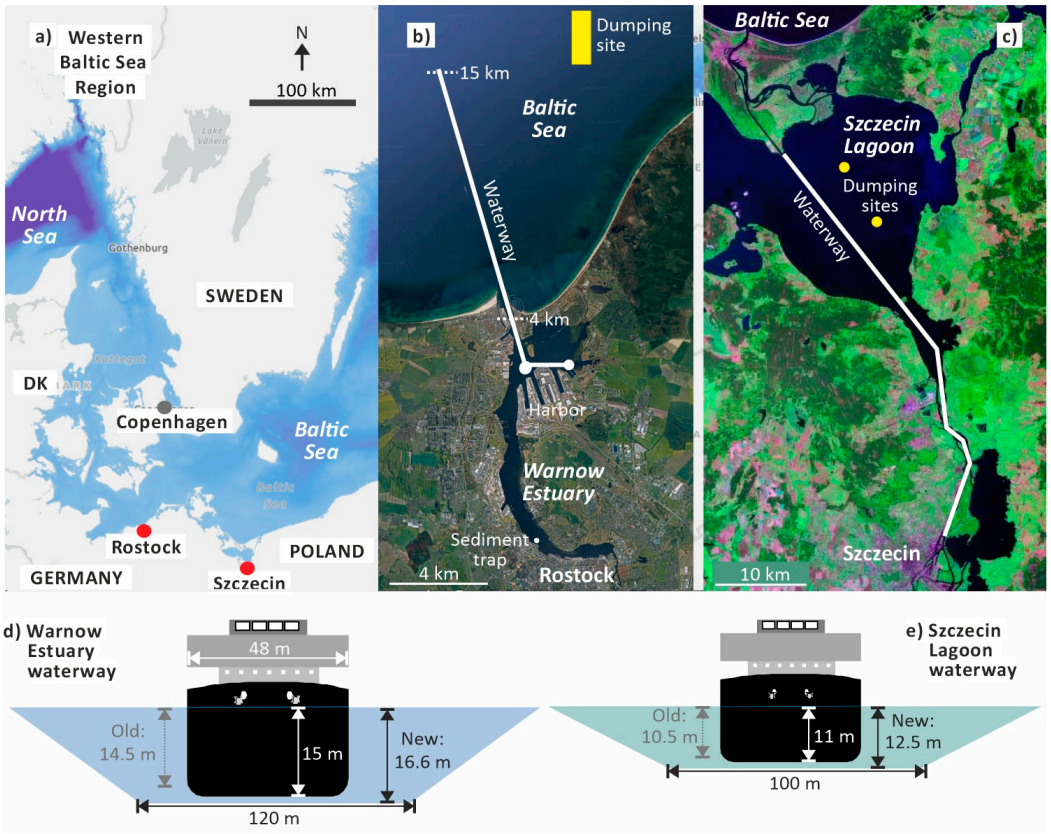



**Figure 1.** (**a**) Location of Rostock and Szczecin harbors; (**b**) location of the waterway/channel through the Warnow Estuary to Rostock harbor and (**c**) across the Szczecin Lagoon to Szczecin harbor. (**d**,**e**) provide details about the state in the 2010's and the recent navigational channel deepening projects.

The Szczecin Lagoon is designated as European Union Natura 2000 site [32]. These sites are protected areas under the EU Birds (2009/147/EC) and Habitats Directives (92/43/EEC), which implement the EU's biodiversity policy. In such sites, port development and dredging operations are restricted and require an appropriate assessment to complement the EIA.

Conversely, the EU Strategy for the Baltic Sea Region (EUSBSR) [33] has three objectives: saving the sea, connecting the region, and increasing prosperity. The strategy explicitly promotes waterway deepening under the priority area "Transport—Improving internal and external transport links".

### *2.2. Environmental Impact Assessments: Process and Results*

The following outlines the conceptual background and regional results of Environmental Impact Assessments (EIAs), providing a foundation for evaluating the complementary value of ecosystem services assessments.

Major building and development projects in the EU have to be assessed for their environmental impacts under the Environmental Impact Assessment Directive (2011/92/EU as amended by 2014/52/EU). The direct and indirect significant impacts on population and human health; biodiversity; land, soil, water, air, and climate; material assets, cultural heritage and the landscape; and the interactions between these factors, are assessed in an EIA [34]. The EIA procedure starts with a screening to determine if the planned project indeed needs an EIA (Figure 2) [35]. Subsequently, the competent authority determines the content, scope, depth of detail, and methods that the developers shall use in their EIA reporting. In this scoping phase, it is also determined if the project is likely to have cross-border impacts. In that case the ESPOO convention applies, this requires the party of

origin to notify the affected party of the expected environmental impacts and to provide the EIA report so that the affected party may comment [36].

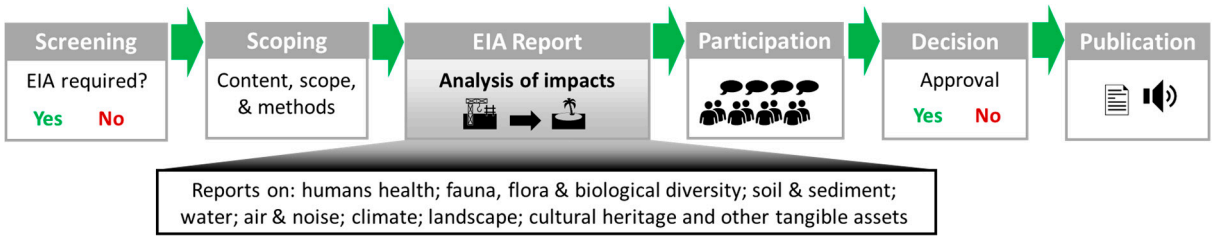



**Figure 2.** The Environmental Impact Assessments (EIA) process according to European Union Directive (2011/92/EU as amended by 2014/52/EU) and the thematic assessment reports provided for the waterway deepenings in Rostock and in Swinoujscie/Szczecin.

The EIA report provides information on the planned project (e.g., location, type, technical design, size); the potential significant environmental impacts, a description of reasonable alternatives that have been examined by the developer; and a description of the characteristics of the project, the location, and planned measures to exclude, reduce, compensate or replace significant adverse environmental impacts [34]. The report needs to be made publicly available so that the public and public agencies (specialist authorities) may provide comments and objections, which the competent authority needs to address in its approval decision that is also to be made publicly available.

Both waterway deepenings, in Rostock and in Swinoujscie/Szczecin, were subject to an EIA. All documents for the EIA procedure in Rostock are available at the website of Federal Waterway and Shipping Administration [26]. An Espoo report on the environmental impacts of the Swinoujscie/Szczecin waterway deepening was provided to the German authorities upon request and is available at the website of the Ministry for economy, infrastructure, tourism and labor [37]. The report provides a summary of the impacts and some extracts of the original EIA report, but the original EIA report is, to our knowledge, not publicly available (in Germany). The protected assets that were subject to the environmental impact study in both cases are in line with what is outlined in the EIA Directive (Figure 2). For both projects, additional studies are also available in the Appendix A (Table A1).

The environmental impact study describes the current status/situation for each protected good (e.g., the degree of already existing impacts), the sensitivity of the protected good, and the expected impacts. For each protected good, a specific study area or spatial extent, in which the impacts are assessed, is determined. In the case of Rostock, these areas ranged from 100 m around the waterway to 3000 m (Table A2). The expected impacts are assessed in terms of their spatial scale and the duration of the impact. The methodological framework followed is that of an ecological risk analysis. The EIA report thereby provides a verbal-argumentative description of the assessment and references the specialist reports that were commissioned beforehand. While the focus is generally on the significant adverse environmental impacts, beneficial impacts are also reported, following a nine-level scale from very high negative to very high positive impacts (Table A3). The method followed in Rostock complied with the "Guidelines for the Environmental Impact Assessment of Federal Waterways" [38]. The assessment method for the EIA in Poland was not specified in the Espoo report. A number of guidelines exist at the EU level [34]; however, it is not clear to what extent they were followed either in Rostock or in Swinoujscie/Szczecin. In the case of Rostock, the entire process, from the application to deepen the waterway to the final approval, took 12 years (Table A4). The EIA reports from Rostock and Swinoujscie/Szczecin both came to the conclusion that no (significantly) adverse impacts were expected. Only for some specific areas, significantly adverse impacts on the protected good "fauna, flora and biological diversity" were expected in Rostock (Table A5). The accompanying landscape conservation plan determined a compensation area of 83.44 ha and the required compensation measure (renaturation of parts of a polder). The Espoo

report on the Swinoujscie/Szczecin waterway did not detail all impact analyses on the protected goods but focused more on potential cross-border impacts. The conclusion was that there are none, as the adverse impacts are locally restricted. Mitigation measures for noise impacts on marine mammals were mentioned, as well as compensation measures, including the extension of Natura 2000 areas and the renaturation of degraded habitats of white and grey dunes. In both cases, the potential impacts on Natura 2000 areas were assessed separately. The Polish report listed 39 Natura 2000 areas within a 20 km radius around the waterway deepening, but only carried out an "appropriate assessment" for seven areas, according to the methodological guidance for the assessment of plans and projects significantly affecting Natura 2000 sites [39]. The Polish report only concluded negligible, very weak and insignificant impacts on Natura 2000 sites [40]. In the case of Rostock, three Natura 2000 sites are in the vicinity of the development area. For each one, a screening report was prepared, which came to the conclusion that no further assessments were necessary as no significant impacts are expected [26].

### *2.3. Selection of Ecosystem Services and the Ecosystem Service Assessment Tool*

The selected ecosystem services are based on the CICES 5.1 classification [41], which is officially used by the European Commission. This hierarchical classification follows the guidance of the United Nations Statistical Division and categorizes ecosystem services into "provisioning", "regulation and maintenance", and "cultural" services. The authors, in collaboration with other scientists, chose 27 ecosystem services relevant for the topic. Pre-tests demonstrated that this number allows for assessment by external stakeholders and experts within a manageable timeframe of approximately 30–45 min, followed by subsequent feedback discussions. The selected ecosystem services are illustrated in Figure 3a.

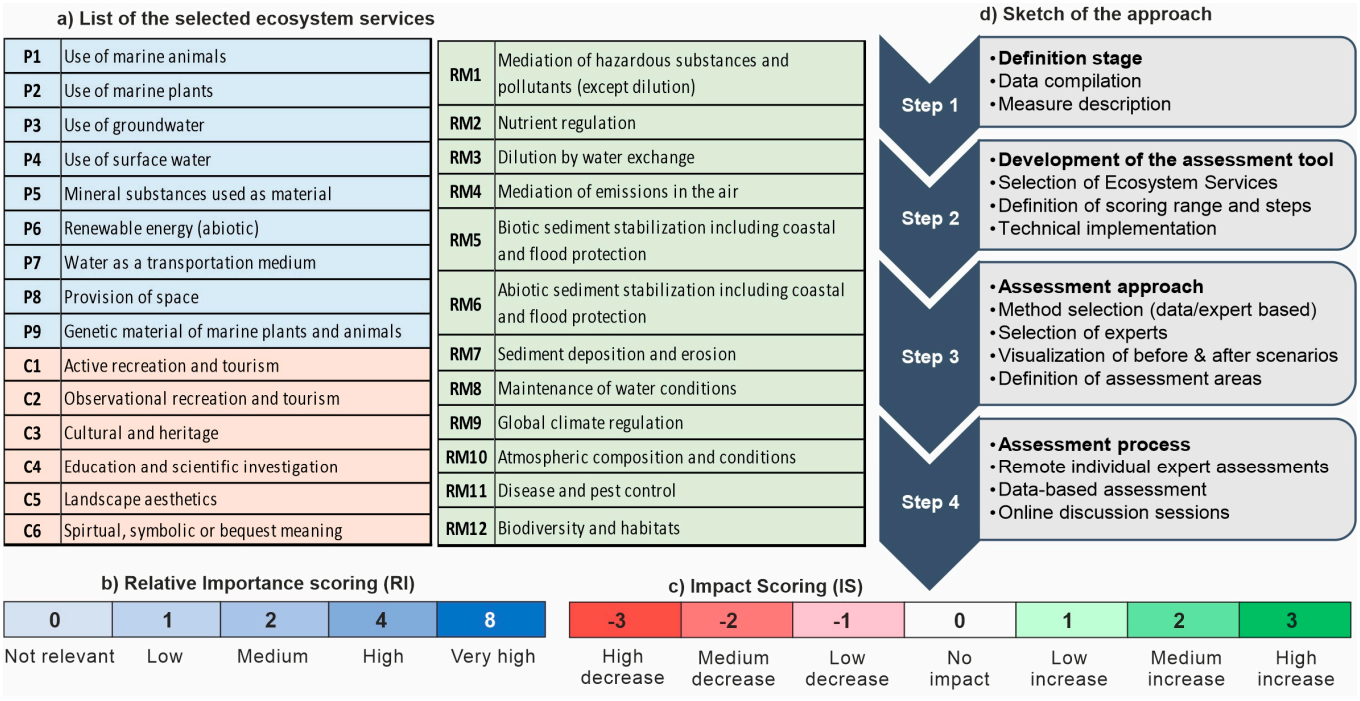



**Figure 3.** (**a**) Overview of the ecosystem services used in the assessment. The colors indicate provision (P), cultural C) and regulating and maintenance ecosystem services (RM). Explanations are provided in Appendix A. (**b**) The sketch provides an overview of the steps of the entire assessment. Scores and ranges used in the (**c**) assessment of changes between scenarios and (**d**) assessment of the relative importance of every ecosystem service.

The ecosystem services were compiled into tables and implemented in an EXCEL sheet to facilitate remote assessments by experts. This Coastal Ecosystem Service Assessment Tool (Co-ESAT) contains additional explanations about the ecosystem services, the scenarios,

the task, and the scoring method and ranges. The tool is a further development of earlier approaches for other topics [20,42]. It allows the expert to enter personal information such as name, institution and field of expertise, as well as a self-assessment of different aspects of their expertise. The table allows one to enter scores for the relative importance (RI) of each service using the classes 0 (not relevant), 1, 2, 4 and 8 (very high relevance) (Figure 3d). It further asks the expert to score the scenario after compared to the situation before the waterway deepening for every ecosystem service. A scale was used ranging from −3 (very high decrease of a service) to +3 (very high increase) (Figure 3c). The tool further facilitates calculations, for example, the multiplication of the relative importance with the ecosystem service score for the change, which ends up in a weighted score, allows one to enter comments and questions and asks for the time spent for the assessment. The full tool is documented in Appendix B. The entire approach is sketched in Figure 3d.

### *2.4. The Scenarios, Assessment Areas and Selection of Experts*

For both the Szczecin (German: Oder) Lagoon and the Warnow Estuary, two scenarios were developed. The scenarios describe the situation before and hypothetically after the waterway deepening. The scenarios were documented in Powerpoint presentations. On 18 slides, these presentations contained pictures, complementing information and compiled background data, e.g., on local setting, major utilizations, land-use and protection status, morphology and geology, chemical and biological status of the waters, and hydrodynamics, as well as detailed information on the deepening measure itself.

The area that is possibly affected by the waterway deepening was visualized, and the experts were asked to consider changes in this area only. In the case of the Oder Lagoon, this area covered about 80% of the Polish part of the lagoon, the Wielki Zalew. The assessment area in the Warnow case study covered 500 m left and right of the waterway, as well as the sediment dumping area. In both cases, the presentations served as information material for the experts and, besides the experts' own knowledge and experience, were a major source of information for the assessment. The areas are based on the EIA investigation area for human protection.

The choice of experts is crucial for the assessment and influences the later outcome. We defined three major fields of expertise, ecology and environmental sciences, ecosystem services, and planning, as well as coastal engineering, and searched for at least three experienced experts in each field. The minimum educational level was a completed master's study course and several years of work experience. Most experts had a doctorate. Another criterion was that the experts represent responsible federal state or national authorities, science, and NGOs. The third criterion was knowledge of the locality. Additionally, we invited coastal and environmental engineering as well as coastal management students to take part in the assessment. This fourth group represented educated citizens with a largely neutral view on the issue. In the Szczecin Lagoon case study, 15, and in the Warnow Estuary case study, 12 experts took place in the assessment. We contacted a much larger number of experts but failed to attract them, or they were not able to provide the assessment within the provided time frame. A shortcoming was that we were not able to attract Polish experts for the Szczecin Lagoon case study.

### *2.5. The Ecosystem Service Assessment Processes*

We used two ecosystem service assessments approaches: a quantitative data and literature-based, subsequently called data-based, approach, and the expert-based approach. Both approaches exclusively focused on potential long-term changes. The data-based assessment was carried out in both case studies. Students with a suitable scientific background compiled data, literature, regional policy and planning documents, as well as monitoring data, and carried out the assessment based on this obtained knowledge and data, using the Coastal Ecosystem Service Assessment Tool. This took one to two months and was part of a master's and a bachelor's thesis [43,44].

In both case studies, the expert assessments were carried out remotely. After the experts indicated their readiness to take part in the assessment, they received the Powerpoint presentation, with the background information, as well as the Coastal Ecosystem Service Assessment Tool. The experts additionally received information on how to fill in the tool and explanations about its scientific purpose. They were asked to return their assessment within two weeks. The results were compiled and analyzed by the two diploma students responsible for the data-based assessments. Afterwards, the experts were contacted and invited to take part in several separate online meetings aiming to settle questions, address comments raised by the experts and discuss results where extreme differences between experts existed. Afterwards, the experts were asked to provide their view on the approach and its value. The online sessions had a duration of 1–1.5 h, were written down and took place in the weeks after the submission deadline of the individual assessments. Afterwards, detailed protocols were prepared. The sessions were prepared and moderated by the students that took care of the data-based assessment.

### *2.6. The 3D Ecosystem Model ERGOM—Szczecin/Oder Lagoon*

The ecology of a largely enclosed brackish system like the Szczecin Lagoon is highly sensitive to changes in morphology and water exchange with the Baltic Sea. Additionally, as a Natura 2000 site, the effects of channel/waterway deepening must be examined in much greater detail [45]. Consequently, we applied the 3D ecosystem model ERGOM (Ecological Regional Ocean Model) to the Szczecin Lagoon, conducting a more in-depth analysis compared to the studies commonly carried out during the EIA process [46], as well as in case of the Oder Lagoon [40]. For the Warnow estuary case study, detailed hydrodynamic model simulations were conducted as part of the EIA. The results indicated only minimal changes in salinity and flow patterns and only in the vicinity of the channel. Consequently, significant impacts on the ecosystem, which could be captured by an ecosystem model, were deemed highly unlikely. As a result, the ecosystem model was not applied to the Warnow estuary.

We employed the coupled circulation and biogeochemical model detailed in Neumann et al. [47]. The circulation model used is the Modular Ocean Model (MOM5.1) [48] featuring a horizontal resolution of 150 m. Vertically, the model is divided into up to 28 layers, each with a thickness of 0.5 m, except for the surface layer, which had a thickness of 0.25 cm. The existing model bathymetry was modified according the EIA planning documents.

The biogeochemical model ERGOM is coupled with the circulation model via the tracer module, which is embedded within the Modular Ocean Model (MOM5.1) code. ERGOM simulates the cycles of nitrogen, phosphorus, carbon, oxygen, and partially sulfur. Primary production, driven by photosynthetically active radiation (PAR), is modeled using three functional phytoplankton groups (large cells, small cells, and cyanobacteria). Chlorophyll concentration in the optical model is derived from these phytoplankton groups [47]. Dead organic matter accumulates as detritus, while bulk zooplankton, representing the highest trophic level in the model, grazes on phytoplankton.

Phytoplankton and detritus can sink through the water column and accumulate in the sediment layer. Detritus undergoes mineralization into dissolved inorganic nitrogen and phosphorus, influenced by water temperature and oxygen concentration. Under oxic conditions, phosphate binds to iron oxide and is retained as sediment particles. These particles can be re-suspended by erosion events and transported by currents to deposition areas. Under anoxic conditions, the reduction of iron oxide liberates phosphate, making it available as dissolved phosphate. Oxygen is produced through primary production and consumed by various processes including metabolism and mineralization. The extracellular excretion of dissolved organic matter by phytoplankton can lead to non-Redfield carbon uptake. A comprehensive description and validation of the model can be found in Neumann et al. [47]. Our ecosystem model is not able to simulate effects on benthic flora, biodiversity and fauna or higher levels of organisms.

For atmospheric forcing, we utilized the High-RESolution Atmospheric Forcing Fields (HiResAFF) dataset provided by Schenk and Zorita [49]. Atmospheric and riverine loads were reconstructed following Gustafsson et al. [50], with both HiResAFF and load data analyzed. The model was forced by meteorological data from the coastDat-2 dataset [51].

## 3. Results

### *3.1. The Coastal Ecosystem Service Assessment Tool and Process*

One objective was to develop and provide an ecosystem services assessment tool, specifically tailored for coastal engineering measures such as waterway deepening, dredging, and sediment dumping. The suitability of the tool can be assessed based on several factors: (1) the choice of ecosystem services; (2) the separation into an assessment of changes in ecosystem services, as well as an assessment of the relative importance of every ecosystem service with respect to waterway deepening; (3) the scoring steps and ranges; (4) the technical implementation in a spreadsheet (Excel); and (5) the time efficiency.

The involved experts were not explicitly asked about the suitability of the tool but had the possibility to comment on it during the online sessions and to enter notes in the assessment sheet. Neither the experts nor the two student moderators reported any issues or suggested improvements for the scoring steps, ranges, or technical implementation of the tool. The time required for remote scoring was noted on the assessment sheets. Among the experts, it ranged from 20 to 120 min with an average of 38 min for the Oder Lagoon and from 13 to 60 min with an average of 35 min for the Warnow. It can be assumed that the overall assessment, including reading the background information and completing the scoring, took about one hour on average. Therefore, selecting 27 ecosystem services appears to be a reasonable balance between detail and required assessment time.

The remote assessment provided flexibility for the experts and ensured comprehensive individual perspectives. The subsequent online discussion sessions lasted an additional 1 to 1.5 h. Meeting protocols indicate that these discussions were essential, particularly for clarifying the meaning of individual ecosystem services. Overall, the total duration of 2.5 h for the tool and the entire assessment process can be considered suitable and time-efficient. The experts' self-assessment of their expertise in different fields helped the moderator prepare for the online discussion and identify any misunderstandings.

The experts' assessment of the relative importance of the selected ecosystem services for evaluating waterway deepening measures provides insight into the suitability of this set of ecosystem services for such projects. Generally, none of the 27 ecosystem services were deemed irrelevant for the Oder Lagoon or the Warnow, although several were considered of low relevance. Perspectives varied significantly among experts from different fields, and even among those with similar backgrounds (Figure 4). Only the student groups and the two students who carried out an assessment based on data and literature considered several ecosystem services to be irrelevant. Specifically, the ecosystem services "Use of marine plants (P2)" and "Renewable energy" were generally considered to have low relevance.

Experts largely agreed on the high relevance of ecosystem services such as "Water as transport medium (P7)", "Sediment deposition and erosion (EM7)", "Biodiversity and habitats (RM12)", and "Active and observational recreation (C1 and C2)". The subsequent online discussions did not indicate that any ecosystem services were missing. Therefore, we can conclude that the chosen set of ecosystem services was suitable.

On average, cultural (C) services were considered the most important, followed by regulating and maintenance (RM) services, and then provisioning (P) services (Figure 4). This trend was observed for both the Warnow Estuary and, even more so, for the Oder Lagoon. The two data-based assessments also showed similar results. The larger number of RM services likely contributed to the lower relevance of each individual ecosystem service, but the findings also underscore the significance of cultural services.

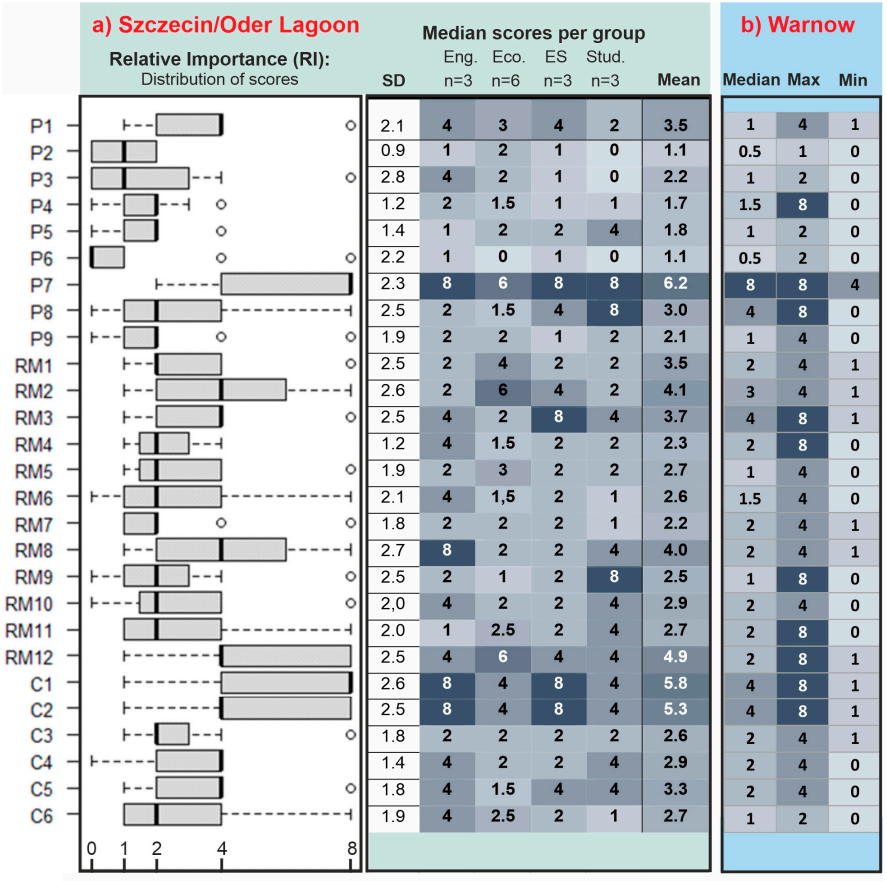



**Figure 4.** Relative importance (RI) of the selected ecosystem services for assessing waterway deepening measures based on expert judgements (scale: 0, not relevant, to 8, highly important. The expert groups are coastal engineers (Eng.), ecologists (Eco.), ecosystem service experts (ESs) and university students (Stud.). (**a**) Szczecin/Oder Lagoon case study; (**b**) Warnow Estuary/Rostock harbor case study.

### *3.2. Warnow Estuary—Ecosystem Service Assessments*

Experts anticipate a significant increase only in the ecosystem service "Water as a transport medium" due to the deepening of the Warnow Estuary. Across all other ecosystem services, based on the median assessment of all 12 experts, minimal to no changes are expected (Figure 5). The inclusion of the student group in the calculation was justified by findings from the Oder case study, showing their scoring aligned closely with that of the experts.

Most ecosystem services show negative values, indicating that channel deepening slightly diminishes their provision. In summary, the projected changes in ecosystem services are modest, suggesting that channel deepening is perceived as having little impact on ecosystem service provision.

The scoring of changes in the data-based approach significantly differs from that conducted by experts. The higher positive and negative values cannot be fully explained, suggesting that the data-based assessment may be insufficient, although it does offer insights; for example, the higher score for the ecosystem service "dilution by water exchange" seems reasonable due to increased water exchange processes with deepening. Nevertheless, the data-based approach should be considered as supplementary rather than definitive.

| No. | Ecosystem Services | Expert scores (n=12) Median | Max | Min | Data-based |
|---|---|---|---|---|---|
| P1 | Use of marine animals | 0 | 1 | -1 | 0 |
| P2 | Use of marine plants | 0 | 0 | -2 | 0 |
| P3 | Use of groundwater | 0 | 0 | -1 | -1 |
| P4 | Use of surface water | 0 | 1 | -2 | 0 |
| P5 | Mineral substances | 0.5 | 3 | 0 | 2 |
| P6 | Renewable energy (abiotic) | 0 | 0 | 0 | 0 |
| P7 | Water as a transportation medium | 3 | 3 | 2 | 3 |
| P8 | Provision of space | 0 | 2 | -1 | -1 |
| P9 | Genetic material | -0.5 | 0 | -2 | -2 |
| RM1 | Mediation of hazardous substance | -0.5 | 1 | -2 | -2 |
| RM2 | Nutrient regulation | -0.5 | 1 | -3 | -2 |
| RM3 | Dilution by water exchange | 0 | 2 | -2 | 2 |
| RM4 | Mediation of emissions in the air | -0.5 | 2 | -2 | 0 |
| RM5 | Biotic sediment stabilization | -0.5 | 0 | -2 | -2 |
| RM6 | Abiotic sediment stabilization | -1 | 1 | -2 | -2 |
| RM7 | Sediment deposition and erosion | 0 | 2 | -2 | 0 |
| RM8 | Maintenance of water conditions | -1 | 2 | -2 | -1 |
| RM9 | Global climate regulation | 0 | 0 | -2 | 1 |
| RM10 | Atmospheric composition | 0 | 0 | -1 | 1 |
| RM11 | Disease and pest control | 0 | 1 | -2 | -1 |
| RM12 | Biodiversity and habitats | -1 | 1 | -2 | 0 |
| C1 | Active recreation and tourism | 0 | 1 | -1 | -1 |
| C2 | Observational recreation | 0 | 2 | -1 | -1 |
| C3 | Cultural and heritage | 0 | 0 | -1 | 1 |
| C4 | Education and sci. investigation | 0 | 2 | 0 | 1 |
| C5 | Landscape aesthetics | 0 | 0 | -1 | -1 |
| C6 | Spirtual or bequest meaning | 0 | 0 | -1 | -1 |

**Figure 5.** Changes in ecosystem service provision between the two scenarios (before and after the waterway deepening measure) in the Warnow estuary (Rostock harbor) based on expert judgements (scale: 3 high increase; 3 high decrease after the measure) as well as results of the data-based assessment.

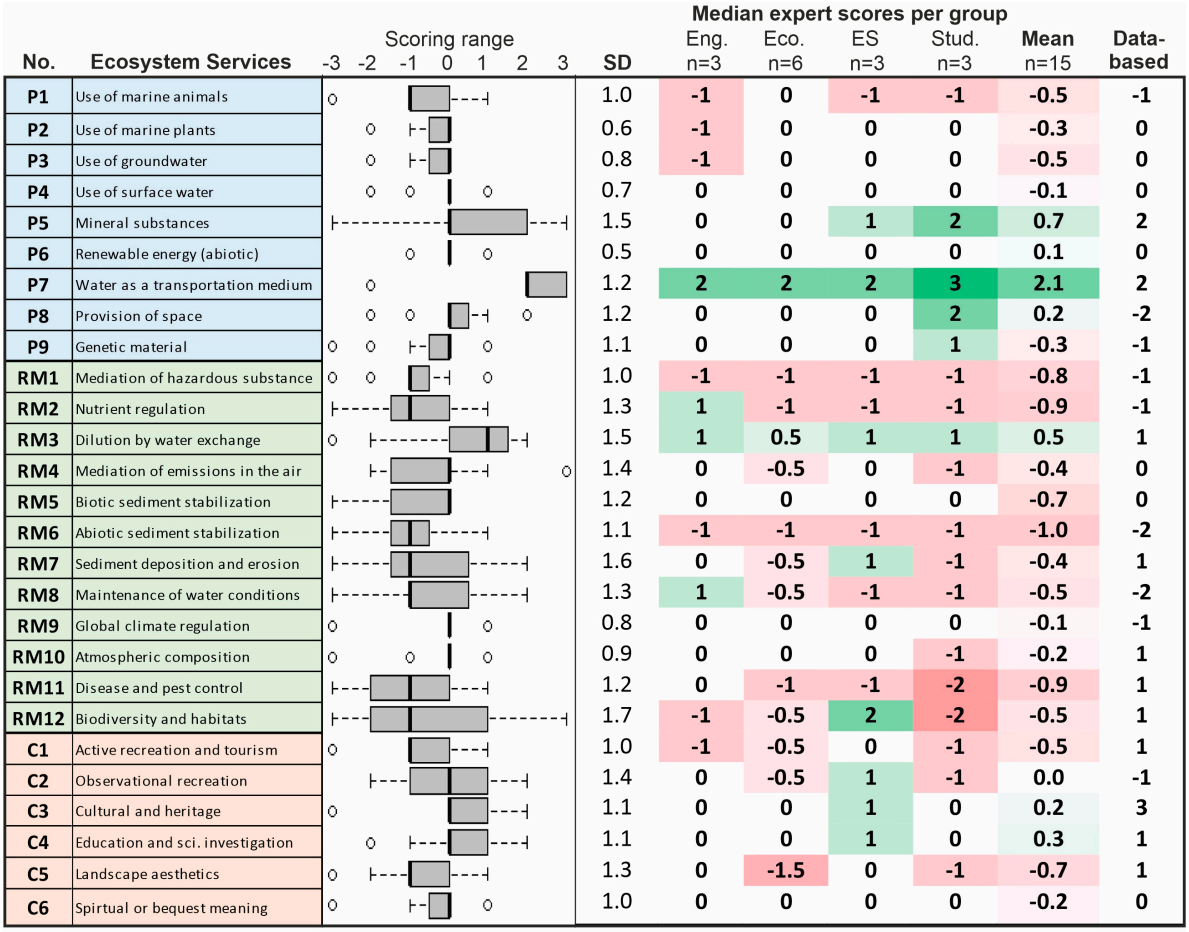
### *3.3. Szczecin/Oder Lagoon—Ecosystem Services Assessments*

Apart from the ecosystem service "Water as a transport medium", experts generally perceived the impact of waterway deepening on the Oder Lagoon as modest (Figure 6). This consensus spans all four groups of experts, with consistent assessment results among them. The standard deviation of scores is typically close to one, indicating a high level of agreement among experts.

One notable discrepancy among the groups pertains to the ecosystem service "Biodiversity and habitats". Engineers and ecologists foresee insignificant changes, while experts in ecosystem services anticipate a moderate increase, and the student group predicts a moderate decrease. Variances also exist regarding "Landscape aesthetics", with ecologists expressing concerns about the presumed increase in ship traffic. Overall, the consensus suggests that waterway deepening is expected to marginally reduce the provision of ecosystem services.

The data-based assessment conducted by a student largely aligns with that of the experts, with a significant difference noted in their assessment of "Cultural and heritage" services, where the student assigns a high positive score.

In summary, the results are considered stable and reliable across different expert backgrounds, indicating that the number of experts involved was adequate for this study. The findings collectively suggest that the impact of waterway deepening on ecosystem service provision is generally perceived as modest, especially in the Warnow Estuary case study.



| No. | Ecosystem Services | Scoring range -3 -2 -1 0 1 2 3 | SD | Median expert scores per group: Eng. n=3 | Eco. n=6 | ES n=3 | Stud. n=3 | Mean n=15 | Data-based |
|---|---|---|---|---|---|---|---|---|---|
| P1 | Use of marine animals | | 1.0 | -1 | 0 | -1 | -1 | -0.5 | -1 |
| P2 | Use of marine plants | | 0.6 | -1 | 0 | 0 | 0 | -0.3 | 0 |
| P3 | Use of groundwater | | 0.8 | -1 | 0 | 0 | 0 | -0.5 | 0 |
| P4 | Use of surface water | | 0.7 | 0 | 0 | 0 | 0 | -0.1 | 0 |
| P5 | Mineral substances | | 1.5 | 0 | 0 | 1 | 2 | 0.7 | 2 |
| P6 | Renewable energy (abiotic) | | 0.5 | 0 | 0 | 0 | 0 | 0.1 | 0 |
| P7 | Water as a transportation medium | | 1.2 | 2 | 2 | 2 | 3 | 2.1 | 2 |
| P8 | Provision of space | | 1.2 | 0 | 0 | 0 | 2 | 0.2 | -2 |
| P9 | Genetic material | | 1.1 | 0 | 0 | 0 | 1 | -0.3 | -1 |
| RM1 | Mediation of hazardous substance | | 1.0 | -1 | -1 | -1 | -1 | -0.8 | -1 |
| RM2 | Nutrient regulation | | 1.3 | 1 | -1 | -1 | -1 | -0.9 | -1 |
| RM3 | Dilution by water exchange | | 1.5 | 1 | 0.5 | 1 | 1 | 0.5 | 1 |
| RM4 | Mediation of emissions in the air | | 1.4 | 0 | -0.5 | 0 | -1 | -0.4 | 0 |
| RM5 | Biotic sediment stabilization | | 1.2 | 0 | 0 | 0 | 0 | -0.7 | 0 |
| RM6 | Abiotic sediment stabilization | | 1.1 | -1 | -1 | -1 | -1 | -1.0 | -2 |
| RM7 | Sediment deposition and erosion | | 1.6 | 0 | -0.5 | 1 | -1 | -0.4 | 1 |
| RM8 | Maintenance of water conditions | | 1.3 | 1 | -0.5 | -1 | -1 | -0.5 | -2 |
| RM9 | Global climate regulation | | 0.8 | 0 | 0 | 0 | 0 | -0.1 | -1 |
| RM10 | Atmospheric composition | | 0.9 | 0 | 0 | 0 | -1 | -0.2 | 1 |
| RM11 | Disease and pest control | | 1.2 | 0 | -1 | -1 | -2 | -0.9 | 1 |
| RM12 | Biodiversity and habitats | | 1.7 | -1 | -0.5 | 2 | -2 | -0.5 | 1 |
| C1 | Active recreation and tourism | | 1.0 | -1 | -0.5 | 0 | -1 | -0.5 | 1 |
| C2 | Observational recreation | | 1.4 | 0 | -0.5 | 1 | -1 | 0.0 | -1 |
| C3 | Cultural and heritage | | 1.1 | 0 | 0 | 1 | 0 | 0.2 | 3 |
| C4 | Education and sci. investigation | | 1.1 | 0 | 0 | 1 | 0 | 0.3 | 1 |
| C5 | Landscape aesthetics | | 1.3 | 0 | -1.5 | 0 | -1 | -0.7 | 1 |
| C6 | Spirtual or bequest meaning | | 1.0 | 0 | 0 | 0 | 0 | -0.2 | 0 |

**Figure 6.** Changes in ecosystem service provision between the two scenarios (before and after the waterway deepening measure) in the Oder Lagoon based on expert judgements (scale: 3 high increase; 3 high decrease after the measure). SD indicates the standard deviation. The expert groups are coastal engineers (Eng.), ecologists (Eco.), eosystem service experts (ESs) and university students (Stud.). Additionally, the results of the data-based assessment are shown.

### *3.4. Szczecin/Oder Lagoon—Ecosystem Model Results*

Based on the model, the waterway deepening has an immediate effect on water exchange between lagoon and the Baltic Sea. More saline Baltic Sea water will enter the lagoon and increase the salinity especially in the Wielki Zalew by 11% and by 5.5% in the entire lagoon (Figure 7a). However, the absolute average salinity is only about 1 g/kg, and the changes are low. Water temperature and ice cover are practically not affected by the waterway deepening, and the effects on dissolved nitrogen and phosphorus concentrations are low. The model suggests a significant reduction in the chlorophyll-a and phytoplankton concentrations between 7% and 11%. The surface water temperatures and the surface oxygen concentrations and are practically not affected by the deepening. Altogether, the waterway deepening has only very limited effects on the lagoon. The absolute changes in the parameters do not change the overall ecological state of the system.

However, the model suggests strong changes in nitrogen, phosphorus and carbon processes (Figure 7b,c). Nitrogen fixation is reduced by 5% in the entire lagoon as a result of reduced cyanobacteria concentrations in summer. Denitrification is reduced between 6% and 8%. This can be explained by a slightly decreased water retention time. The model suggests important increases in the nutrient burial in the sediment. The waterway deepening increases the burial of N, P and C by 70% to 74%. In absolute numbers, it means that 807 t N/a, 112 t P/a and 4661 T C/a are stored additionally in the sediments. This

takes place exclusively in the Wielki Zalew, while the shallower western bay (Kleines Haff) does not show any nutrient burial in the sediments.

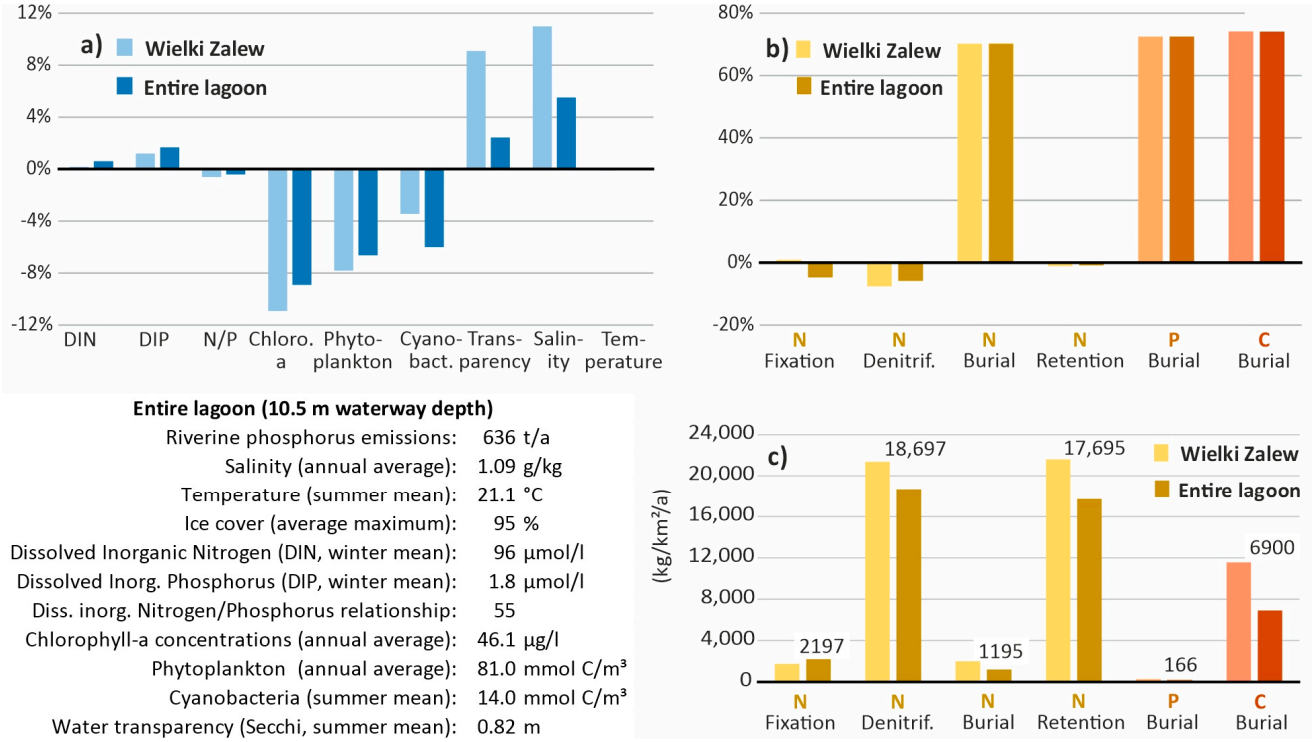



**Figure 7.** Results of the 3D ecosystem model simulations reflecting the situation before (10.5 m waterway depth/draught) and after the waterway deepening to 12.5 m draught, spatially averaged over the entire Oder Lagoon, as well as the eastern bay (Wielki Zalew). (**a**) Relative differences between selected parameters. Below are the absolute values for these parameters for the Oder Lagoon with 10.5 m waterway depth. (**b**) Relative differences for nitrogen-, phosphorus- and carbon-related processes before and after the waterway deepening and (**c**) the corresponding absolute values.

According to the 3D ecosystem model, the burial of organic matter (nutrients and carbon) in the sediments depends strongly on water depth. In a water depth down to about 8–10 m, storm-induced resuspension does not allow for a permanent burial. Re-suspended sediments leave the lagoon and are washed into the Baltic Sea or are trapped in deeper areas of the lagoon. The waterway is the deepest part of the lagoon, and the model suggests that the deepening to 12.5 m draught strongly increases this trap function. Consequently, more frequent sediment dredging is required to maintain the channel depth.

With respect to nitrogen, three processes, namely N-fixation, denitrification and burial in sediments, determine the total N retention in the lagoon. Quantitatively, denitrification is the most important process. Between 2010 and 2019, on average, 12,845 t N/a was removed via denitrification and 821 t N/a was buried in sediments, while N-fixation added 1510 t N/a to the water body. This means that the total N retention in the lagoon is 17,695 t N/a. The waterway deepening reduces this retention function by about 1% (144 t N/a). However, these numbers indicate that the lagoon is an important sink for nitrogen.

## 4. Discussion

### *4.1. The Ecosystem Service Assessment Tool—Lessons Learned*

The 27 ecosystem services selected appeared to have a reasonable balance between detail and the required assessment time and were considered as suitable for this topic. In general, more ecosystem services were considered relevant for the Oder Lagoon compared to the Warnow Estuary. Additionally, the average Relative importance was higher, at 2.9 for

the Oder Lagoon versus 2.1 for the Warnow Estuary. This clearly indicates that the two case studies represent different environmental and socio-economic settings, namely an urban environment and a largely natural protected system. These differences suggest that the tool and the included ecosystem services are generally applicable and transferable to other thematically comparable case studies.

The imbalance in the number of ecosystem services across the three ecosystem service categories—cultural, regulating/maintenance, and provisioning—combined with the different scores for their relative importance, complicates comparisons between categories and individual ecosystems. To address this, the tool principally allows for weighting, where the relative importance is multiplied by the scores of changes in ecosystem services. However, this option has not been used since the absolute results were not in focus. In other settings, for example, a stakeholder discussion process, a weighting might make sense to better visualize which ecosystem services have the highest importance. This would allow a prioritization between the single ecosystem services.

Examining the minimum and maximum expert scores for each ecosystem service reveals a wide range, highlighting diverse expert perceptions. This underscores the necessity of involving a group of experts to balance these differing views. The involvement of nine experts (and three students) proved necessary but also sufficient to achieve stable results. This number of experts appears generally suitable for waterway deepening projects.

Overall, the assessment approach of ecosystem service changes resulting from waterway deepening proved effective in both case studies, suggesting potential applicability to comparable projects worldwide. While these assessments reflect expert perceptions well, the results are associated with high uncertainties and hardly provide reliable data.

### *4.2. Environmental Impact Assessments—State and Deficits*

In the European Union, major construction and development projects must undergo environmental impact assessments (EIAs) according to a defined legal framework, specifically the Environmental Impact Assessment Directive (2014/52/EU). In EU member states, such as Germany, additional specific guidelines exist for particular projects, including those involving navigation waterways [38]. An evaluation of EIA implementation in Germany concludes that EIAs generally meet quality criteria, are comprehensive and complete, and are relevant and effective for environmental protection, providing societal benefits [52].

However, the report also highlights several shortcomings [52]. For instance, the EIA process is not always well suited to the specific type of project, and the consideration of protected assets and spatial coverage can sometimes be inadequate or poorly justified. The early involvement of specialists and approval authorities is crucial for success, but it often occurs too late, and the authorities involved may lack the necessary expertise. Similarly, public involvement and information dissemination, which are essential, sometimes occur too late in the process. The report emphasizes the importance of a well-presented EIA summary for the acceptance of a project, noting that a transparent evaluation process enhances public support. Therefore, greater attention should be paid to these aspects.

Looking at the international literature, several challenges and deficiencies in EIA processes are identified. These issues mostly relate to procedural aspects, the quality of environmental information, and the integration of this information into decision-making. A European Union report has called for improvements in screening, scoping, the consideration of alternatives, monitoring, public participation, and EIA quality control [53]. Similarly, researchers advocate for improved procedures based on high-quality data, impact analyses, mitigation measures, and holistic, integrated monitoring plans. They also note weaknesses, such as the subjective evaluation of impacts and inconsistencies [54]. A low quality of the EIA reports may accrue due to a lack of training and capacity building for those responsible [53], and even if the presented environmental information is sound, it does not necessitate integration into decision-making [55]. Jay et al. [55] found that, in many cases, the results of EIA are considered as useful additional information but hardly influence the development decisions, which are rather based on political considerations.

A common concern regarding European environmental policy is the issue of over-regulation [56]. Concerns with respect to EIAs are particularly due to the costs and delays they impose on project implementation. Although the direct cost of an EIA typically accounts for around or below 1% of the total project cost [57], the necessary studies can significantly increase overall investment expenses. In Germany, the median duration of the EIA approval process, from application to decision, is nearly two years, with some cases extending beyond three years [58]. For complex projects, such as the deepening of the Weser River, the timeline from planning to implementation spanned over two decades, with the EIA being an important contributing factor to this prolonged timeline. Attempts to address this issue in Germany, such as the "Maßnahmengesetzvorbereitungsgesetz", a legislative act, have not been successful [59]. Therefore, enhancing the time and cost-efficiency of EIAs is crucial. To overcome some of these deficiencies, we explore two topics: the use of ecosystem models and/or ecosystem service assessments.

### *4.3. Benefits of Ecosystem Model Applications in EIAs*

The EIA focuses on both the short- and long-term consequences of a project on the environment, addressing a hypothetical future state. The local data and knowledge used are based on the current state, and the quality of the EIA depends largely on the knowledge of the experts involved and the methods they employ. These methods can vary between different projects, as they are not predefined in legal framework documents. However, with respect to waterways in Germany, detailed guidelines [38] and a wide range of generally accepted procedural rules and publications exist. They serve as a framework and ensure a procedure according to the current state of the art.

The experts and companies involved in environmental assessments typically possess extensive experience, which gives them a competitive advantage. However, this experience is often kept internal, limiting knowledge sharing and transparency. The quality of expertise and decision-making processes could greatly benefit from well-documented, comparable case studies. To achieve this, systematic retrospective analyses are needed to extract lessons learned for future projects, along with thorough documentation of the results.

An alternative transparent approach for gaining insights into a future environmental state is the application of models. In navigation channel deepening and dredging projects, the use of 3D hydrodynamic models is particularly important and is often employed, as in the case of the Warnow estuary deepening. For coastal water deepening projects of this kind, a hydrodynamic model may be sufficient, since the ecological effects are generally considered low. However, in closed systems like the Oder Lagoon, which has a high environmental protection status and sensitive ecology, the use of a 3D ecosystem model may be more appropriate, providing new insights and additional data.

A comparison between the EIA and 3D ecosystem model results for the Oder Lagoon project generally shows that the EIA was sufficiently comprehensive. Both approaches suggest that the environmental impact of the waterway deepening on the lagoon is limited, even in such an ecologically sensitive area. However, the model provides new insights, such as the quantification of increased organic sediment burial resulting from the two-meter channel deepening. Between 1950 and 2000, approximately 1.5 million cubic meters of wet organic and mineral sediment were dredged and dumped annually from the channel across the Oder Lagoon [60]. An estimated 70% increase in inorganic sediments, as suggested by the model, would result in additional dredging and dumping costs. The model further indicates that the channel's sediment trap function prevents accumulation in other parts of the lagoon, increasing the risk of coastline and bottom erosion. However, these aspects could be covered by hydrodynamic models with an integrated sediment transport module, as well, which are often employed in large projects.

Our ecosystem model further indicates the ecological implications of nitrogen, phosphorus and carbon burial in the sediments for both the lagoon ecosystem and the downstream Baltic Sea. The model results emphasize the lagoon's role as a retention basin for nutrients, particularly nitrogen. The total nitrogen retention in the lagoon is 17,695 tons per

year, and the waterway deepening would reduce this retention by about 1% (144 tons per year). Considering the total flow-normalized nitrogen loads to the Oder Lagoon between 2010 and 2014 of 61,950 tons per year [61], this means that 28.6% of all external nitrogen loads are retained in the lagoon. The effects of the waterway deepening on nutrient retention and budgets, as well as the implications for Baltic Sea management, were not considered in the EIA for the Oder Lagoon.

Another benefit of using models in EIAs is the ability to assess the effects of alternative measures or modified project implementation strategies, which, when based solely on expert knowledge, remain speculative. For this kind of study, a high depth of investigation is not necessarily required. This means that a high model performance is not mandatory, as long as the model effectively reflects the differences between alternative environmental states.

Our application illustrates that ecosystem models are valuable tools for environmental assessments. Moreover, using these models can significantly strengthen the data foundation for evaluating ecosystem services. A variety of ecosystem services can be directly or indirectly calculated using data generated by ecosystem models, offering new insights into the benefits of different environmental states—before and after a given measure—for both human use and society [62].

The use of 3D ecosystem models is currently limited by the availability of reliable models and computational capacity. However, in the Baltic Sea region, these limitations are expected to be overcome within the next decade, provided that reliable input data and expertise are available. One argument against the application of 3D ecosystem models in EIAs is the relatively low ecological impact of channel deepening on coastal systems. Additionally, there is a risk that the qualitative improvements offered by these models could lead to increased time and costs for EIAs. This would contradict ongoing efforts to streamline and reduce the costs and duration of the EIA process.

### *4.4. Ecosystem Service Assessments in EIAs*

Despite a large number of studies on ecosystem service assessments, there are still complaints that the concepts remain theoretical and rarely support decision-making processes and policy implementation [63]. However, impact assessment processes are generally considered highly suitable for being linked to and supported by ecosystem service assessments [64]. Several conceptual frameworks exist for embedding ecosystem services into existing impact assessment practices [10,13,65].

In 2021, the International Association of Dredging Companies (IADC) released a report that presented a conceptual framework, with a particular focus on dredging and marine construction projects [66]. The report suggests that considering ecosystem services might lead to more sustainable and adaptive solutions and support the project decision-making process. The provided framework incorporates ecosystem service assessments at various stages of the project cycle, including baseline, prospective, retrospective, and adaptive assessments for different case studies. However, for applications in the European Union, where specific requirements and guidelines for EIAs are in place, this global framework is too general. In the European Union, the potential role of ecosystem service assessments in EIAs requires a more detailed investigation.

Ecosystem service assessments and EIAs share several similarities. Both are broad and comprehensive, cover a wide range of topics, are spatially flexible, and can be applied to comparable spatial units. EIAs address, besides environmental aspects, other factors such as human health, cultural values, and material assets. For example, in the Warnow case study, factors like noise emission, bathing water quality, and air quality were considered. However, in practice, EIAs typically focus on the consequences of a measure on nature and the environment. In contrast, ecosystem service assessments adopt an anthropocentric perspective. While EIAs emphasize potential damages and risks, ecosystem service assessments focus more on human benefits. Ecosystem services are usually divided into three categories: provisioning and regulating services, which focus on the natural system

and its functioning, and cultural services, which directly describe the value to humans and society. Recent studies highlight that measures and environmental changes in a region particularly affect cultural ecosystem services [20,22]. Complementing especially information on cultural services might be one of the benefits of ecosystem service assessments in EIAs. This implies that ecosystem service assessments are carried out during the EIA process. However, if ecosystem service assessments are conducted in addition to an EIA, there is a risk of redundant analysis. Challenges also remain in properly integrating ecosystem services, quantifying them, developing impact indicators for prediction and assessment, and identifying beneficiaries at appropriate scales [67].

Many studies have shown that public participation is a crucial factor in improving EIA procedures [53–55] and that focusing on ecosystem services can enhance public engagement [68] and improve stakeholder engagement [67]. The benefits include identifying and prioritizing ecosystem services and beneficiaries who might experience negative impacts if service provision declines, thereby supporting the determination of the EIA's scope and the delineation of the study area [67,69].

### *4.5. Benefits of Expert-Based Ecosystem Service Assessments in EIAs*

What are the benefits, strengths, and weaknesses of our expert-based ecosystem service assessments, and what role can they play in EIAs?

Our approach, which involves the structured engagement of an expert group, the comparative assessment of ecosystem services between the present state and alternative scenarios, and the selection of relevant ecosystem services, is generally suitable for similar coastal and hydraulic engineering projects. Moreover, this approach and the chosen ecosystem services are transferable to other regions. The experts involved considered all the included ecosystem services to be relevant, and the approach is fundamentally applicable within an EIA.

In general, the expert opinions on the consequences of waterway deepening align well with the findings of environmental impact reports and 3D ecosystem model results. In general, we can summarize that models and experts consider the effects of waterway deepening to be very limited. The experts' views, on average, seem reasonable, and utilizing their knowledge is particularly valuable when data are lacking.

However, our approach has its weaknesses. The quality of the expert-based ecosystem assessment depends on the background, knowledge, and perception of the involved experts, which introduces subjectivity and limits the reliability of the results. We involved 12 to 15 experts, which seems sufficient to stabilize the results, reduce subjectivity, and capture a full spectrum of opinions. Nevertheless, the selection and motivation of experts are crucial aspects that require careful consideration and expert mapping before the assessment. The problem of subjectivity is underscored by other expert-based assessments as well, namely that the results reflect opinions rather than facts [20] and possibly a bias [70]. Moreover, when applied to hypothetical future scenarios with high levels of uncertainty, these assessments risk being not only misleading but potentially counterproductive [22]. Other case studies highlight limitations arising from the unbalanced representation of stakeholders and interest groups, as well as an insufficient number of participants with adequate expertise [71]. Even cultural background and nationality can affect expert-based assessment results [72]. On the other hand, expert-based assessments can broaden the view of involved persons and especially emphasize the role of cultural changes [70], serve as a tool visualize trade-offs, analyze patterns and processes at regional scales and hence facilitate decision-making [73].

If the ecosystem service assessment is conducted alongside an EIA, it could benefit from the environmental studies already prepared. If 3D ecosystem model results are available, the database serving as background information for the experts would be even more robust. Additionally, ecosystem services could be partially converted into monetary terms, offering financial insights into the benefits of an investment and quantifying the connections between ecology and the economy [62]. All these data help reduce subjectivity

in expert-based assessments and are expected to reduce the observed high variability in expert scores, leading to more stable results. A sound data basis provides a foundation for a data-driven ecosystem service assessment as well.

In our retrospective ecosystem service assessment, the experts involved identified cultural services as highly important. This suggests that cultural aspects are particularly relevant when evaluating measures, and this dimension of our assessment could effectively complement an EIA. It is possible that cultural services play a more significant role in urban systems compared to natural ones, as the benefits of ecosystem services to humans may be more pronounced in urban environments. Consequently, ecosystem service assessments might hold greater importance in these settings. The added value of incorporating an ecosystem service assessment into the EIA process would likely be similar to that observed in our retrospective analysis.

The alternative approach is to conduct an expert-based ecosystem service assessment early in the EIA process, specifically during the scoping phase. Our method is designed for flexible adaptation to the unique needs of coastal engineering and hydraulic projects and is both easy and quick to apply. The entire process does not require specialized knowledge and can be carried out by educated laypersons with moderation skills. When implemented during the scoping phase of an EIA, only general documents and background information need to be compiled and prepared; the EIA results themselves are not necessary at this stage. Assessing the importance of each ecosystem service allows experts to tailor the system to better reflect their understanding and perspective on the project.

If formally applied at an early stage of an EIA, our approach would need to be adapted from an expert-based to a stakeholder-based model. In this scenario, stakeholders identified and defined by the responsible licensing authority and the planning commissioner would participate in the ecosystem service assessment, replacing the experts. These stakeholder-based assessments could be valuable for capturing stakeholder views and concerns early on, helping to define investigation topics, protective assets, and spatial coverage. This approach could also foster public participation by highlighting the project's impact on the human usability of an ecosystem, supporting dialogue forums, and gathering public opinions beyond just the stakeholders if provided in an easily accessible online format. Additionally, it could serve as a complementary structural framework for summary presentations by incorporating a human-use perspective. Different to data-based ecosystem service assessments, the assessments carried out with and by stakeholders will remain qualitative. The results hardly enable a translation of changes into monetary values.

Stakeholder-based ecosystem service assessments could be used to evaluate both the long-term and short-term effects of a project. In contrast, data-based assessments are limited to assessing long-term effects. These assessments focus on comparing tangible, measurable changes that have occurred or are expected to occur as a result of the project, impacting the human use of the system.

Figure 8 summarizes our experiences in a Strength–Weaknesses–Opportunities–Threats (SWOT) diagram, incorporating insights from additional literature [74–76]. We believe that especially stakeholder-based ecosystem service assessments could be formally integrated into EIAs, even within the highly structured European Union EIA framework, particularly during the early scoping stage. This integration could enhance cooperation and communication with stakeholders, help to reduce conflicts, and potentially save time. Additionally, it could improve the compilation and addressing of stakeholder concerns, potentially reducing costs associated with unnecessary studies.

| Strengths | Opportunities |
| --- | --- |
| • Complementing holistic, interdisciplinary approach with anthropocentric view on the nature<br>• Identification of beneficiaries, social consequences and impacts on communities<br>• Flexible, conceptually simple and enables fast applications<br>• Suitable for different spatial scales<br>• Supports public participation and engagement of stakeholders | • Increase awareness of the importance of the biophysical environment<br>• Increased acceptance of measures<br>• Reduced conflicts between project developers and local population<br>• Detection of additional impacts<br>• Joint holistic understanding among planning levels and involved actors<br>• Framework for communication and meetings<br>• Improved quality when complemented by data and models |
| **Weaknesses** | **Threats** |
| • Depends on perception of the measure and provided background information<br>• Depends on knowledge/expertise of experts<br>• Outcome depends on considered spatial scale<br>• Results with limited reliability | • Redundant and duplicate analyses<br>• Lack of experience and unclear responsibility for execution<br>• No legal obligation to include ESA in EIA<br>• Heterogeneous approach when based on experts, data and models |

**Figure 8.** SWOT analysis of the use of expert/stakeholder-based ecosystem service assessments (ESA) within Environmental Impact Assessment (EIA) studies.

## 5. Conclusions

In the European Union, there is a well-established framework for Environmental Impact Assessments, which is considered successful but faces demands for reduced time and costs. We investigate the potential of ecosystem models and ecosystem service assessments to enhance EIA processes. Our findings suggest that ecosystem models are valuable tools for environmental assessments and offer new insights. However, some argue against the use of 3D ecosystem models in EIAs due to the relatively low ecological impact of channel deepening on coastal water ecosystems and the potential increase in time and costs, which could be counterproductive.

Comparing model results with expert-based ecosystem service assessments reveals a good agreement, and experts' views generally appear reasonable. The use of ecosystem models strengthens the data foundation for evaluating ecosystem services, reduces subjectivity in expert assessments, and is expected to lessen the observed variability in expert scores. Data and model results also provide a robust basis for a data-driven ecosystem service assessment.

In our retrospective assessment of case studies, experts highlighted the importance of cultural services, suggesting that information on these services can complement EIAs. Ecosystem service assessments can be formally integrated into the European Union EIA framework and carried out within the EIA process. Our method is adaptable to the needs of coastal engineering and hydraulic projects and is both easy and quick to apply. The process does not require specialized knowledge and can be executed by educated laypersons with moderation skills. However, our approach has weaknesses and suffers from subjectivity.

The primary benefit of applying our expert-based ecosystem service assessments during the early scoping stage of an EIA is the potential to enhance cooperation and communication with stakeholders, reduce conflicts, and save time. Additionally, it could improve the compilation and addressing of stakeholder concerns, potentially reducing costs associated with unnecessary studies. For this purpose, our approach would need to be adapted into a stakeholder-based model.

The case studies in the literature focus on retrospective assessments or hypothetical future management options. Future research should investigate whether the proposed benefits of expert-based ecosystem service assessments in stakeholder involvement [20,71,73] align with expectations in 'real-world' early-stage applications. In the context of our study, this implies that our approach needs to be tested during the actual scoping phase of an Environmental Impact Assessment for a coastal water engineering project.

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## Appendix A. Complementary Data on EIA's in Both Case Studies

**Table A1.** Protected goods that were subject to the EIA in Rostock and Swinoujscie/Szczecin.

| Rostock | Swinoujscie/Szczecin |
|---|---|
| Humans, human health | Humans, human health |
| Fauna, flora and biological diversity | Fauna, flora and biological diversity |
| Soil/sediment | Soil |
| Water | Water |
| Air | Air/noise |
| Climate | Landscape |
| Landscape | Cultural heritage and other tangible assets |
| Cultural assets and other material assets | |

**Table A2.** Spatial extent, or study area, for each protected good investigated for impacts in the Rostock waterway deepening.

| Protected Good | | Spatial Extent of Investigated Impacts |
|---|---|---|
| Humans | | Sound emissions of the 35 dB(A) night isophone |
| Fauna, flora and biological diversity | Marine biotopes | 200 m around the waterway and the deposit area |
| | Riverside biotopes | Breitling and Unterwarnow, up to the paved riverbank or up to 1 m contour line for unpaved banks |
| | Macrozoobenthos and macrophytes | 200 m around the waterway and the deposit area |
| | Fish and cyclostomi | 500 m around the waterway and the deposit area, plus Unterwarnow area |
| | Marine mammals | 3000 m around the waterway and the deposit area |
| | Resting birds | Estuarine area + 500 m around the waterway and the deposit area |
| | Breeding birds | Pagenwerder, parts of the Breitling riverside system with comparatively near-natural habitat characteristics or unpaved bank boundaries as well as anthropogenically influenced parts on both sides of the development route |
| Soil | | Under-water soils of the estuary and 200 m around the waterway and the deposit area |
| Water | | The estuary and 200 m around the waterway and the deposit area |
| Climate and air | | 100 m around the waterway and the deposit area |
| Landscape | | 500 m around the waterway and the deposit area |
| Cultural assets and other material assets | | 200 m around the waterway and the deposit area |

**Table A3.** Assessment of the potential impairments or improvements of changes accruing from the waterway deepening in Rostock.

| Impairment | | | | | Improvement | | | |
|---|---|---|---|---|---|---|---|---|
| **Very High (−16)** | **High (−8 to −12)** | **Medium (−4 to −6)** | **Small (−1 to −3)** | **None (0)** | **Small (1–3)** | **Medium (4–6)** | **High (8–12)** | **Very High (16)** |
| Significantly adverse | | Insignificantly adverse | | Neither adverse nor beneficial | Insignificantly beneficial | | Significantly beneficial | |

**Table A4.** The process from application to final approval of the Rostock waterway deepening.

| | |
|---|---|
| 14 April 2009 | Application of the state of Mecklenburg–Western Pomerania to deepen the seaward approach to the port of Rostock |
| December 2010 | Forecast of expansion-related changes in ship-generated loads<br>Statement on the environmental risk assessment |
| 31 January 2011 | Feasibility study (impacts on hydrodynamic) |
| March 2011 | Environmental risk assessment with an FFH impact assessment |
| 7 May 2013 | The Federal Ministry of Transport, Building and Urban Development approves the main investigation for two variants of the channel deepening (after preliminary investigations of the expansion measure) |
| 13 March 2014 | Scoping meeting |
| 10 October 2014 | Determination of the scope of investigation |
| 2016–2018 | Inventories (ecological, geo-technical, pollutant load report, noise & air pollution, 3D-HN modeling, modeling of ship-generated wave loads |
| 18 July 2017 | Information event |
| 2018–2019 | Preparation of the application documents for the planning approval procedure (environmental impact study, landscape conservation plan, FFH preliminary assessment, expert contribution on species protection, technical contributions to the WFD and MSFD, technical planning, dredged material disposal concept |
| 26 March 2019 | Information event |
| 30 August 2019 | Application for planning approval |
| 23 September–22 October 2019 | Publication of the documents |
| 23 September–22 November 2019 | Opportunity for the public and public authorities to submit objections and comments |
| 25 February 2020 | Discussion meeting/public hearing |
| 19 May 2021 | Planning approval decision |

**Table A5.** Conclusions on the expected impacts from the EIA report in Rostock for each protected good.

| Protected Good | Conclusion on Expected Impacts |
|---|---|
| Humans and human health | No significant impacts are expected. However, the noise required a dredging prohibition during night. |
| Fauna, flora and biological diversity | Impacts are predominantly insignificantly detrimental or neither detrimental nor beneficial. Some impacts are insignificantly beneficial. In some areas, significantly adverse impacts are expected. |
| Soil | Insignificant adverse impacts are expected |
| Water | Mostly no adverse nor beneficial effects; some insignificant adverse as well insignificant beneficial impacts are expected. However, several avoidance measures were taken. |
| Air | No significantly adverse impacts are expected |
| Climate | No significantly adverse impacts; one insignificantly beneficial impact |
| Landscape | No significantly adverse impacts |
| Cultural assets and other material assets | No significantly adverse impacts |

## Appendix B. The EXCEL—Ecosystem Service Assessment Tool for Coastal Engineering Applications

| | |
|---|---|
| **Personal Information:** | |
| **Expert´s name** | |
| **Institution** | |
| **Background / Field of Expertise** | |
| **Expert´s self-assessment:** | *1 = low, 2 = medium, 3 = high* |
| Knowledge in ecosystem service assessments | |
| Knowledge in coastal engineering | |
| Knowledge in Envir. Impact Assessments | |
| Local expertize | |

| oring for Relative Importance (RI) | | | | |
|---|---|---|---|---|
| 0 | 1 | 2 | 4 | 8 |
| Not levant | Low | Moderate | High | Very high |

| Impact Scoring (=IS) | | | | | | |
|---|---|---|---|---|---|---|
| -3 | -2 | -1 | 0 | 1 | 2 | 3 |
| High decrease | Medium decrease | Low decrease | No impact | Low increase | Medium increase | High increase |

| | Ecosystem Services (ES) | Description/ Examples | Relative Importance (RI) of each ES (0,1,2,4 or 8) | Weighting Factor | Scenario after compared to the situation before the waterway deepening: Impact Score (IS) (-3 to +3) | Weighted Score (RI*IS) | Comments or questions |
|---|---|---|---|---|---|---|---|
| 1 | **Use of marine animals** | Use of wild and reared (from aquaculture) animals, e.g. fish, mussels as source for human nutrition, for energy conversion or material purposes | | *0.00* | **0** | *0.00* | |
| 2 | **Use of marine plants** | Use of wild and cultivated plants as human food source or supplements, as material e.g. as fertilizer in agriculture or reed for thatched roofs or as biomass for energy conversion | | *0.00* | **0** | *0.00* | |
| 3 | **Use of groundwater** | Using groundwater for drinking and process water | | | **0** | | |
| 4 | **Use of surface water** | Using surface water for example as cooling water in the industry or river water for drinking purposes | | *0.00* | **0** | *0.00* | |
| 5 | **Mineral substances used as material** | Material that can be used for construction, coastal protection or beach nourishment, e.g. the dredged material | | *0.00* | **0** | *0.00* | |
| 6 | **Renewable energy (abiotic)** | Using abiotic characteristics of the ecosystem for Wind energy, solar power or flow and wave energy | | *0.00* | **0** | *0.00* | |
| 7 | **Water as a transportation medium** | Use of water e.g. by cargo ships or ferries as a transport route | | *0.00* | **0** | *0.00* | |
| 8 | **Provision of space** | Provision of space that can be used, e.g. for building or for the construction of fairways. | | *0.00* | **0** | *0.00* | |
| 9 | **Genetic material of marine plants and animals** | Seeds, spores, plants or marine animals (e.g. fish or mussels) that can be used to maintain or establish a new population | | *0.00* | **0** | *0.00* | |
| 1 | **Mediation of hazardous substances and pollutants (except dilution)** | Mediation processes like filtration, decomposition, accumulation, sequestration and storage by microorganisms, algae, plants, animals or sediment e.g. filtration by mussels or decomposition of hazardous substances (e.g. oil) by bacteria | | *0.00* | **0** | *0.00* | |
| 2 | **Nutrient regulation** | Decomposition processes like denitrification or fixing processes and their effect on sediment quality, e.g. sequestration and storage of phosphor in sediment enhancing remineralization processes (e.g. formation of vivianite) | | *0.00* | **0** | *0.00* | |
| 3 | **Dilution by water exchange** | Dilution of pollutants and nutrients by water exchange between the Lagoon and the Baltic Sea | | *0.00* | **0** | *0.00* | |
| 4 | **Mediation of emmisions in the air** | Mediation of Emmisions in the air like: polluants e.g.Sulfur dioxide or particulate matter, noise e.g. from cargo ships or smell by plants and trees or wind | | *0.00* | **0** | *0.00* | |
| 5 | **Biotic sediment stabilization including coastal and flood protection** | Controlling or preventing costal erosion by decreasing flow and wave energy by biotic factors like reed belts or seagrass meadows | | *0.00* | **0** | *0.00* | |
| 6 | **Abiotic sediment stabilization including coastal and flood protection** | Regulation of wave energy and flood protection by hydromorphology e.g. by sandbanks, slowly rising foreshore or natural dunes | | *0.00* | **0** | *0.00* | |
| 7 | **Sediment deposition and erosion** | Transport and storage of sediment by currents | | *0.00* | **0** | *0.00* | |
| 8 | **Maintenance of water conditions** | Maintenance of chemical composition of seawater column and sediment like oxygen level, temperature and salinity to ensure favorable living conditions for biota or processes like remineralization of phosphorus and denitrification | | *0.00* | **0** | *0.00* | |
| 9 | **Global climate regulation** | Ecosystem contribution to carbon sequestration and regulation of greenhouse gas | | *0.00* | **0** | *0.00* | |
| 10 | **Atmospheric composition and conditions** | Regulation of air, temperature and humidity, including evapotranspiration | | *0.00* | **0** | *0.00* | |
| 11 | **Disease and pest control** | Control of the development and occurrence of pathogens such as blue-green algae or vibrions and spread and dominance of invasive species | | *0.00* | **0** | *0.00* | |
| 12 | **Biodiversity and habitat** | Maintaining nursery populations and habitats (incl. Breeding and feeding grounds) for wild plants or animals | | *0.00* | **0** | *0.00* | |
| 1 | **Active recreation and tourism** | Use of the ecosystem for recreational and sports activities such as swimming, sailing, fishing, boating or wind- and kitesurfing | | *0.00* | **0** | *0.00* | |
| 2 | **Observational recreation and tourism** | Using nature to relax, e.g. with opportunities for landscape viewing such as lookout towers or excursion boating | | *0.00* | **0** | *0.00* | |
| 3 | **Cultural and heritage** | Using the ecosystem to understand the local history or culture, such as a historic village, a tradtional fishing ground, or finding historic items that contribute to cultural heritage | | *0.00* | **0** | *0.00* | |
| 4 | **Education and scientific investigation** | Using nature for scientific studies or research and for educational purposes like excursions for students or tourists | | *0.00* | **0** | *0.00* | |
| 5 | **Landscape aesthetics** | The inherent beauty of nature | | *0.00* | **0** | *0.00* | |
| 6 | **Spirtual, symbolic or bequest meaning** | Elements of living system that have symbolic, bequest or spiritual meaning, like red list or iconic species or special landscapes etc. | | *0.00* | **0** | *0.00* | |
| | | | | *0.00* | | ***0.00*** | |
| | **Time spent for the assessment (in minutes)** | | | | | | |

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