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Estonian Marine Institute and the Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia

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AUTHOR'S CONTRIBUTIONS

Paper I Contributed to the design and planning of the research and to the conceptual development of PW4B, responsible for corresponding software application development, participated in the manuscript drafting and writing.

Paper II Led the design and planning of the research, responsible for NG SRW geoportal concept and corresponding software application development, drafting and writing the manuscript.

Paper III Contributed to the formal analysis, investigation, drafting and writing the manuscript.

Paper IV Contributed to the formal analysis, investigation, drafting and writing the manuscript.

Paper V Led the design and planning of the formal analysis, investigation, drafting and writing the manuscript.

LIST OF ABBREVIATIONS

ADSAM-G	Accidental Damage and Spill Assessment Model – Grounding
AIS	Automatic Identification System
CEA	Cumulative Effects Assessments
CSA	Common Situational Awareness
DST	Decision Support Tool
DSS	Decision Support Systems
ESI	Environmental Sensitivity Index
GIS	Geographic Information Systems
SDSS	Spatial Decision Support Systems
SDST	Spatial Decision Support Tools
PGIS	Participatory Geographic Information Systems
PM	Participatory modelling
MSP	Maritime Spatial Planning
GOFREP	Mandatory Ship Reporting System in the Gulf of Finland Traffic Area (Baltic Sea)
NG-SRW	Next-Generation Smart Response Web
NEBA	Net Environmental Benefit Analysis
PADM	Particle Dispersion Model
PW4B	PlanWise4Blue
RESI	Regional Environmental Sensitivity Index
STW	Seatrack Web
VTS	Vessel traffic service – a marine traffic monitoring system
WMS	Web Map Services

1. INTRODUCTION

1.1. Spatial decision support systems

Spatial data are data connected to a location, a place on Earth (Jankowski, 2008; Keenan & Jankowski, 2019). Based on that, spatial decision-making exploits the geographic relationships within this data to make decisions. Spatial Decision Support Systems (SDSS) combine spatial and non-spatial data, the analysis and visualization functions of Geographic Information Systems (GIS), and decision models in specific domains, to compute the characteristics of problem solutions, facilitate the evaluation of alternative solutions, and the assessment of their trade-offs.

Combinations of software and modelling, and their ease of integration has greatly extended the range of SDSS applications to the current diversity (Sugumaran & Degroote, 2012). The availability of external spatial data has allowed a richer representation of spatial problems of considerable value to decision-makers (Locander et al., 1979). While other types of DSS application have made use of external data, these data are usually closely related to the domain of the decision-maker and its integration has often proved challenging.

Spatial applications generally combine organization-specific data with data on the geographic properties and relationships of the area encompassing the decision problem, while the latter data are typically sourced outside the organization and are not specific to the organization or the decision problem. The progress of algorithmic, computational, and communication approaches both directly made SDSS technically feasible and indirectly provided the availability to users of third-party spatial data, which made SDSS applications economically feasible (Keenan and Jankowski, 2019).

The changes in SDSS are enabled by the ongoing improvements in the capacity of widely available technologies to support spatial data collection, spatial data manipulation, spatial analysis and when appropriate technology became available, SDSS quickly formed a Group SDSS, where multiple users interact in the decision-making process (Keenan & Jankowski, 2019). Furthermore, compared to traditional DSS, data from outside the organization using the DSS play a much greater role in SDSS applications, because richer decision modelling is made possible by the inclusion of relevant external data. This, however, requires reliable and secure data and information exchange platforms.

While SDSS continue to have a role in exploiting new technology and new representations, public participation systems represent a distinct and essential contribution of SDSS to the DSS field generally (Ploskas et al., 2015). Given the dynamic and complex nature of the issues that SDSS solve, making space for meaningful learning by all the different groups involved may prove advantageous since this helps them apply learned knowledge during problem-solving (Rodel et al., 2017).

When a SDSS assists in decision making in a specific field or theme, the SDSS is often referred to as a Spatial Decision Support Tool (SDST). Emergency responses, including life-threatening situations, are a critical field of application of SDST. Their complexity demands that modelling methods be available to, and user-friendly by, decision-makers, especially in challenging circumstances (Keenan & Jankowski, 2019). Emergency response systems demand rapid decision making, clarity of information display, and the viability for complex spatial decision-making to be successful (Andrienko et al., 2007).

As an example of such emergency responses, the assessment of oil spill effects should integrate risk and vulnerability, which have economic, ecological, cultural, political, geographical, and environmental consequences. The wide range of effects suggests a modular framework for SDST for oil spill response, i.e., that an ideal tool should enable incorporation of one or multiple information layers concerning the spatial effect of oil spills (Ivshina et al., 2015). Other model specifications may vary. For instance, increased oil transport in ice-covered waters presents a need to incorporate the complexities of dynamic sea ice into the preexisting hydro-dynamical models (Arneborg et al., 2017).

Another SDST example concerns changing ecosystems due to direct human activities (Raudsepp et al., 2013) and climate change (Isaev et al., 2017). Namely, intensification and diversification of human-induced pressures in marine ecosystems have raised concerns over several sustainability-diminishing consequences, such as overexploitation of resources and loss of valuable habitats. Often the relationships between environment and the biota are complex and involve high uncertainty. Due to this complexity, the applicable SDST should be as clear and simple as possible in order to give the potential users a full understanding on the outputs of the tool. Only then can policymakers and stakeholders interpret the information to identify possible strategies in the decision-making process under current and future human pressures (Rodel et al., 2017). However, because intended users sometimes fail to embrace SDST, it has been suggested that SDST should better incorporate social aspects involved in SDSS design, development, testing and use. Socio-psychological aspects of the use of SDST in creating common operational pictures are crucial, e.g., concerning information overload and the suitability of different communication methods to convey information in the SDST (Luokkala et al., 2017).

1.2. Collaborative GIS

Referring to Balram & Dragicevic (2006), collaboration deals with a shared sense of meaning and achievement in the group process and the Collaborative GIS is defined as an eclectic integration of theories, tools, and technologies focusing on, but not limited to, structuring human participation in group spatial decision processes. It is argued further that the goal of Collaborative GIS is to leverage collaboration towards a collective process, while in collective participation, the participatory group, technology, and data operate as a single fused system.

According to Rinner (2006), collaboration almost imperatively entails argumentation, that is, the exchange of personal views on certain topics, using logical reasoning; argumentation is often structured into discussions or debates with contributions by individual participants responding to each other. It is added further that collaboration and decision-making of humans usually entails logical reasoning expressed through discussions and individual arguments. Importantly, where collaborative work uses geospatial information and where decision-making has a spatial connotation, argumentation will include geographical references.

The real-time collaborative GIS possesses features common to general real-time systems, and the ability for users from different domains to collaborate on solving spatial problems and making spatial decisions simultaneously from different locations (Sun & Li, 2016). The design science research framework is a methodological approach for perceiving a real-world problem, designing, and developing a solution for the problem and then studying the solution (Dresch et al., 2015). The remarkable utility of collaborative GIS for maritime spatial planning was affirmed by the design and evaluation of Baltic Explorer CGIS application based on the DSR framework (Koski et al., 2021).

1.3. Operational oil spill response

All countries benefit from increased international commerce, because trade and consumption generate welfare. When free trade is supported, maritime traffic is often the most efficient way to transport goods among countries. However, heavy maritime traffic and oil transportation cause a significant environmental risk. To date, oil spills are ranked among the major threats to the stability of the marine environment and can have severe impacts on nearshore biodiversity and functioning (Peterson et al., 2003). The spills coat the shoreline with oil resulting in devastating consequences (Paine et al., 1996; Peterson, 2001). In subtidal habitats, responses are less known but the effects are still expected to last decades after the spill (Gundlach et al., 1983; Dauvin, 1998). Recent drastic spills have demonstrated that oil combat management has failed to achieve environmental sustainability, because decision makers lack knowledge and time to safeguard all important and vulnerable nature areas.

Oil transport in the Baltic Sea has snowballed over the last decade, the Gulf of Finland being one of the busiest oil shipping routes in the world (HELCOM, 2018a). The coastal waters of the Gulf of Finland also host environmentally valuable ecosystems, which face risk from heavy vessel traffic (Sonninen et al., 2006). However, accident statistics indicate a high level of maritime safety in the Baltic Sea, where accidents typically result in minor consequences in terms of oil pollution (Goerlandt et al., 2017; HELCOM, 2018a).

Risks of significant oil spills remain in open water (Goerlandt & Montewka 2015; Helle et al., 2015) and during winter (Valdez Banda et al., 2015; Valdez Banda et al., 2016). For example, the spill caused by the Runner-4 accident in 2006 (Wang et al., 2008) led to oil patches drifting into the shallow waters around

Tallinn with significant detrimental ecological and economic consequences. Because the effectiveness of spilled oil mechanical recovery is limited both in open water (Lehikoinen et al., 2013) and in icy conditions (Lu et al., 2019; 2020), appropriate plans and tools are needed to minimize damage to ecosystems in case of a sizeable oil spill. This task is arduous because the impact of spilt oil varies significantly by shoreline type and many clean-up methods are shoreline specific (NOAA, 2002). Therefore, strategies to contain or mitigate oil spills on or near sensitive shorelines need to establish if a response is necessary and the nature and extent of the reaction. These strategies also significantly affect the final cost of mitigation (Montewka et al., 2013).

SDSS play a role in almost all emergencies, including marine oil spills (Pourvakhshouri and Mansor, 2003; Pourvakhshouri et al., 2006). SDST represent an important aid to tactical oil spill response planning. Most SDST employ oil trajectory and weathering models to calculate how processes such as evaporation, dissolution, emulsification, dispersion, and biodegradation affect the movement of oil slicks and changes to oil slick properties (Li et al., 2016).

Recent publications of applied SDST include Ciappa (2020), Amir-Heirdari and Raie (2019), and Zodiatis et al. (2016). Unfortunately, existing operational SDST do not yet fully integrate oil slick movement and weathering with response planning. Moreover, current SDST do not thoroughly combine with information on the intrinsic value and environmental sensitivity to oil spills, such as the probabilistic approach presented by Kokkonen et al. (2010), or with operational models to estimate the spatial distribution of oil spills (Tabri et al., 2018).

1.4. Cumulative effects assessment of human activities

Maritime spatial planning (MSP) is a powerful instrument to put "ocean space" on sustainable development agendas. MSP can provide sustainable development goals, but only if the planning solutions are supported by a solid evidence-based understanding of how anthropogenic activities affect marine ecosystems. MSP makes this empirical knowledge available to diverse groups of scientists, politicians, fishermen, and entrepreneurs. As such, MSP enables stakeholders to achieve ecological, economic, and social objectives to ensure effective long-term use of marine resources and to mitigate multisectoral conflicts over the use of the sea space (Douvere and Ehler, 2010; Stelzenmüller et al., 2015.; EU, 2014; Aps et al., 2018).

Wide implementation of marine spatial plans as required by the Directive on Maritime Spatial Planning of the European Union (EU) poses novel demands for the development of SDST. Putting MSP into practice poses unprecedented challenges in the design and development of SDST, as the tools should guide decision-makers in ecosystem-based allocation of human activities at sea that can aid the sustainable use of marine living and non-living resources. In the European Union, the Maritime Spatial Planning Directive is a strong driver of development

(EU, 2014), but the same challenges to achieve environmental and socio-economic objectives are seen in many seas globally (Retzlaff and LeBleu, 2018). To achieve the goal set by MSP, the SDST should include elements to support ecosystem-based management on different geographical scales (national to macro-regional), carry out cumulative effects assessment (CEA), and facilitate communication at the science-policy interface.

Cumulative effects can be defined as impacts on the environment that result from pressures of several human activities acting together, such as shipping, fisheries, and wind parks, as caused by past, present or any possible foreseeable future actions (Judd et al., 2015). A central concept for most cumulative effects assessments (CEA) is that human activities can trigger different pressures and that these pressures affect other parts of the ecosystem (Knights et al., 2013). CEA reduce complexity and allow for a transparent assessment of uncertainty, streamline the uptake of scientific outcomes into a science-policy interface, and thereby bridge the gap between science and decision-making in ecosystem-based management (Stelzenmüller et al., 2018).

In the last decade there has been a major increase of initiatives to collect, systematise, and share MSP-relevant knowledge and to develop spatially explicit information systems to manage and process diverse geospatial information into structured and planning-relevant outputs (Kannen et al., 2016; Janßen et al., 2019). In parallel to this development, the research community has put effort into the development of specific functionalities of SDST with different planning objectives. For instance, cumulative effects/impact assessment tools were developed to understand the ecological risks and consequences of anthropogenic activities at sea on vulnerable marine resources (e.g., Stelzenmüller et al., 2013; Murray et al., 2015). The scientific community has strived to provide frameworks to review and evaluate SDST for MSP to address their effectiveness within a decision-making process, incorporate stakeholder perception and guide future development priorities. For instance, Bolman et al. (2018) provided a framework to address objectives and development processes behind DSTs, with the final aim to understand their usefulness for marine management and decision-making. Pınarbaşı et al. (2017) reviewed the most common SDST and proposed a matrix to assess their purpose, gaps, functionalities with respect to different stages of the MSP implementation and end-user spectrum. Krueger and Schouten-de Groot (2011) assessed 118 MSP tools by addressing their functionalities, success factors and stakeholder needs, based on a predefined set of criteria elaborated through literature review and interviews. Kannen et al. (2016) provided a catalogue of spatial and non-spatial tools that addresses integration challenges in MSP, their strengths/weaknesses, and their basic conditions for application. Despite this growing segment of literature, most of the studies lack a conclusion on how the efforts taken in research and the software development community have contributed to recent advancements in SDST. Manifold initiatives across European seas emerged in the last years that aimed to design geospatial information platforms oriented to MSP and ecosystem-based management (PORTODIMARE, 2020; SIMCELT, 2017; EMODnet, 2020) and capabilities of these tools need to be reviewed.

Moreover, despite this plethora of information, the existing tools for spatially explicit CEA are still limited to a simplified pressure-response system (mainly single pressure on a single or multiple nature assets) (e.g., HELCOM, 2018b). This stems from earlier research that has focused mainly on the impacts of individual pressures in isolation (e.g., Todgham and Stillman, 2013) and therefore the relative contribution of different human stressors and their interactive effects on ecosystem structure, function and services remain poorly understood. Over the last decade, however, a large body of literature has evolved that specifically targets interactive effects of multiple pressures on a large variety of ecosystem assets and their services (e.g., Przeslawski et al. 2015; Gunderson et al. 2016). Despite this new evidence on the cumulative effects of multiple pressures on the biota, the existing algorithms of CEA examine each human activity individually (e.g., commercial fishing and dredging) without addressing the combined effects of different activities and the impact scores are based on expert judgement rather than scientific evidence. This limitation renders the guidance of ecosystem-based allocation of human activities at sea highly biased, undermining achieving societal environmental and socio-economic sustainability objectives. We still lack effective communication between science and policy as there are no suitable models to disseminate the complex relationships between pressure, nature assets, and ecosystem services to stakeholders responsible for managing nature assets. Improving management strategies demands realistic and easy-to-use links from scientific knowledge to maritime policy and management of human activities affecting the marine environment (Stelzenmüller et al., 2018).

The Maritime Spatial Planning Directive 2014/89/EU establishes a framework for MSP aimed at promoting the sustainable growth of maritime economies, the sustainable development of marine areas and the sustainable use of marine resources. The directive defines the MSP as a process by which the relevant Member State's competent authorities analyse and organise human activities in marine areas to achieve ecological, economic, and social objectives. The Estonian MSP addressed cumulative effects of different planning options in two ways. First, the draft included some generic descriptions of the individual and synergistic effects of various human activities on different nature assets with no specific spatial analyses. Second, whenever spatial information on human activity was available, the PlanWise4Blue (PW4B) tool (**I**) developed by this thesis was used to predict the individual and synergistic effects of all these human activities, either those currently present or those planned for future implementation.

The Estonian MSP recognizes offshore wind energy production and herring fishery as critical economic drivers in the marine region. Environmental effects related to the establishment of marine wind parks have not yet been described in relevant detail (e.g., Dannheim et al. 2019). However, increasing evidence linking wind park construction with environmental change must be considered when assessing cumulative impacts on the marine environment. For example, the construction of offshore wind farms damages the reproduction potential of fish stocks. It should be done without physically disturbing fish spawning grounds or at least relieving disturbance during critical spawning periods. In addition, sediment dispersal in important recruitment habitats for fish and during reproduction times should be avoided, and other adverse effects such as electromagnetic fields should be minimized (Bergström et al., 2012). On the other hand, once construction finishes, offshore wind parks provide rigid, stable, and elevated substrates favourable for reef-forming biota as spawning habitats for many fishes, thereby enhancing spawning (Šaškov et al., 2014). Yet internationally regulated open sea pelagic trawl fishing itself imposes a direct adverse impact on the efficiency of herring stock recruitment, an effect that also requires assessment (Lundin, 2011). In trawl fisheries, the survival of young herring selected from the trawl cod-end is low. The trawl fishery removes a larger amount of age 0 to 1 herring from the stock than indicated by landing statistics (Suuronen et al., 1996a, 1996b).

Maritime transport is estimated to grow globally and in the Baltic Sea (e.g., HELCOM, 2018a). Larger port areas on land and deeper fairways would probably be needed. Still, opportunities for port expansion are confounded by their proximity to conservation areas and adverse effects posed on different nature assets. Therefore, shipping itself and maritime efforts to sustain shipping (e.g., dredging, dumping, mining) will exert considerable pressure on marine habitats (including herring spawning grounds), birds and seals.

Finally, the planning also incorporated novel aquaculture sectors in the Baltic Sea area (i.e., mussel and macroalgal farming). These aquaculture types are considered the most promising compensatory measures to mitigate increased eutrophication in the Baltic Sea. Both algae and mussels store nutrients, which are removed from the marine environment upon harvesting. These activities can significantly enhance local water quality, which improves the condition of benthic habitats and favours associated fish, bird, and mammal populations (Lindahl et al. 2005; Gren et al. 2009). In other words, it is vital that the evaluation of the human impact on nature assets also focus on possible benefits because it provides insight on possible remediation measures.

1.5. Objectives

The thesis has three overarching objectives: (1) to review and synthesise the capabilities of current SDST for MSP in the European seas; (2) to develop novel state-of-the-art SDST for ecosystem-based marine management based on the theoretical framework of the Real-time Collaborative GIS (Sun & Li, 2016) and (3) to test the developed SDST in pilot areas.

First, when reviewing the capabilities of current geospatial SDSTs, 14 criteria were used to analyse the conceptual (e.g. SDST objectives, functionalities or user-developer community), technical (e.g. programming language, software framework, data input) and practical aspects (e.g. stakeholder engagement, SDST application in MSP process) of the following DSTs: Mytilus, Tools4MSP Geoplatform, Symphony, the Baltic Sea Impact Index (BSII), PlanWise4Blue (PW4B) tool and the MSP Challenge Simulation Platform including Ecopath with Ecosim. Particular attention was paid to cumulative effects assessment (CEA) capabilities, a functionality that is present in all the screened SDST (**III**). As a subtask of this objective, the status and prospects of integrating the concept of ecosystem service in some of these geospatial tools was also assessed (**IV**).

Under the second objective, the Next-Generation Smart Response Web (NG-SRW) tool (**II**) was developed by this doctoral study to alleviate the limitations of the existing SDST for oil spill response planning, particularly in the Gulf of Finland. The NG-SRW is a web-based application intended to provide a quasi-real-time dynamic assessment of the oil spill potential effect on sensitive shorelines, biological and human-use resources. Importantly, when defining sensitivities of shorelines and associated nature values, the application incorporates relationships between the magnitude of oil spill and the resilience of the biota in the Gulf of Finland (Kotta et al., 2008a; Leiger at al., 2012). In this SDST the expected spread of oil spill is predicted using the direct web-based access to external Seatrack Web (STW) particle dispersion model (PADM) weather-driven 3d-simulation (Ambjörn et al., 2011). The relevant information (the plausible spread of oil spill and expected environmental damage) is tailored to match the needs of the targeted end-users. Finally, a preliminary test of the integrated NS-SRW tool has been executed in a stakeholder workshop with maritime professionals and the results indicate that the tool may be useful for specific oil-spill response related organizations and that it is relatively easy to understand and use (Goerlandt et al., 2019). Currently, the NG-SRW tool is operational in Estonian marine and coastal areas; however, the SG-SRW system has yet to be tested practically in case of a future oil spill.

A second example of SDST for ecosystem-based marine management developed during the thesis and presented here is the PlanWise4Blue (PW4B) tool (**I**). The tool is a free-to-use resource, available online for marine managers and policymakers without scientific backgrounds and based on the best available scientific data. The tool combines existing scientific evidence with an expert judgement which is then communicated through a dynamic online tool to environmental managers and the public. Most importantly, the PW4B tool can quantify the single and synergistic effects of most important human activities on a broad range of nature assets. As such, the newly developed CEA analyses centres on the most up-to-date scientific knowledge and data on different nature assets and specific pressure effects rather than subjective expert judgements (**I**, **V**).

Under the third objective, we employed the PW4B tool in two case studies. The first case study covered the entire Estonian marine area and assessed the environmental effects of the Estonian MSP. Results of this study informed managers of the environmental sustainability of Estonian planning solutions. In the planning process, the cumulative environmental effects of the combined effects of human activities (fisheries, aquaculture, wind energy, mining, and maritime transport sectors) were assessed on nature assets (selected seaweed, invertebrate, fish habitats, as well as bird and mammal species) to suggest effective mitigation strategies and to attain sustainable planning solutions (**I**).

The second case study employed the PW4B tool to predict the environmental consequences of plausible management scenarios on benthic habitats in Estonian waters (**V**). These scenarios focus on different types of human pressures: nutrient loading (managed on land), wind park development (managed at sea), and non-native species (practically unmanageable pressure when non-indigenous species have already established in the area). The nutrient loading scenarios included a business-as-usual projection (the current amount of nutrient input) and the HELCOM Maximum Allowable Inputs (MAI) target (nutrient input reduced by 25%). Wind park scenarios included the projected offshore wind farm areas according to the Estonian maritime spatial plan (Estonian MSP, 2020). The non-native species scenarios included the two most influential invasive species in the region: Ponto-Caspian round goby, *Neogobius melanostomus*, and North American mud crab, *Rhithropanopeus harrisii*. Both species arrived in the north-eastern Baltic Sea in the early 2000s (Ojaveer, 2006; Kotta & Ojaveer, 2012) and have since significantly modified local coastal environments, the latter being associated with intensifying symptoms of eutrophication (Ojaveer et al., 2015; Kotta et al., 2016; Kotta et al., 2018).

2. MATERIALS AND METHODS

2.1. Study area

2.1.1. Oil-spill response study

The Gulf of Finland hosts environmentally valuable ecosystems within the Baltic Sea while also playing a vital role in the economic and social prosperity of its adjoining countries (Sonninen et al., 2006). Concern continues to mount over the detrimental effects of accidental oil spills on both the Gulf of Finland's ecosystems and its economic and social prosperity. Consequently, national authorities around the Baltic Sea have committed to implementing a pollution response system to respond to pollution incidents that threaten the marine environment. This agreement includes engaging in contingency planning, surveillance, sharing information, and providing appropriate mutual assistance (HELCOM, 2013).

In the Gulf of Finland region, this response system is operational and continues to be advanced, with, for instance, the recent development of a maritime simulator for oil spill response training (Halonen & Lanki, 2019) and the addition of the Mandatory Ship Reporting System in the Gulf of Finland Traffic Area (GOFREP) – established by IMO in 2003 (IMO, 2003) and in operation since 2004 – to improve navigation safety to prevent accidental ship-based spills. GOFREP provides mandatory ship reporting, including identification and monitoring of vessels, strategic planning of vessel movements and provision of navigational information and assistance, in both international and national (VTS – vessel traffic services) waters within the Gulf of Finland (IMO, 2006). The mandatory ship reporting system in the Gulf of Finland is shown in Figure 1.

GOFREP is managed jointly by the Finnish Transport Agency, the Estonian Maritime Administration, and the Federal Agency for Maritime and River Transport of Russian Federation and under the auspices of GOFREP Traffic Centres of Estonia (Tallinn Traffic), Finland (Helsinki Traffic) and the Russian Federation VTMIS Centre in Petrodvorets (Saint Petersburg Traffic).

The targeted end-users for SDSS oil spill response are primarily the national maritime administrations responsible for oil spill response operations and the regional response secretariat. In addition, the SDSS involves VTS operators as well as stakeholders representing the societal environmental, economic, and social interests, whose interests can be affected by oil spills. Given the numerous user types and their wide geographic locations, a web-based platform is the optimal strategy for improving oil spill response and related issues.

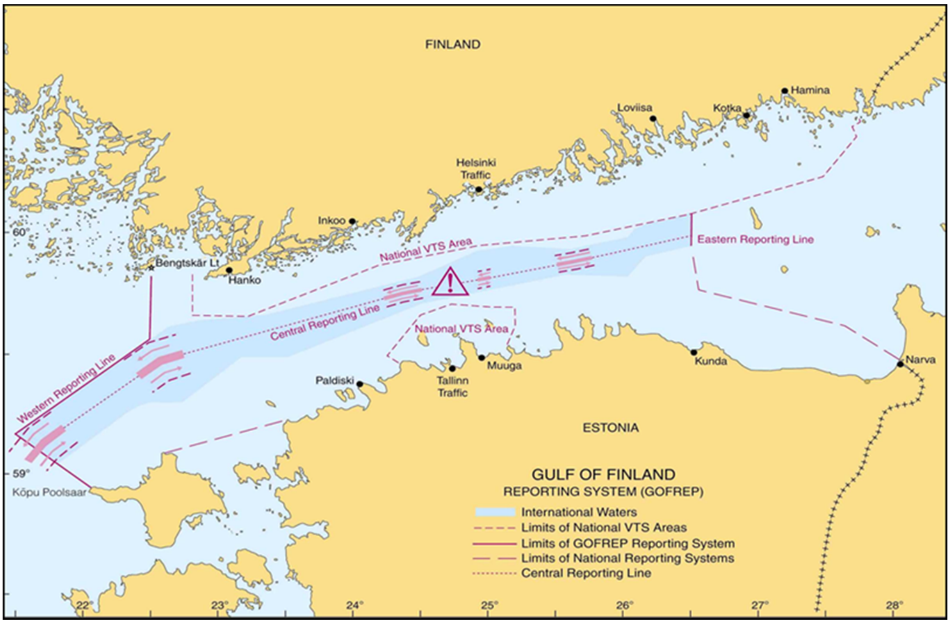

Figure 1. The mandatory ship reporting system in the Gulf of Finland (Baltic Sea), (**II**, Fetissov et al., 2020).

2.1.2. Cumulative effects assessment study

Coastal waters of Estonia belong to north-eastern part of the Baltic Sea. The Baltic Sea is a semi-enclosed brackish waterbody which lacks a tidal cycle and therefore, an intertidal habitat. The low salinity allows only a few marine species to extend their distribution to the north-eastern part of the sea with freshwater species restricted to even more diluted bays and estuaries (Kautsky and Kautsky, 2000). Low species richness and the presence of organisms near their physiological tolerance renders vulnerable the whole ecosystem of the Baltic Sea (Bonsdorff & Blomqvist, 1993; Westerbom, 2006).

The coastal waters of Estonia are characterized by different environmental gradients (e.g., salinity, wave exposure) and complex topography, including extensive shallows. Salinity can be above 7 in the Baltic Proper, while river inflows reduce salinity to nearly zero in the inner parts of some bays. Areas highly exposed to waves are characterized predominantly by the presence of hard substrate, such as limestone cliffs or granite boulders. Moderately exposed areas typically contain sediments of sand, gravel, and pebbles. Bottom sediments in most sheltered bays along the coastline consist predominantly of fine sand and silt. Although the summer temperature of surface water in some bays can occasionally reach 28 °C, summer temperatures are usually < 20 °C and ice cover in winter may remain for over three months. There exists a gradient in trophic conditions from highly eutrophicated waters in sheltered bays to moderately eutrophied open sea (Kotta et al., 2008b).

2.2. Methods

2.2.1. Analysing SDST for MSP in the European seas

In total six SDST supporting different aspects of MSP were analysed (Figure 2): Mytilus (Hansen, 2019), Tools4MSP (Menegon et al., 2018a and b), Symphony (Hammar et al., 2020), Baltic Sea Impact Index (BSII; Bergström et al., 2019), PlanWise4Blue (PW4B; **I**) and the MSP Challenge Simulation Platform (Abspoel et al., 2021). We selected these SDST because (1) these were considered the most long-lasting and advanced SDST for MSP-oriented investigation applied at European level; (2) these were applied and tested across different stakeholder groups, including experts and non-experts, and at national and transboundary levels in their respective study domains; and (3) they can be flexibly applied for both national marine spatial plans and macro-regional studies (**III**).

In Table 1 an overview of the six SDST is provided, in terms of application domains, the tools implemented and key references to the SDST. Notable is that two BSII and Mytilus are applied in the Baltic Sea, Tools4MSP is applied in the Adriatic-Ionian Region (Mediterranean Sea), MSP Challenge Simulation Platform is applied in the North Sea, Baltic Sea and Firth of Clyde and PW4B and Symphony are applied on national level, respectively in Estonia and Sweden (**III**).

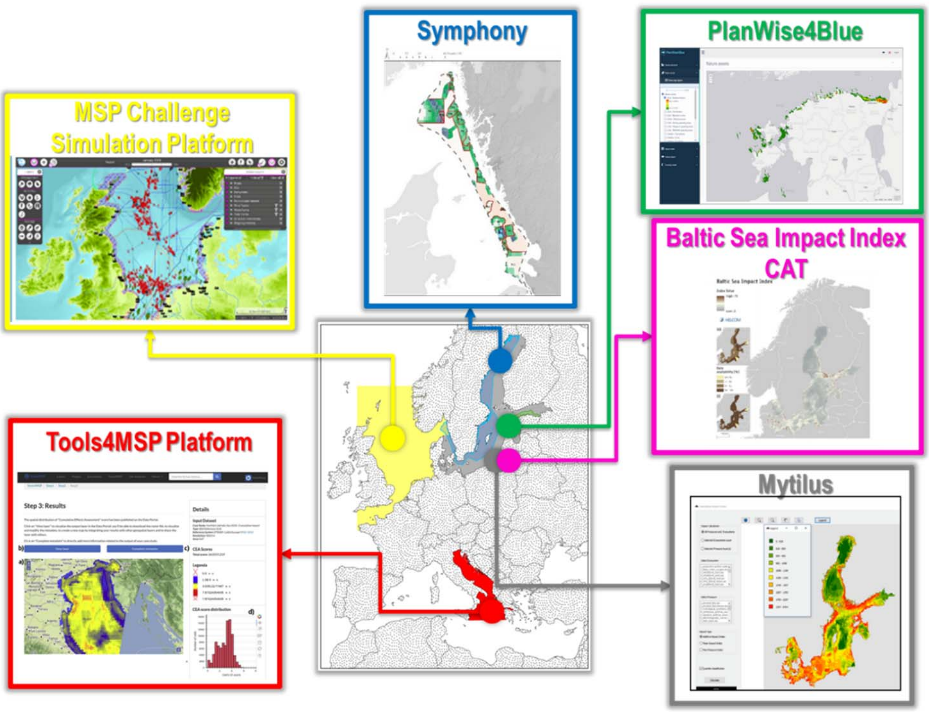

Figure 2. The six SDST reviewed in this study including geographic areas of application (**III**).

Table 1. Summary of SDST, their domains, tools and sources. Note: CEA – Cumulative Effects Assessment, MUC – Maritime Use Conflict (**III**).

DST	Application Domain	Tools	Sources
Mytilus	Baltic Sea	CEA	BONUS BASMATI, 2020; Hansen 2019
Tools4MSP Geoplatform	Adriatic-Ionian Region	CEA, MUC	Menegon et al., 2018a and b; Farella et al., 2020; PORTODIMARE, 2020
Symphony	Sweden	CEA	Hav, 2019; Hammar et al., 2020
Baltic Sea Impact Index Impact Assessment Tool (BSII CAT)	Baltic Sea	CEA	Bergström et al., 2019; PanBalticScope, 2019
PlanWise4Blue	Estonia	CEA	PlanWise4Blue, 2020; **I**
MSP Challenge	North Sea. Baltic Sea, Firth of Clyde	CEA	MSP-Challenge, 2020; Steenbeeck et al., 2020; Abspoel et al., 2021

The SDST developers and managers were engaged in this research using a questionnaire that helped organize responses in a systematic manner. The questionnaire covered the following aspects, specific criteria can be found in **III**:

1. Conceptual aspects – describes the objective, the functionalities of the SDST and characterizes its developer and user community. This aspect refers to 4 criteria.
2. Technical aspects – describes the technical implementation of the SDST in terms of programming language, framework, data inputs, graphical user interface, API and other services and the source code availability. This aspect refers to 4 criteria (25 questions)
3. Practical aspects – describes the practical outcomes in terms of support to MSP process, application on national and or on pilot study level, link of the functionalities to support decision making. This aspect refers to 5 criteria.
4. CEA-capabilities – describes the assessment criteria under consideration of the cumulative effects assessments instrument supported by the SDST. This includes the CEA definition, CEA model characteristics, key assumptions, means to propagate pressures, pressure-biota interaction application context of the CEA, means to assess and communicate uncertainty. In total 7 criteria were identified.

The results of the evaluation of the SDST against the four aspects were investigated using Sankey diagram based on ggplot2 and ggalluvial library from R programming (CRAN Repository Maintainers, 2020). Sankey diagrams are particularly useful to visualize the relationship of each DST to each specific criterion.

Here, the status and prospects of integrating the concept of ecosystem service in some of these geospatial tools was also assessed using a mixed method approach of literature review and structured questionnaire at case studies (**IV**).

2.2.2. Oil-spill emergency response framework

Oil spill response is an extremely complex and challenging cross-disciplinary activity. In the decision-making process, it combines a wide range of issues and activities under emergency conditions that include the nature of the material spilled, changes in physical and chemical properties (weathering) and biodegradation, local environmental conditions, sensitivity of impacted natural resources, and effectiveness of response/clean-up technologies (Ivshina et al., 2015). As a complex, dynamic, and distributed operation, oil spill response involves multiple actors (Luokkala and Virrantaus, 2014).

The scope of emergency oil spill response SDST usually covers the short-term predictions of spill behaviour and movement for tactical response planning, and marine and coastal impacts, usually restricted to acute ecosystem impacts (Chang et al., 2014). Adapted framework for classifying oil spill response and impacts is presented in Figure 3. Hence, based on a review by Li et al., (2016), it is found that most SDST focus on the elements 1B, 2A, and 3A, whereas some tools also consider elements 1A and 2B as a part of the tools.

Referring to IPIECA (2005), "Once oil has been spilled, urgent decisions need to be made about the options available for clean-up, so that environmental and socioeconomic impacts are kept to the minimum. Getting the correct balance is always a difficult process and conflicts inevitably arise which need to be resolved in the best practicable manner. The advantages and disadvantages of different responses need to be weighed up and compared both with each other and with the advantages and disadvantages of natural clean-up, a process sometimes known as Net Environmental Benefit Analysis (NEBA)". NEBA is one of the considerations used to select spill response equipment that will effectively remove oil, are feasible to use safely in particular conditions, and will minimize the impact of the spill on the environment.

To support NEBA, knowledge of the marine and coastal ecosystem and human use values is required by a decision maker. Environmental Sensitivity Index (ESI) maps have been an integral component of oil-spill contingency planning and response in the United States since 1979, serving as a quick reference for oil spill responders (NOAA, 2002). The ESI maps rank shorelines into 10 classes in relation to sensitivity, natural persistence of oil, and ease of clean-up. They also provide information on coastal biological and human-use resources sensitive to oil spills.

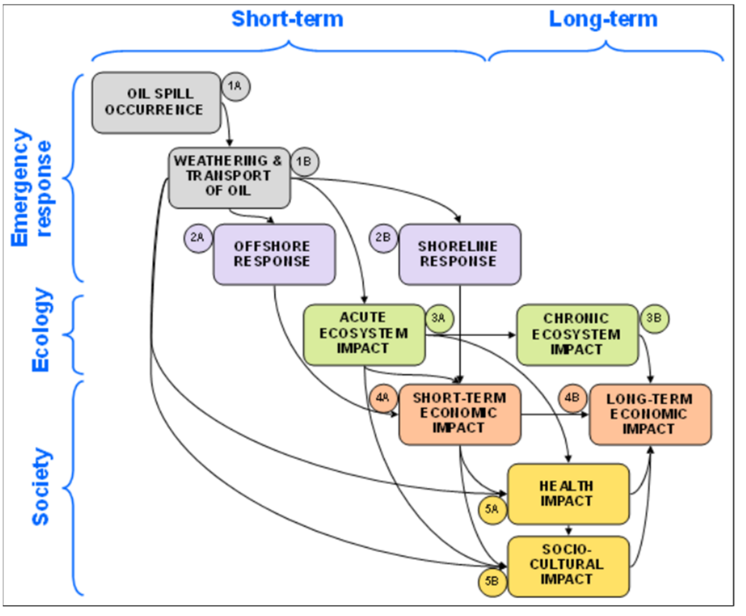

Figure 3. Framework for classifying oil spill response and impacts (**II**, modified from Chang et al., 2014).

The ESI framework was developed to reduce the environmental consequences of a spill and to help prioritize the placement and allocation of resources during clean-up efforts (Jensen et al., 1998). One of the primary objectives of oil spill planning and response, after protecting human life, is to reduce the environmental consequences of the spill and the clean-up efforts. This objective is best achieved if the locations of sensitive resources are identified in advance.

Some countries outside the US have adopted the ESI approach to classify their own shorelines for similar oil spill contingency planning. Within the Gulf of Finland context, the resulting maps are referred to as Regional Environmental Sensitivity Index (RESI) maps (Aps et al., 2016a). Furthermore, it is stated that shores cannot be handled as static systems, implying that shore classification systems, including ESI and RESI classifications, must consider shore dynamics (Aps et al., 2014).

In the Baltic Sea context, the Bayesian inference to oil spill-related situation assessment is used to facilitate the NEBA-based decisions in selecting the best available oil spill response alternative, and in evaluating the threat or probable overall environmental impact of the spill (Aps et al., 2009a; Aps et al., 2009b).

An initial version of a SDST integrating oil drift and ecosystem information layers was proposed by Fetissov & Aps (2011) and Haapasaari et al. (2014), and an initial conceptual outline of a more integrated spill response SDST by Aps et al. (2016a).

In this thesis the Next-Generation Smart Response Web (NG-SRW) tool was developed to support the informed decisions on oil spill response (**II**). The NG-SRW is a web-based application intended to provide a quasi-real-time dynamic assessment of the potential effect of oil spills on sensitive shorelines, biological and human-use resources. Oil pollution related ecological sensitivity maps, ESI and RESI map layers are used in combination with the Seatrack Web simulation results to assess the threat to sensitive environments and to decide on the most appropriate response actions. The NG-SRW considers the environmental sensitivity to oil spills by incorporating physical environment and community ecology into ecosystem models. First, relationships between the magnitude of oil spill and the resilience of coastal biota were established, and second, the assessment on how environmental variability modulated ecosystem response to oil spills was made (Kotta et al., 2008a; Leiger at al., 2012). Consequently, it becomes possible to operationally allocate oil combating resources to those areas that need the most protection in the case of oil accident. The targeted end-users for NG-SRW are primarily the national maritime administrations responsible for oil spill response operations and the regional response secretariat. In addition, the NG-SRW involves VTS operators as well as stakeholders representing the societal environmental, economic, and social interests whose interests can be affected by oil spills. The detailed architecture and functionalities of the NG-SRW tool is presented in the Results section.

2.2.3. The calculation of CEA in the PlanWise4Blue (PW4B) web portal

Accurate CEA assessments require solid ecological understanding of cause-effect relationships between pressures and biota and sound estimates of associated uncertainties. Because the total effect is not the sum of single effects, but interactions overwhelmingly prevail in nature, it is essential that the synergistic effects of different pressures on nature assets are also quantified and integrated into the assessment. The existing assessments for the Baltic Sea region and for other European waters, however, are not yet able to incorporate this complexity and express impact as the sum of the individual effects of different pressures on different nature assets. Moreover, these assessments are based largely on expert judgement and not original data (e.g., HELCOM, 2018b).

The procedure first involved meta-analysis of published or raw data that indicated separate and/or synergistic effects (either from experimental manipulations or ecosystem changes observed before and after impact). Then effect coefficients and their corresponding uncertainty are calculated (**I**).

Mathematical formulae to calculate effect coefficients (effect sizes) require logarithmic mean of a human-induced impact e_i (or series of impacts) and the logarithmic mean of a control e_c.

$$E_i = \ln(e_i) \text{ and } E_c = \ln(e_c)$$

The effect of an individual study (E_S) is defined as the difference between the impact (E_I) and the control (E_C):

$$E_S = E_I - E_C$$

The uncertainty of E_S (U_S) is calculated from the 95% confidence interval of the impact (U_I) and the control (U_C):

$$U_S = \sqrt{{U_I}^2 + {U_C}^2}$$

If necessary (different studies report different error measurements), the 95% confidence interval (U) can be calculated from the standard deviation (SD) or standard error (SE):

$$U = SD * t_{0.05(2),N-1}/\sqrt{N}$$

$$U = SE * t_{0.05(2),N-1}$$

where N is the number of samples and $t_{0.05(2),N-1}$ is the t-score.

Then the effect coefficients (effect-size estimates) are linked to existing spatial prediction of different nature assets into a cumulative effect assessment framework (e.g., Liversage et al. 2019). Some of these pressures are largely manageable and some are not (e.g., non-indigenous species) and to assess the existing unmanageable pressures, the developed assessment scheme considers the cumulative effects of manageable pressures with respect to unmanageable pressures.

The PW4B tool integrates maps of different pressures and nature assets using pressure – nature asset specific effect coefficients by incorporating effect coefficients derived from literature-based and data-driven meta-analysis. When effect evidence is lacking, expert knowledge is used to estimate the effect coefficients. Although effect coefficients of some combinations of pressures still rely on expert judgement rather than empirical data, the PW4B tool will in future use more objective input as new data become available (**I**). The calculation of effect coefficients and their corresponding uncertainty depends on the type of data or summary statistics available. Standard errors for model predictions were calculated by bootstrap (100 replications) using the “dpd” R package (Greenwell, 2017).

The spatial resolution of the cumulative effect model of the PW4B tool is 1 km^2, and the temporal timescale is 1 year. PW4B runs a CEA assessment by first analysing the spatial distribution of different human activities in the Estonian MSP. In this analysis all Estonian sea areas are classified based on the unique combinations of human activity found in each area (Figure 4). The nature-value and pressure-specific coefficient of cumulative effect in each region of interest is then multiplied by the respective value of the nature asset (e.g., the density of wintering birds) to ascertain the expected changes of this nature asset (Figure 5). The established methodological framework for CEA is updated dynamically by incorporating both the map layers of nature assets as well as the matrix of the separate and interactive effects of human use on nature assets. The CEA methodology allows different stakeholders to examine different spatial allocation scenarios and assess the expected extent of environmental effects of each scenario.

The cumulative effect matrix represents impact coefficients derived from literature-based and data-driven meta-analysis. The nature-value and pressure-specific coefficient of cumulative effect in each region of interest is then multiplied by the respective value of the nature asset to ascertain the expected changes of this nature asset. The resulting map represents the predicted cumulative effects of the studied human pressure on this nature asset.

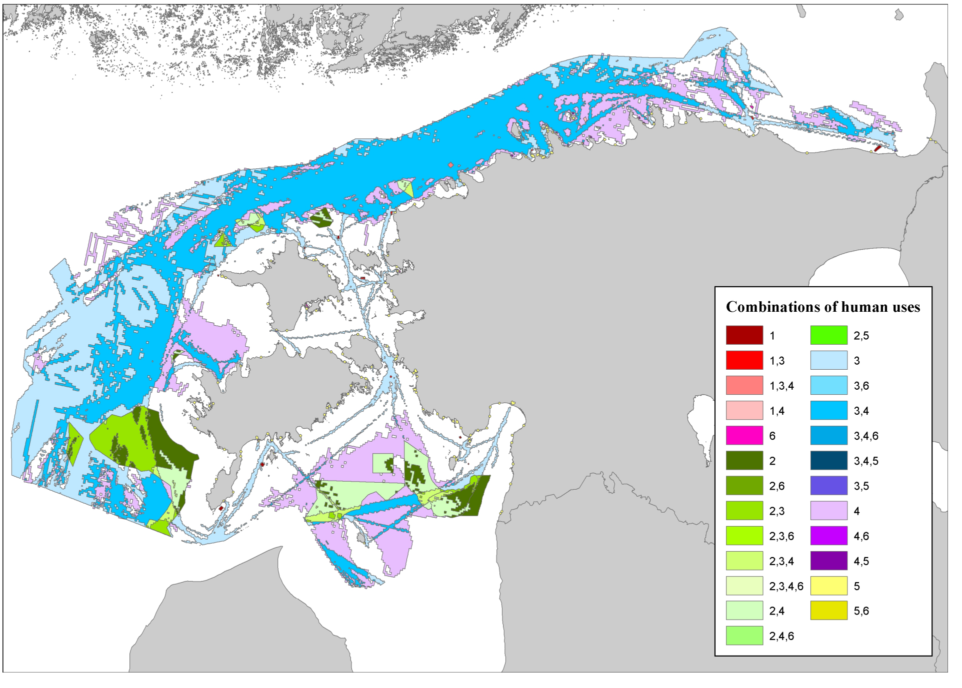

Figure 4. Different combinations of human activities in the Estonian MSP. The code of pressures are as follows: 1 – dredging, 2 – areas suitable for wind energy development, 3 – shipping, 4 – open-sea pelagic trawl fishing, 5 – harbours, 6 – areas dedicated for mining (**I**).

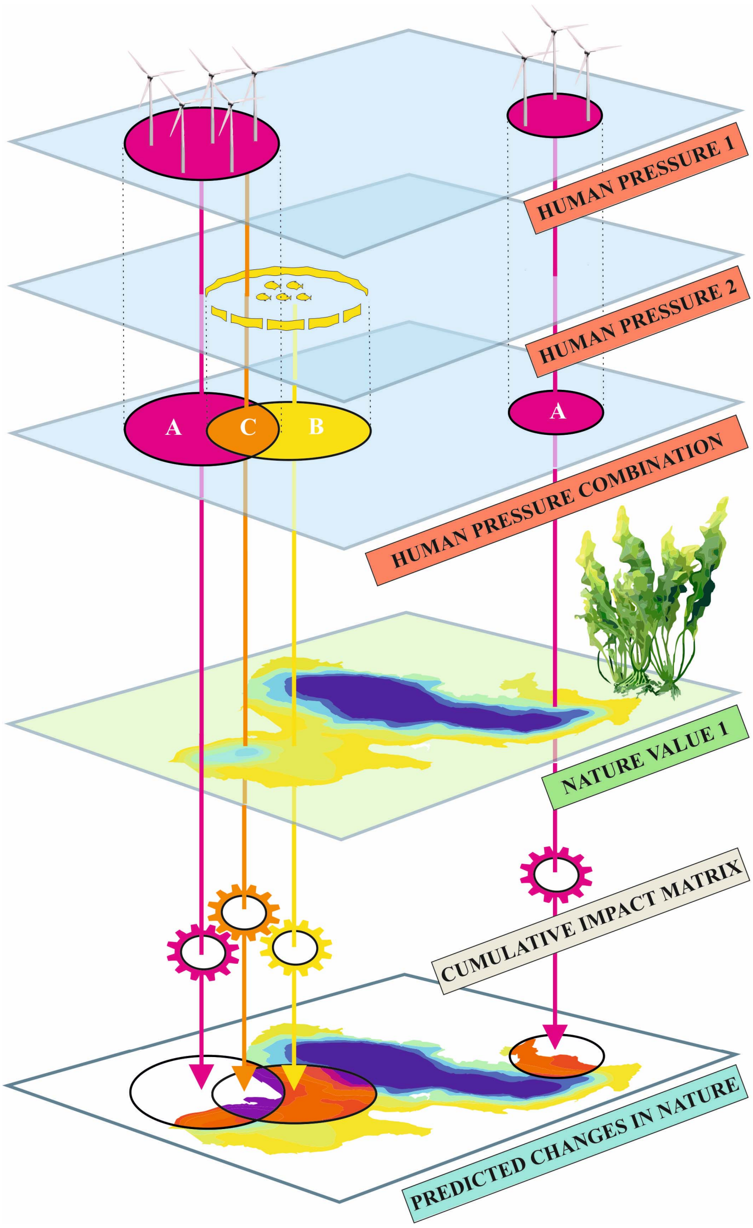

Figure 5. A schematic representation of the cumulative effect assessment of the PW4B portal. The portal first classifies the region of interest based on the unique combinations of human activity found in each area. In this example, separate and interactive effects of the two pressures (human pressure 1 = wind park, human pressure 2 = aquaculture development) are applied on a single nature asset (nature value 1 = seaweed habitat) (**I**).

In another study (**V**) where the PW4B tool was used to predict the environmental consequences of possible futures on benthic habitats in Estonian waters the following scenarios were used:

1. Current nutrient load
2. Future nutrient reduction (HELCOM MAI target of 25% nutrient reduction)
3. The presence of non-native species (round goby and mud crab)
4. Projected wind parks (according to the Estonian maritime spatial plan)
5. Current nutrient load + non-native species
6. Current nutrient load + non-native species + wind parks
7. Future nutrient reduction + non-native species + wind parks

Through these scenarios we could assess the relative impact of different human pressures on benthic environments as well as evaluate the effects of management scenarios that involve more than one human pressure. These spatial effects of these human pressures (current and projected) were generated by the PW4B portal (**I**).

3. RESULTS AND DISCUSSION

3.1. Capabilities of current SDSTs for MSP in the European seas

The studied SDST are designed to target multiple objectives (**III**). Among the objectives identified the most recurrent are: (1) Supporting ecosystem-based management (Mytilus, Tools4MSP, MSP-Challenge, BSII-CAT), (2) contribute to the National MSP process (PW4B, BSII CAT), (3) support decision makers in planning scenario building (Mytilus, MSP-Challenge), (4) increase MSP knowledge through a data platform (Tools4MSP and BSII-CAT) and (4) provide means for CEA analysis (Mytilus, PW4B).

The tools have been developed in a variety of settings with academic institutions as the main developers: MSP Challenge (Breda University of Applied Science), PW4B (Estonian Marine Institute, University of Tartu) and Mytilus (Aalborg University, Denmark). The Tools4MSP software was developed by the national research institution, namely the National Research Council – Institute of Marine Sciences (CNR-ISMAR, Italy). Symphony is the only SDST developed by a national planning agency, the Swedish Agency for Water and Marine Management (SwAM). The BSII CAT was developed under an international regional sea convention (HELCOM, Baltic Sea Environment Protection Commission) with support from its contracting parties. On overall, target users are national and regional planning authorities and decision-makers that need tools to support their MSP and marine environmental management processes. Other users are academic and research institutions, private sector, NGOs, students, and the general public. The Sankey diagram illustrating the conceptual aspects reviewed in the six DSTs: objectives, functionalities, developers, and users is presented in Figure 6 (**III**).

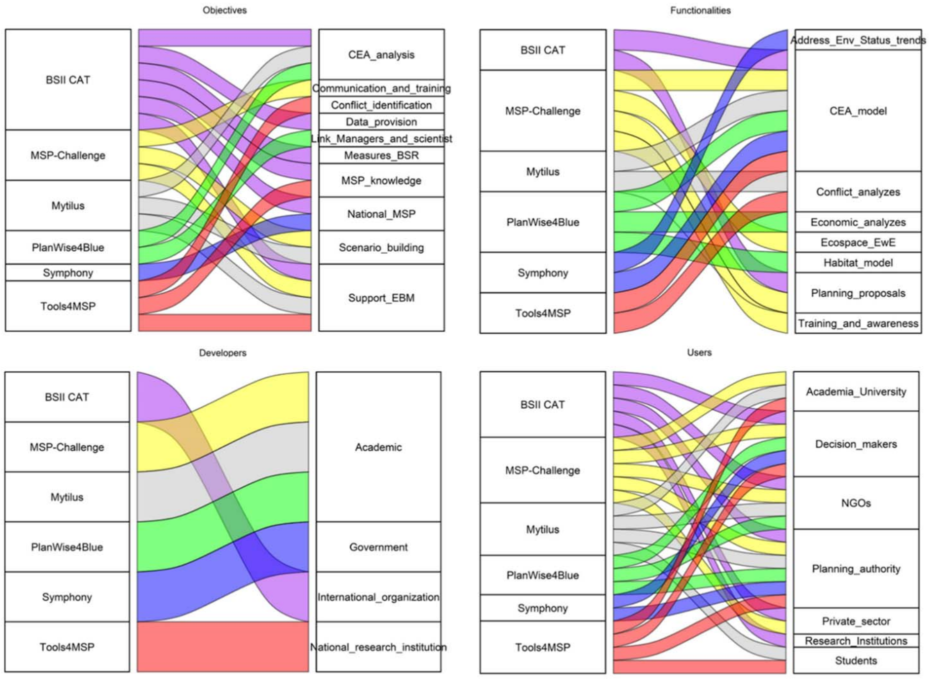

Figure 6. Sankey diagram illustrating the conceptual aspects reviewed in the six SDST: objectives, functionalities, developers, and users (**III**).

Three of the reviewed SDST are desktop-based (Mytilus, MSP Challenge, BSII), while Tools4MSP, Symphony, PW4B and BSII-CAT are web-based, and therefore do not require any installation setups. The most used programming languages (Figure 7) for SDST development are Python (Tools4MSP and BSII CAT) and Javascript (PW4B, Symphony). Mytilus was developed in Delphi 10.1 Integrated Development Environment (IDE) for high performance calculations, MSP Challenge uses the .NET Framework and Symphony is coded in Java. The software framework used for the SDSTs are distinct and include the ArcGIS (MSP Challenge and BSII CAT), Unity (MSP Challenge), Geonode and (Tools4MSP), Delphi 10.1.IDE (Mytilus) and ASP NET MVC (PW4B) (**III**).

The Graphical User Interfaces (GUI) provide different functionalities, such as exploration and visualization of geospatial data (all SDST), up- and downloading of geospatial data, sharing of data and knowledge (MSP Challenge, Tools4MSP and BSII CAT), and the possibility to run geospatial tools and visualize results (PW4B, Tools4MSP and Mytilus, BSII CAT). MSP Challenge supports the interactive and collaborative development of spatial plans and provides access to a knowledge base on the MSP process and the anthropogenic and ecological characteristics of the study region. The Sankey diagram illustrating the technical aspects reviewed in the six SDST: programming language, software/software framework, GUI functionalities, input data and source code availability is showed in Figure 7 (**III**).

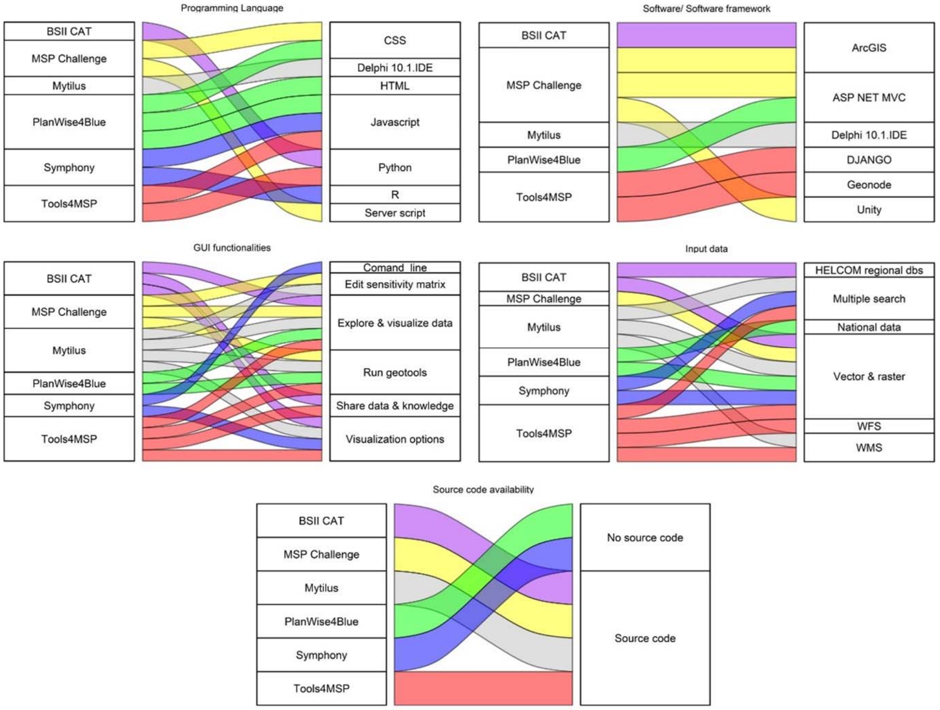

Figure 7. Sankey diagram illustrating the technical aspects reviewed in the six SDST: programming language, software/software framework, GUI functionalities, input data and source code availability (**III**).

Most SDST focus on the analysis of current conditions and the analysis of future conditions of the IOC-UNESCO Step-by-Step approach to MSP (Ehler and Douvere, 2009). Mytilus, Tools4MSP, Symphony and MSP Challenge also support stakeholder engagement. Implementation and validation of actual plans depend on formal adoption by national or regional authorities (Douvere and Ehler, 2010). SDST like Tools4MSP have been applied in MSP pilot studies, such as for the Emilia-Romagna Region (Barbanti et al., 2017; Farella et al., 2020). Symphony has been used in the development and assessment of the Swedish national MSP by SwAM (HaV, 2019; Hammar et al., 2020). The BSII CAT was recently evaluated and developed in relation to the assessment of transboundary aspects during MSP (Bergström et al. 2019). MSP Challenge has been used to engage stakeholders in the North and Baltic Seas, and the Clyde marine area; and PW4B was used within the Estonian MSP process (Estonian MSP, 2020; Nõmmela et al., 2019; **I, III**).

Uncertainty analysis is an essential component to address the inherent complexity of marine ecosystems and their interactions with anthropogenic activities (Carr et al., 2003; Wilson 2017). Most surveyed SDST do not provide explicit functionalities to visualize or treat uncertainty. The exception is Symphony, which provides data quality and availability maps, although currently only outside of the tool. The most common strategy to address uncertainty in the SDST is by reporting uncertainty in data through a dedicated metadata section of the geospatial dataset (Symphony, BSII CAT and Mytilus) (**III**). For PW4B uncertainty was not communicated through the SDST when the cumulative effects of the Estonian MSP were assessed, but the calculation algorithms include the errors of the nature asset assessment and sensitivity scores, i.e., those arising from the literature-based meta-analysis (**I**). The Sankey diagram illustrating the practical aspects reviewed in the six SDST: Application in MSP pilot, steps in MSP process, uncertainty communication, stakeholder use of SDST and outputs communication is presented in Figure 8.

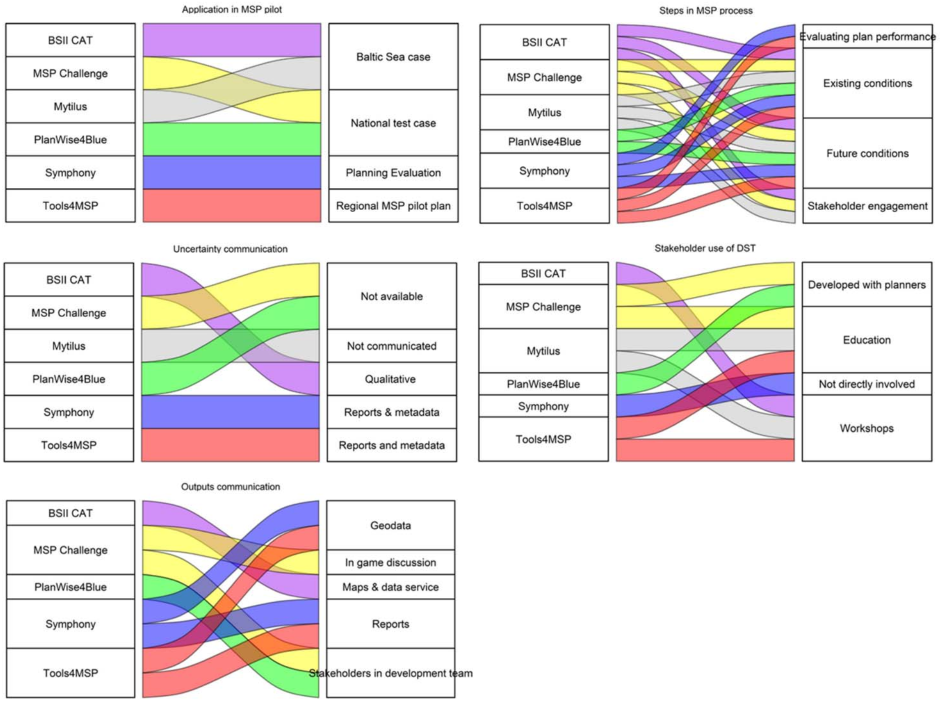

Figure 8. Sankey diagram illustrating the practical aspects reviewed in the six SDST: Application in MSP pilot, steps in MSP process, uncertainty communication, stakeholder use of SDST and outputs communication (**III**).

The CEA applications of SDST showcase different characteristics. For instance, Symphony and Mytilus provide scenario-comparison functionalities to compare the effects of different spatial planning strategies; the PW4B determines impacts on environmental components in terms of lost nature assets in terms of surface area (e.g., benthic habitat) or counts (e.g., bird number). In the Tools4MSP, the pressure distance model functionalities can accommodate different pressure propagation, such as, for instance, hydrodynamic models to address eutrophication effects from terrestrial N and P loads. The MSP Challenge is the only SDST that provides CEA simulations over time (**III**).

Key assumptions on CEA implementation concern mainly the pressure propagation models, which mimic equal pressure dispersion in all directions for Tools4MSP, Symphony, BSII CAT, MSP Challenge and PW4B. Most SDST lack indirect pressure-effects interaction modes, with the exception of MSP Challenge, which considers predator-prey relationships explicitly and dynamically. The Sankey diagram illustrating the CEA capabilities reviewed in the six SDST: CEA input data, pressure definition, Land-Sea Interaction (LSI) sources, Pressure-Environment (P-Env) interaction and pressure propagation is showed in Figure 9 (**III**).

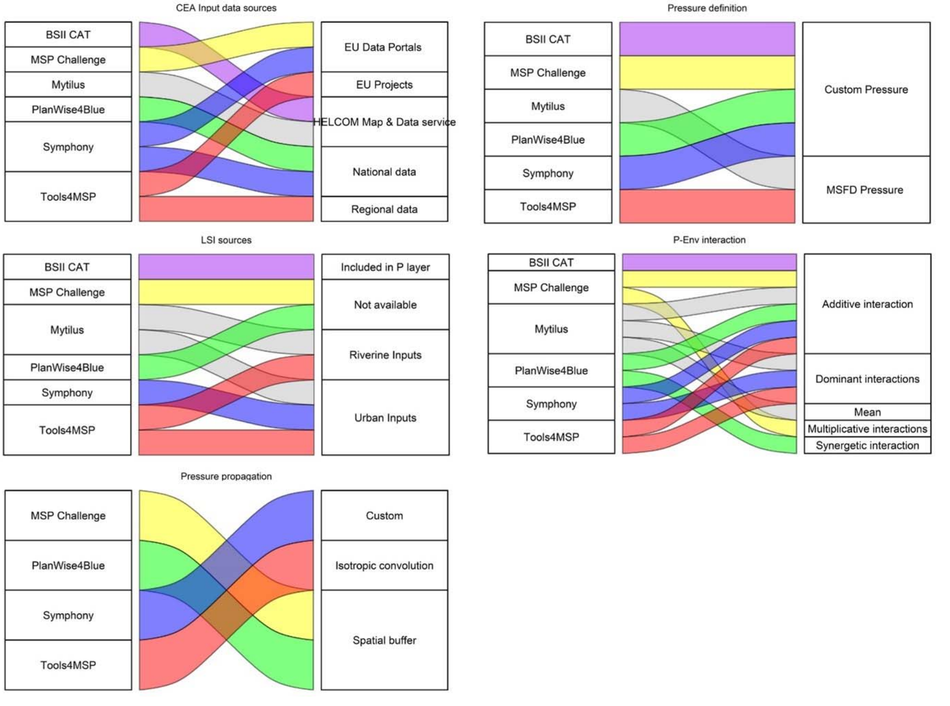

Figure 9. Sankey diagram illustrating the CEA capabilities reviewed in the six SDST: CEA input data, pressure definition, Land-Sea Interaction (LSI) sources, Pressure-Environment (P-Env) interaction and pressure propagation (**III**).

The used framework in the analysis and comparison of SDST for MSP resulted in a generic evaluation of core functionalities of the SDST on conceptual, technical, and practical level. The engagement with developers and SDST managers provided higher level of insight into the technical development of the SDST, the specificities of the CEA instrument offered by the SDST, a set of recommendations for the further development of SDST and ways of mutual support and learning by the developed community. The framework also allowed investigation of different aspects of stakeholder involvement related to SDST use, in the design of SDST and applicability of SDST in different stages of an MSP process. In most cases planners were involved in the development of SDST as they addressed planning constraints within their daily working activities (**III**).

The modelling approaches used within the CEA analysis show some limitations. The modelling techniques to model land-sea interaction processes, such as the dispersion of riverine inputs such as nutrients (N and P) or other pollutants (e.g., heavy metals, pharmaceuticals) were applied using different modelling approaches. The simulation of riverine inputs requires additional modelling capabilities, ideally through the application of hydro-dynamic models, such as SHYFEM (Shallow water HYdrodynamic Finite Element Model; De Pascalis et al., 2016) or HYPE (Hydrological Predictions for the Environment; Arhemier et al., 2012), which are not always available and require extensive modelling capabilities and data processing.

The propagation of pressures takes into consideration three different approaches, a spatial buffer (e.g., PW4B), an isotropic convolution function (Tools4MSP) or other customized approaches (e.g., BSII CAT). Further research and collaboration are required to identify standard procedures to consider pressure propagations that can be applied in absence of dynamic models. This would facilitate comparison of results among different sea areas that are particularly important in transboundary planning contexts. In addition to that, the SDST demonstrate different versions of environmental pressure categories, some were customized to adapt better to local or macro-regional environmental impacts and planning needs (e.g. PW4B, BSII CAT), others (Tools4MSP and Mytilus) apply standardized pressure categories, such MSFD pressures. To facilitate comparison among SDST results should enable a cross-reference among custom vs. MSFD pressures (**III**).

One key limitation of the current CEA tools is that the assessments use mostly expert-based knowledge to determine the sensitivity scores of pressures on nature assets and they often assume that the effects are additive (**III**). The CEA tools rarely consider the plethora of evidence on the interactive effects of human activities on different nature assets although there is increasing evidence that different combinations of stressors often have non-additive impacts, potentially leading to synergistic and unpredictable impacts on ecosystems (e.g. Stockbridge et al., 2020). As an exception, in the PW4B tool the sensitivity scores are based on the best available scientific knowledge (experimental and survey data) linked through a meta-analytical frame (i.e. storing pressure and nature asset specific standardized effect sizes) (**I**).

Due to the complexity of the marine realm, mapping and assessment of ecosystem services is still in its infancy and there remains a need to develop and agree upon the appropriate development in these services to support their integration into the spatial decision support tools. The analysis of the status and prospects of integrating the concept of ecosystem service in some geospatial tools showed that this concept is only poorly integrated to the existing decision support tools see e.g. Tools4MSP (Depellegrin et al., 2020). The main challenges are the lack of harmonized ecosystem services classifications in the marine realm and the scarcity of geo-referenced data with sufficient resolution on ecosystem functioning and services they deliver. Nevertheless, data scarcity should not prevent ecosystem services assessments from being carried out and expert judgement approaches should be promoted in case of data deficiency. Moreover, the interoperability among data storage and processing systems should be guaranteed to ensure that Decision Support Tools remain operational (**III**, **IV**).

Ultimately, the development of the current CEA tools is characterized by the generic lack of coordination among different research centres. This is mostly because these different tools have been elaborated along a predefined set of criteria elaborated by local or regional stakeholder needs during various strategic environmental assessments. The most important improvement to the CEA tools is regular updating of the input data, i.e. nature data layers and information concerning impacts, and refinement to the model algorithms. This research should be carried out in a collaborative manner resulting into more harmonized and efficient tools characterized with enhanced predictive capacity and a reduction in uncertainty.

3.2. Web tool for oil-spill emergency response

3.2.1. Next-Generation Smart Response Web – theoretical background and software

The NG-SRW application is based on Real-time Collaborative GIS (Sun & Li, 2016) theoretical framework and the concept of user-defined Common Situational Awareness (CSA) (Aps et al., 2016b; **II**). Referring to framework for classifying oil spill response and impacts (Chang et al., 2014), the tool addresses oil spill occurrence (phase A1, see Figure 2), weathering and transport of oil (1B), offshore response (2A), shoreline response (2B), acute ecosystem impact (3A), short-term economic impact (4A) and socio-cultural impact (5B). Specifically, the tool aims to use the CSA in an online operational environment, by utilizing all available information into the decision-making process.

The NG-SRW was developed and implemented as an information collecting and sharing facility of the CSA system (Aps et al., 2016b; **II**). The tool employs the .NET MVC with MS SQL database engine, JavaScript, ESRI ArcGIS API for JavaScript, ESRI ArcGIS Server and ArcInfo, HTML5, CSS technology allowing its use on any device with Windows, iOS or Android operating systems. The Single Page Application (SPA) allows users to interact dynamically with all controls, data, and elements on a single page, without the need to reload the page after each action. The NG-SRW tool consists of Server and Client/User Interface. The GIS data are prepared, analysed and stored in the geodatabase with ArcGIS Desktop and Python scripts. ArcGIS Server is used to share GIS data as WMS and the Geoprocessing tool Services. Auxiliary tables store oil spill model results, information on WMS layers, model parameters and user interface tables based on MS SQL database WMSs are portrayed with ESRI ArcGIS API for Javascript.

User interface implemented on the client side supports execution of the relevant geoprocessing services. The basic configuration of the NG-SRW SDST is presented in Figure 10.

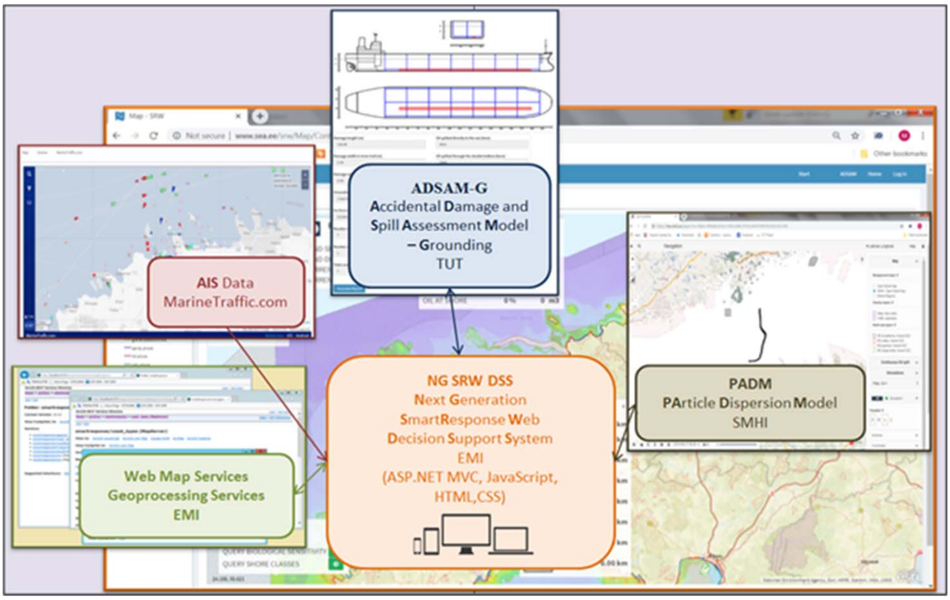

Figure 10. Basic configuration of the NG-SRW application (**II**).

3.2.2. Components of external supporting network

Seatrack Web (STW)

The STW is a fully operational web-based oil drift forecasting system for the Baltic and part of the North Sea, developed by Swedish Meteorological and Hydrological Institute **(**SMHI) and the Danish Maritime Safety Administration (DAMSA) (Ambjörn et al., 2011), which allows users to simulate an oil drift on the server with the results displayed on their computer within a minute. The server has access to the most recent weather and ocean forecasts, thereby providing the user the optimal decision tool to assess oil spills. The oil weathering and transport data are based on the STW PArticle Dispersion Model **(**PADM) weather-driven 3d-simulation (Ambjörn et al., 2011), which includes the latest ice code improvements (Arneborg et al., 2017; Lu et al., 2019). The STW oil drift calculation system is the official HELCOM drift model/forecasting and hindcasting system used by national authorities and research organizations to simulate oil spills (HELCOM, 2020).

STW is used to predict the location of oil spills after some hours, thereby enabling optimal allocation of oil recovery equipment and shoreline protection. As such, STW addresses 1A oil spill occurrence and weathering and transport of oil (phases 1A and 1B, Figure 2) of oil spill response. Future development of STW would see improvement of the interaction between oil and complex, dynamic ice conditions, in particular ridges and the movement of oil under the ice sheet, as well as refinement to the display of model and parameter uncertainties.

Accidental Damage and Spill Assessment Model – Grounding (ADSAM-G)

ADSAM-G is an online platform to assess rapid oil outflow from grounded tankers developed by Tallinn University of Technology (TalTech) (Tabri et al., 2018), which addresses oil spill occurrence (Phase 1A, Figure 2). ADSAM-G incorporates tanker size and configuration (as accessible from AIS) to estimate the amount and duration of oil leakage by inputs of the size of the rupture and load. This information is integrated with impact conditions, including vessel speed and bottom profile. Currently, ADSAM-G is applicable to oil tankers and leaks from vessel grounding; future development will see inclusion of other types of vessels and collision. In addition, oil outflow calculations are rather simple; refinement is needed to include the effects of wave action and currents.

Environmental Sensitivity Index (ESI) map layers

Mapping of the environment sensitivity to accidental oil pollution is vital to oil pollution preparedness, response, and cooperation. Referring to NOAA (2002), Environmental Sensitivity Index (ESI) maps provide information on shoreline classification (ranked according to sensitivity, natural persistence of oil and ease of clean-up), biological resources (an assessment of the vulnerability of organisms to oil), and human-use resources (an assessment of sensitivity to oil and value from human use). The assessment of sensitivity of the biota considers sensitivity (the capacity of an ecosystem to tolerate disturbances) and recovery (rebuild itself after the events of disturbances). NG-SRW uses ESI maps as a visual background for the results of the simulations based on ADSAM-G and STW (Aps et al., 2014; Aps et al., 2016a). As such, this application is of universal use to the geographical area concerned. GIS data are stored on a GIS server in the MS SQL Server geo-database and shared as WMS. The ESI map layers currently available for NG-SRW are for Baltic Sea areas under Estonian jurisdiction.

3.2.3. Implementation of NG-SRW

Initially, NG-SRW connects through the direct external web-based access to the ADSAM-G module (Tabri et al., 2018), which provides initial information on the magnitude of accident damage and the extent of an oil spill resulting from a shipping accident. Subsequently, NG-SRW accesses the STW application through external web-based direct connection to PADM weather-driven 3d-simulation module (Ambjörn et al., 2011), which enables independent analysis of spill drift and weathering by providing its own user interface for calculation of oil spill scenarios. Therefore, NG-SRW SDSS takes advantage of the development of calculation kernel of STW application, which in the current version includes recent improvements of the ice code (Arenborg et al., 2017), but presents it within a different user interface.

MarineTraffic.com provides real-time Automatic Identification System (AIS) information, such as the current position, speed, and direction of vessels. Necessary basic information on the size of vessels is obtainable for use in the ADSAM-G model. In addition, there are lights, stations, and ports databases. All necessary information is readily obtained from the MarineTraffic map, which is embedded into NG-SRW. The NG-SRW is also linked to Environmental Sensitivity Index (ESI) map layers, implemented through the imported WMS. Developed by this doctoral study, NG-SRW serves as a platform that collects and enables interaction with different streams of oil spill response related online information, by which authorities can access, filter, visualize, and share information collected during an emergency response as shown in Figure 11.

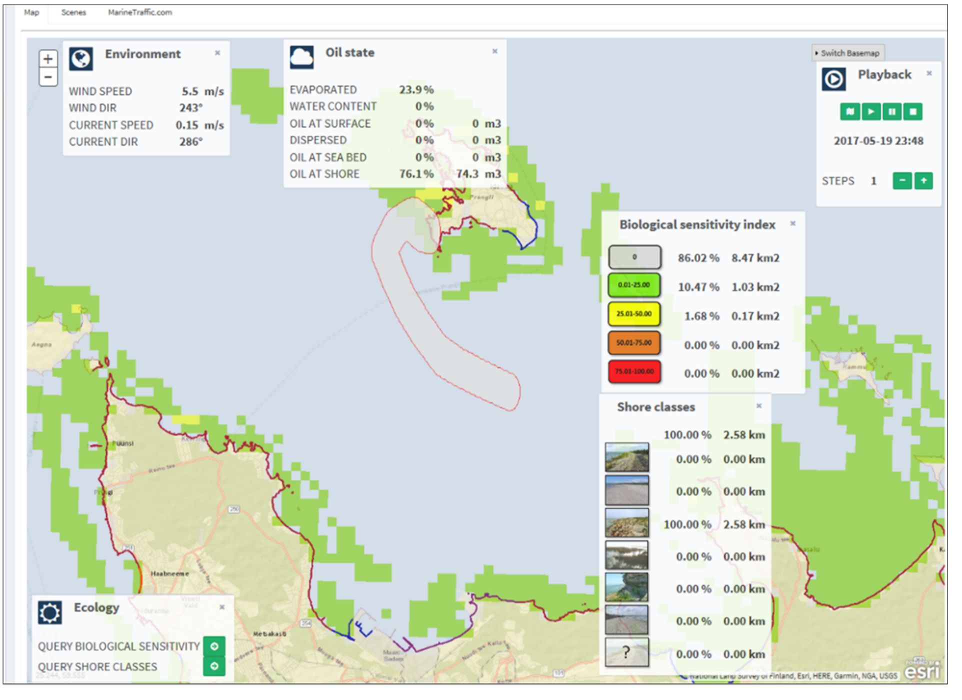

Figure 11. NG-SRW application enables the direct integration of spill monitoring and evaluation functions into oil spill preparedness and response management processes (**II**).

Users control the content to be included in and excluded from an oil spill response scenario, thereby allowing users to select a set of criteria to address a particular oil spill accident response unit according to their needs. This ability is essential to cater to the different decision makers and stakeholders (Aps et al., 2016b). The proposal of a new SDST demands consideration of its expected effectiveness in practical response operations (Nordström et al., 2016). This effectiveness is difficult to assess because maritime oil spills are rare, and because the large range of conceivable scenarios limit quality of assessment information. A comprehensive evaluation of the performance of the SDST is, therefore, not yet available, although current assessment is positive.

First, the development of the NG-SRW (**II**) is rooted in the theoretical basis of Real-time Collaborative GIS framework, recognizing the importance of Common Situation Awareness in a dynamic context of decision makers, actors, and stakeholders. Furthermore, the web-based external input sources of NG-SRW are used extensively by different users in a variety of contexts, for instance, the PADM weather-driven 3d-simulation as implemented in STW is the operational tool for oil spill drift in the Baltic Sea as recommended by HELCOM (2020), and AIS data are used extensively for navigation support and real-time situational awareness of shipping activity (Fournier et al., 2018). Finally, a preliminary test of the integrated NS-SRW tool has been executed in a stakeholder workshop with maritime professionals (Goerlandt et al., 2019); results indicate that the tool may be useful for specific organizations, and that it is relatively easy to understand and use.

While the current implementation of the NG-SRW is considered a significant step forward in NEBA-based oil spill response, addressing NG-SRW's limitations is important both for preventing over-reliance on the tool, and for guiding future research and development. NG-SRW is based largely on distributed databases and the imported WMS. Therefore, NG-SRW is usable in the applicable geographical area and complements most of the national or regional accidental oil spill response systems. However, the lack of harmonized ESI/RESI map layers limits wider and cross-border application of the NG-SRW. Incorporation of harmonized ESI/RESI maps for the whole Baltic Sea region is necessary for future development (**II**).

A dynamic CSA that identifies shorelines sensitive to oil spills are critical in determining the kind and extent of response that may be appropriate. These choices ultimately dictate clean-up costs. Therefore, Baltic Sea ESI/RESI maps are needed that display detailed ecological and the socio-economic values of shorelines and coastal waters. In addition, NG-SRW would improve if maps were incorporated that assess response performance under specific meteorological and sea ice conditions (**II**).

Finally, the functionality and effectiveness of the NG-SRW needs to be evaluated in simulation-based testing, response training exercises, and in real operations. Simulation-based testing would serve as the first approach, e.g., using cross-border simulator environments (Halonen & Lanki, 2019). Further evaluation could then be focused on genuine exercises, which would examine the social context of the emergency response, the interactions of end-users with NG-SRW, and how NG-SRW supports wider communication and information exchange (e.g., Luokkala et al., 2017). Such research can inform design updates that consider human-machine interaction issues, team resource management, and the development of learning-oriented training programmes.

3.3. Web tool for cumulative effects assessment (CEA) of human activities

3.3.1. The PlanWise4Blue (PW4B) theoretical background and software

The PW4B development and implementation is based on Real-time Collaborative GIS (Sun & Li, 2016) theoretical framework. The PW4B tool (**I**) software development is based on the ASP.NET MVC with PostgreSQL database engine, JavaScript, ESRI ArcGIS API for JavaScript, ESRI ArcGIS Server, HTML5, CSS technology enabling its use on any device (phone, tablet, and computer) with Windows, iOS or Android operating systems. Single Page Application (SPA) approach was used in development, which enables users to interact dynamically with all controls, data and elements on one page, without the need to reload the page after each action. PL/pgSQL Procedural Language was used to create conditional and impact matrix tables and to fill them with data. The Python programming language was used in the analysis, the obtaining of different human pressure combinations, and calculations of cumulative effects of various pressure-types on nature assets.

The PW4B tool as a complex system consists of Server and Client/User Interface sides. The GIS data are prepared, analysed and stored in the geodatabase with ArcGIS Desktop and Python scripts. ArcGIS Server is used to share GIS data as WMS as well as the Geoprocessing tool Services. Auxiliary tables, such as conditional and impact matrix tables used in preparation and calculation phases, information on WMS layers, model parameters and user interface tables, are stored in PostgreSQL database and processed using PL/pgSQL procedural language. WMSs are visualized on the Client side with ESRI ArcGIS API for Javascript. User interface implemented on the client side supports setting models parameters, execution of Geoprocessing services, which are the main engine for the models, and viewing the results (Figure 12).

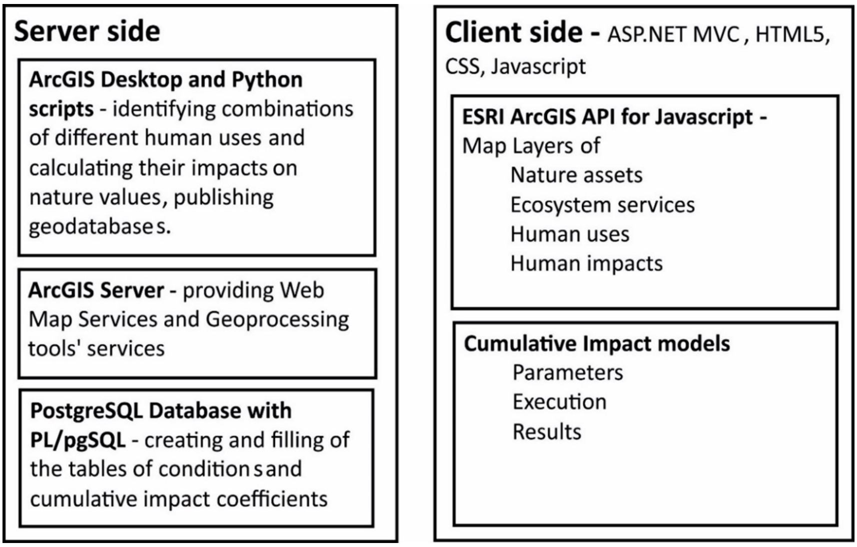

Figure 12. Basic configuration of PW4B tool and based technology used in development (**I**).

The PW4B is a user-friendly geoportal tool (Figure 13) that combines novel spatial modelling products of environmental background (e.g., maps of benthic habitats) with spatial data related to marine resources use with an emphasis on fishery, shipping and energy. Moreover, the PW4B tool incorporates information on ecosystem indicators (e.g., the number of wintering birds) that can quantify the intensity of ecosystem services (in contrast to many earlier assessments based solely on the presence/absence of ecosystem services).

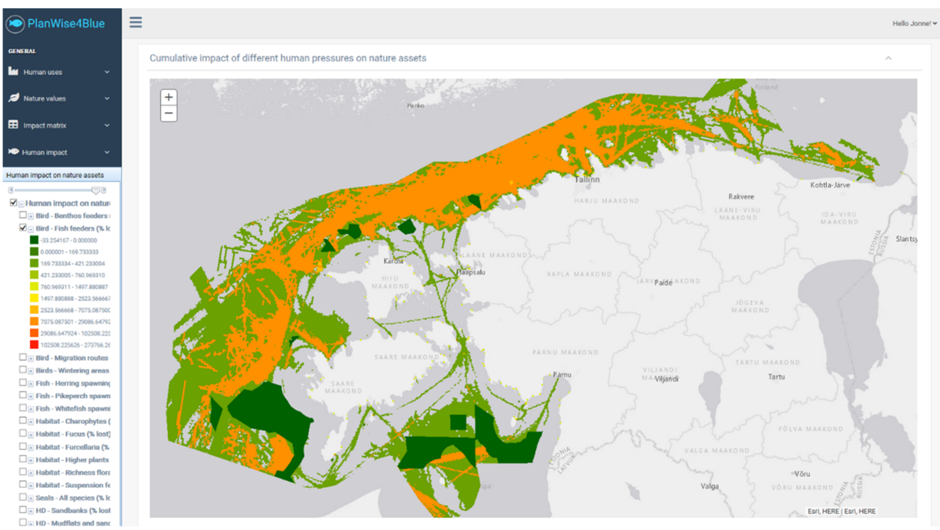

Figure 13. User interface of the PlanWise4Blue tool (**I**).

3.3.2. PW4B CEA analyses of the Estonian MSP scenario

Human activity occurs almost everywhere in the Estonian sea but is more intense in offshore areas due to shipping, commercial fishing, and future wind farm development. The cumulative effects of these human uses vary greatly for different nature assets. The current Estonian maritime spatial planning was predicted to result in a moderate loss of these nature assets primarily in near coastal areas e.g., bladderwrack habitats, herring spawning grounds, resting areas of seals (Figures 14–16). This moderate loss is due to a lack of spatial overlap between human pressures and nature assets under the current MSP scenario. Most human pressure is situated in offshore areas, whereas the above nature assets are typically located in shallow coastal waters. Nevertheless, the cumulative human impact on near coastal nature assets is greater than the current MSP assessment as many key pressures (e.g., land-based nutrient input, fish farms, introduction of non-indigenous species) are not yet included as map layers in the current MSP but can potentially be assessed in the PW4B tool (**I**).

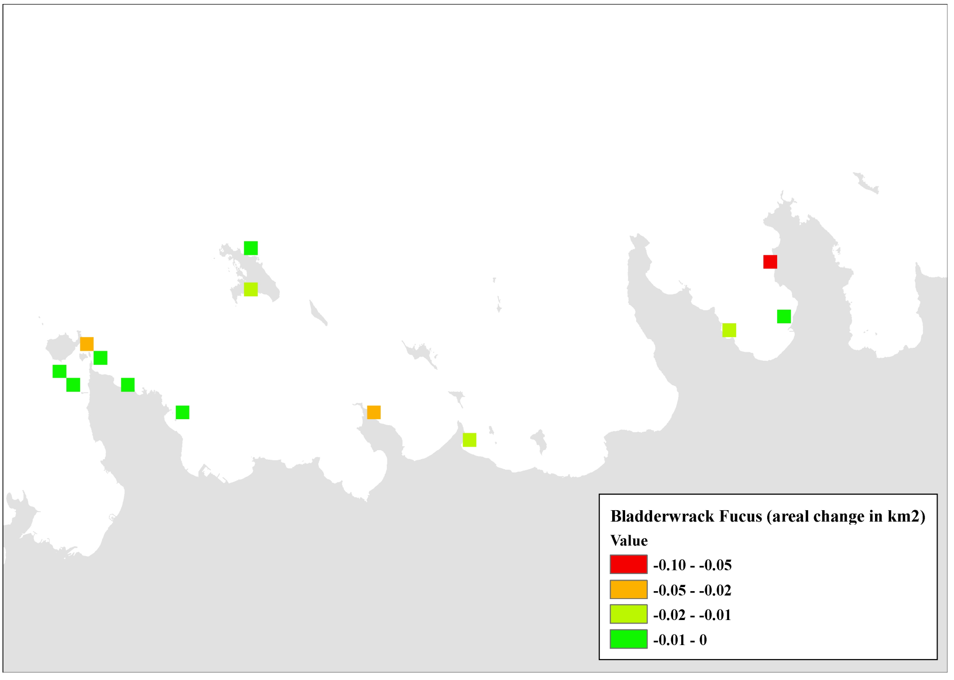

Figure 14. Areal change of bladderwrack habitats in the current Estonian MSP scenario in the central Gulf of Finland area (habitat change in km^2 in a 1 km^2 cell).

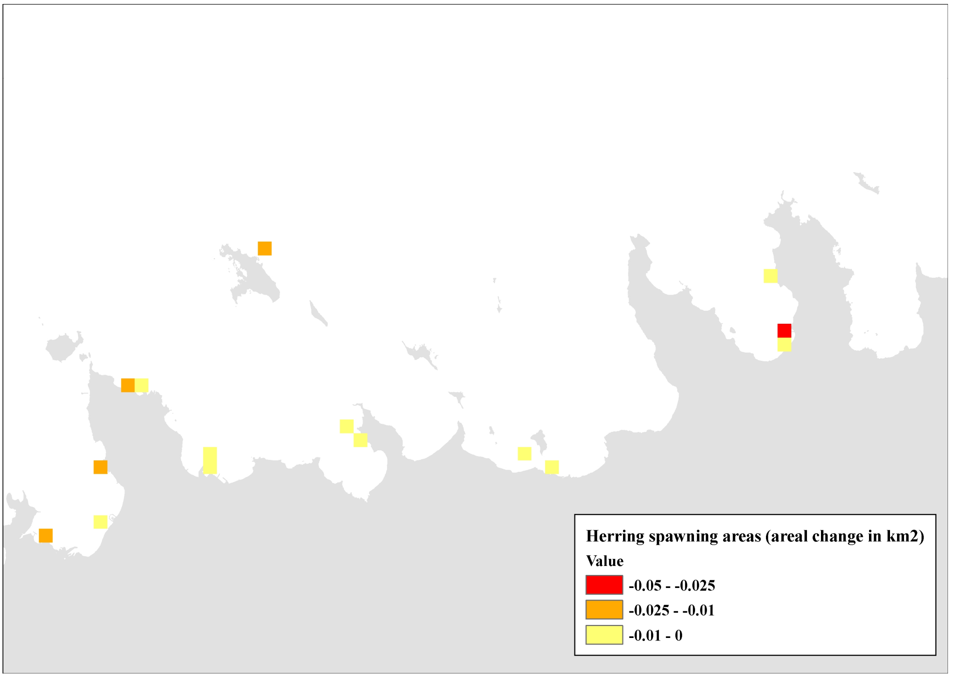

Figure 15. Areal change of herring spawning grounds in the current Estonian MSP scenario in the central Gulf of Finland area (change in km^2 in a 1 km^2 cell).

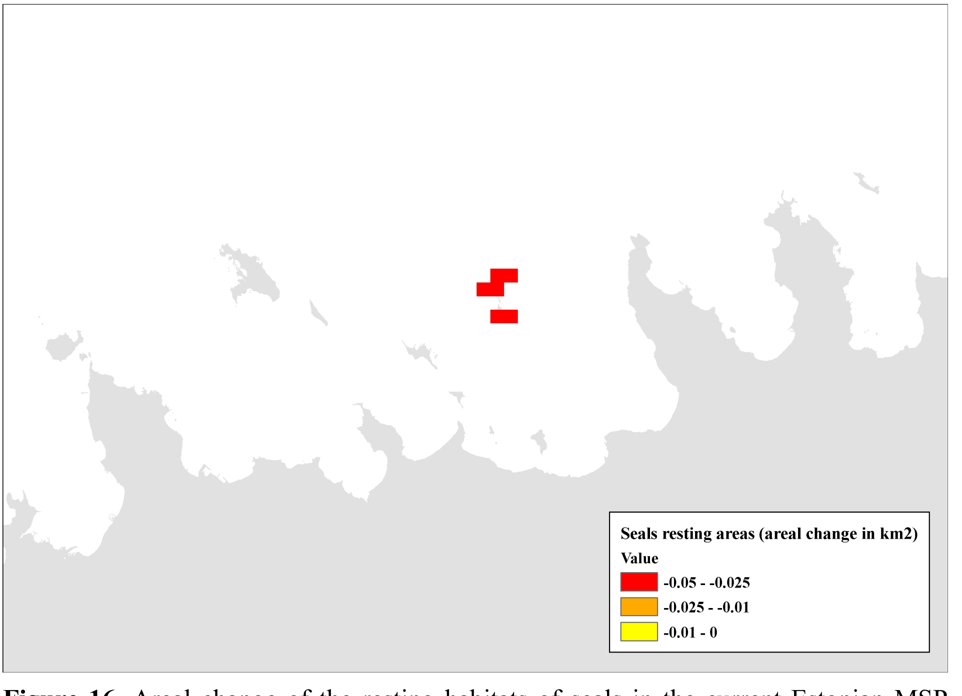

Figure 16. Areal change of the resting habitats of seals in the current Estonian MSP scenario in the central Gulf of Finland area (change in km^2 in a 1 km^2 cell).

Substrate heterogeneity is an important structuring factor for benthic seaweed communities in the study region (Kautsky et al., 1999; Martin & Torn, 2004; Kotta et al., 2008b) and any human activity (e.g., harbour construction/maintenance) that modifies a mosaic of substrate at small (100 m) spatial scales most likely reduces the spatial extent of habitat forming seaweeds. Moreover, harbours and shipping are often a source of elevated nutrient loading. Overly high nutrient loads will likely cause a decline in the biomass of habitat forming species in the bladderwrack habitats (Hällfors et al., 1984). This decline is likely not a direct consequence of nutrients on perennial seaweed species, rather the indirect result of a worsening of light conditions caused by an increase of opportunistic filamentous algae on perennial seaweeds (e.g., Wallentinus, 1984; Pedersen, 1995; Morand & Briand, 1996; Torn et al., 2006).

The greatest negative effect on herring spawning grounds is due to shipping, with commercial open sea pelagic trawl fishing responsible for significant and unaccounted herring mortality in the 0 and 1 age groups (Suuronen et al., 1996a; 1996b). In addition, human activities that negatively affect perennial seaweeds, such as harbour construction, dredging and extraction of minerals, are expected to disintegrate herring spawning grounds. Specifically, herring spawning occurs in early May during migration to the coast (Lundin, 2011). Herring spawn in shallow waters along the entire Baltic Sea coast except for its most freshwater embayments. Spawning grounds are often located in areas with moderate to good water exchange and with high primary productivity. Herring spawn mostly on hard bottoms covered with brown and red algal species, such as *Furcellaria lumbricalis*, *Pylaiella littoralis* and *Fucus vesiculosus*, which likely reflects the prevalence of these algae in the Baltic Sea rather than a preference towards specific algal species (Aneer, 1989). However, spawning on firm algae that has extensive 3D structure (e.g., *F. lumbricalis*) can be advantageous, as such substrates can accommodate more eggs and ensure their proper aeration during early developmental stages (Messieh and Rosenthal, 1989). In general, the quality of spawning grounds exhibits low natural interannual variability. However, actual use of the spawning grounds and the efficiency of herring year-class production usually vary depending on seasonality in water temperature, pelagic primary and secondary production, and likely also on the intensity of human activity in the area. After spawning, herring migrate from the coast back to deeper waters where they remain for the rest of the year (Rajasilta et al., 1993).

Fishing and shipping were identified as the two most important human activities affecting the integrity of seal resting areas in Estonian waters. As seal numbers increased in the Baltic Sea region, fishermen started to report elevated bycatch of seals in different fishing gear including trawls (Lunneryd et al., 2003). Despite the increased by-catch of seals, the increase in seal population has continued; possibly the bycatch consists mostly of young seals that would suffer high natural mortality (Vanhatalo et al., 2014). Nevertheless, reduction of seal by-catch demands deployment of more environmentally friendly gear. Vessels can also have severe impact on seals (Jones et al. 2017). Shipping traffic is a major component of underwater low-frequency noise and is likely audible to seals over long ranges. Seals are unable to communicate above a particular noise threshold

(Bagočius, 2014), and may even cause auditory damage (Southall et al., 2007); in the long run seals start avoiding important habitats (Morton & Symonds, 2002).

Currently, the PW4B tool is limited to the resting areas of seals and this explains why the predicted cumulative effects of human activities on seals was low. To quantify realistic impacts of the exposure of shipping traffic on marine mammals requires density maps of seals based on the existing movement data of seals fitted with UHF global positioning satellite telemetry tags which are overlain with maps of predicted ship noise.

Offshore human activities had an overall negative effect on birds but positive effects on the habitats of suspension feeders. The effect on birds was due to shipping and partly on fishing. The greatest risk of shipping to waterbirds are oil spills and marine accidents. Despite increasing shipping traffic, the number of recorded oil spills has decreased; nevertheless, the concentrations of total petroleum hydrocarbons in the water column (an indicator of oil spills) have not decreased (Skov et al., 2011). Currently, over 10% of Baltic Sea birds has oil residues on their feathers, which can be explained only by unreported oil spills (Larsson & Tydén, 2005). In addition, incidental bird mortality in fishing gear is observed in all countries around the Baltic Sea. Unfortunately, no comprehensive surveys on the bird by-catch exist at the pan-Baltic scale; therefore, the actual numbers of caught birds are unknown and the current assessment is certainly an underestimate. The construction of wind energy parks would result in a loss of benthic feeding birds of only 0.04% but a loss of bird wintering area by 10%. The greatest impacts on wintering waterbirds are expected during the operation phase when suitable bird habitats are unavailable for long periods (Bergström et al. 2014). Nevertheless, existing evidence also indicates that water birds quickly adapt to wind parks and the long-term effect of wind energy development is not as severe as short-term monitoring assessments suggest (Skov et al., 2011).

A moderate effect of wind park development to benthic feeding birds relates to the creation of hard bottom habitats at a depth range that is otherwise absent in offshore regions, thereby providing support for totally different fauna and flora (Wilhelmsson & Langhamer, 2014). Artificial hard substrate, when properly mimicking natural substratum, is an ideal habitat for suspension feeding mussels. The key benthic suspension feeding mussel in the Baltic Sea region is *Mytilus edulis/trossulus*, whose habitat is dependent largely on the availability of hard substrate. Within its habitat (hard bottom areas) higher abundances generally coincide with high food availability (Kotta et al., 2015). Food supply is a crucial factor for benthic suspension feeders with sedentary lifestyle, as mussels can deplete near-bottom water layer quickly (Fréchette et al., 1989) and starve even with abundant phytoplankton if there is insufficient water movement. In general, offshore areas are characterised by high wave energy, which replenishes the food supply (Kotta et al., 2015). A high density of suspension feeders in turn is expected to attract benthic feeding bird populations and counteracts mortality due to wind park development.

Moreover, when novel aquaculture activities such as mussel or macroalgal farming are established in wind park areas, as suggested in the current draft of the Estonian MSP, predicted losses of wintering bird areas are significantly reduced.

Algal and mussel farming offers a means by which to remove nutrients, thereby inhibiting eutrophication in the Baltic Sea and to improve the quality of many nature assets including wintering birds (Petersen et al. 2014).

Currently hundreds of tons of mussels are harvested in the Baltic Sea, but there is potential for much more. The production potential of mussels is currently limited by outdated legislation and an underdeveloped market for farmed mussels. Moreover, most farms have been established in sheltered waters where a lack of space has been presented to argue against large-scale mussel farming. However, technical development would enable establishment in offshore areas, especially in conjunction with wind parks.

Eutrophication is considered the greatest threat to the integrity of the Baltic Sea ecosystem and is caused primarily by excessive amounts of legacy nutrients stored in the sediment and water (Conley et al. 2009). Due to the interactive effects of nutrient loading and other human pressures on different nature assets, high eutrophication levels set limits on the sustainable intensity of other human activities. Therefore, in addition to the spatial planning of traditional sectors, MSP solutions should analyse the potential of compensatory measures to reduce adverse effects of eutrophication in the Baltic Sea.

When the PW4B approach is compared to the other actively used tools of CEA (**III**), the other tools tend to predict a much less detailed impact and the most impacted areas do not necessary overlap (e.g., **I**). There are multiple reasons that account for these different outcomes. First, the algorithms of other tools examine each human activity individually (e.g., commercial fishing and dredging) without addressing the combined effects of different activities. However, the seas are affected by several human activities simultaneously; realistic effect estimates require assessment of the interactions of different pressures. For example, commercial fishing may have a moderate environmental impact. However, if large-scale dredging is also carried out in the same area, the combined effect is significantly greater than the sum of their individual effects. Dredging changes the nature of the seabed and the disturbs biota (oxygen is depleted in the bottom water layer and sediments and benthos may be destroyed). Second, other algorithms mostly assess the effects of individual human activities on an ordinal scale (e.g., small, medium, large) and the data layers of natural values are on a nominal scale (natural value is present or absent). However, a realistic assessment of the magnitude of the impact of human activities depends on the abundance of a natural value at a given spatial point. However, in order for the natural environment to be able to offer us various benefits in the long run, it is important that the level of natural values does not fall below a critical level. For example, the presence/absence of different benthic habitats in Estonian marine areas is defined by the threshold biomasses of the characteristic habitat-determining species. If we want to know to what extent human activities reduce or increase the area of such valuable habitats, the calculation algorithms for the effects of human activities must be based on realistic estimates of the density of natural values and/or biomass. The PW4B algorithm is based on continuous layers of nature assets data (e.g., bird population density) and impact coefficients obtained from scientific literature or databases, which determines the relative increase or decrease in nature asset for a given combination of human activities. This aspect accounts for other tools' inability to distinguish between the extent of human activity in areas varying the density of natural values. The maximum effects of the PW4B tool were found where the population densities of natural values were the greatest. Third, other CEA approaches do not consider the positive impact that human activities can have on the environment. This consideration aspect is vital if we want to assess the suitability of compensatory measures against the background of existing human impacts, e.g., the use of algae and/or shellfish farming to mitigate the negative environmental impact of fish farming.

3.3.3. PW4B CEA analyses of the plausible futures

This study uses the PW4B tool (**I**) to predict the environmental consequences of feasible management scenarios on benthic habitats in Estonian waters. All the tested scenarios predict some degree of habitat loss for the reef environment and its associated species-specific habitats. As an exception, a nutrient reduction scenario with the presence of wind parks and non-native species predicts 13% habitat gain for suspension feeders. The most severe negative impacts are caused by scenarios with current nutrient load in combination with other pressures (non-native species and wind parks). Total habitat loss is greater for algae-based habitats, indicating that *Fucus vesiculosus* and *Furcellaria lumbricalis* habitat types are more vulnerable to human impacts than reef environment and suspension feeder habitats. The least damaging impact scenarios on the studied habitats are future nutrient reduction (no habitat loss) and the combination of other pressures (non-native species and wind parks) with nutrient reduction (slight habitat loss) (**V**).

The tested scenarios predict habitat loss for the sandbank environment and associated habitats. As an exception, a nutrient reduction scenario with the presence of wind parks and non-native species as well as a scenario with non-native species predict habitat gain for higher plants habitat. Similar to reefs, the most substantial negative impacts are caused by scenarios with current nutrient load in combination with other pressures (non-native species and wind parks). The greatest habitat degradation is experienced in the *Zostera marina* habitat (up to 86%); however, this habitat type is especially sensitive to excessive nutrient input as habitat loss is significantly less when the nutrient load is reduced. Therefore, the least damaging impact scenario of all the studied natural values with no or minor habitat loss is future nutrient reduction and the future nutrient reduction combined with other pressures (**V**).

This suggests that an excessive nutrient load is expected to damage benthic environments to a greater extent than any other studied human pressures, and this effect was observed even without the presence of other pressures. Only suspension feeding mussels favoured elevated nutrient loading. Mussels inhabiting the study area are filter feeders, and elevated nutrient loading is expected to improve their food availability. Resource gradients have an important role in shaping the biomass distribution of mussels in the study area (Kotta et al., 2015).

The impacts of human pressures were often greater at habitat scale (e.g., *Fucus vesiculosus* habitat) than at environment scale (e.g. reef habitat hosting *Fucus vesiculosus*, *Furcellaria lumbricalis* and *Mytilus trossulus* habitats). Therefore, it is advantageous to assess the impacts of human-induced pressures at a smaller-scale habitat level rather than at an environment level to ensure more accurate and effective marine conservation assessment. Otherwise, we may miss important impacts caused by human-induced activities that lead to underestimating how each species responds (**V**).

Wind park development had the least substantial impacts on the studied benthic habitats. The predicted maps showed that wind parks predict only a small positive impact on suspension feeders, creating 1 km^2 of new habitat. Therefore, wind parks are expected to increase the areal coverage of reef and sandbank habitats by a minimal amount, as the foundations of wind turbines create a stable artificial substrate for *Mytilus trossulus*. Nevertheless, because of elevated densities of filter-feeding mussels, wind parks are expected to mitigate adverse effects of eutrophication since filter feeders are expected to clean the water from nutrients (Kotta et al., 2009). This is, however, not the case for macroalgae habitats, as the existing evidence show some habitat loss for macroalgae due to wind parks (**V**).

The environmental impact analyses of wind energy developments were based given specific technological assumptions, i.e. wind turbines are built on a concrete foundation with a texture suitable for the attachment of seaweeds and large invertebrates and filled with stones. The wind turbine foundation is expected to be < 100 m in diameter. The height of the concrete stem cone is 10 m. The maximum height of the wind turbine tip is 300 meters, and the maximum diameter of the rotor is 250 m. The spacing between the wind turbines was estimated to be between 4 and 7 turbine diameters, i.e. a minimum of 800 meters. The cumulative impacts model does not consider environmental impacts during construction, but the environmental impact of gravity foundations is clearly less than other existing techniques (**V**).

Our analyses indicate that a business-as-usual scenario will cause permanent losses in benthic habitats due to the combined adverse effects of excessive nutrient input and non-native species in both soft and hard bottom habitats. Both reefs and sandbanks are considered hotspots for biodiversity in the Baltic Sea that require strict conservation measures as the modification or loss of habitats can pose a serious threat to marine ecosystems. The number of habitat-forming species in the Baltic Sea is relatively low; therefore, few alternative species are available to replace the function of species that might disappear due to the habitat decline (**V**).

The reefs habitat change comparing the combinations of current nutrient load + non-native species + wind park development versus 25% nutrient reduction + non-native species + wind park development scenarios is presented in Figure 17. Further, the sandbanks habitat change comparing the combinations of current nutrient load + non-native species + wind park development versus 25% nutrient reduction + non-native species + wind park development scenarios is shown in Figure 18 (**V**).

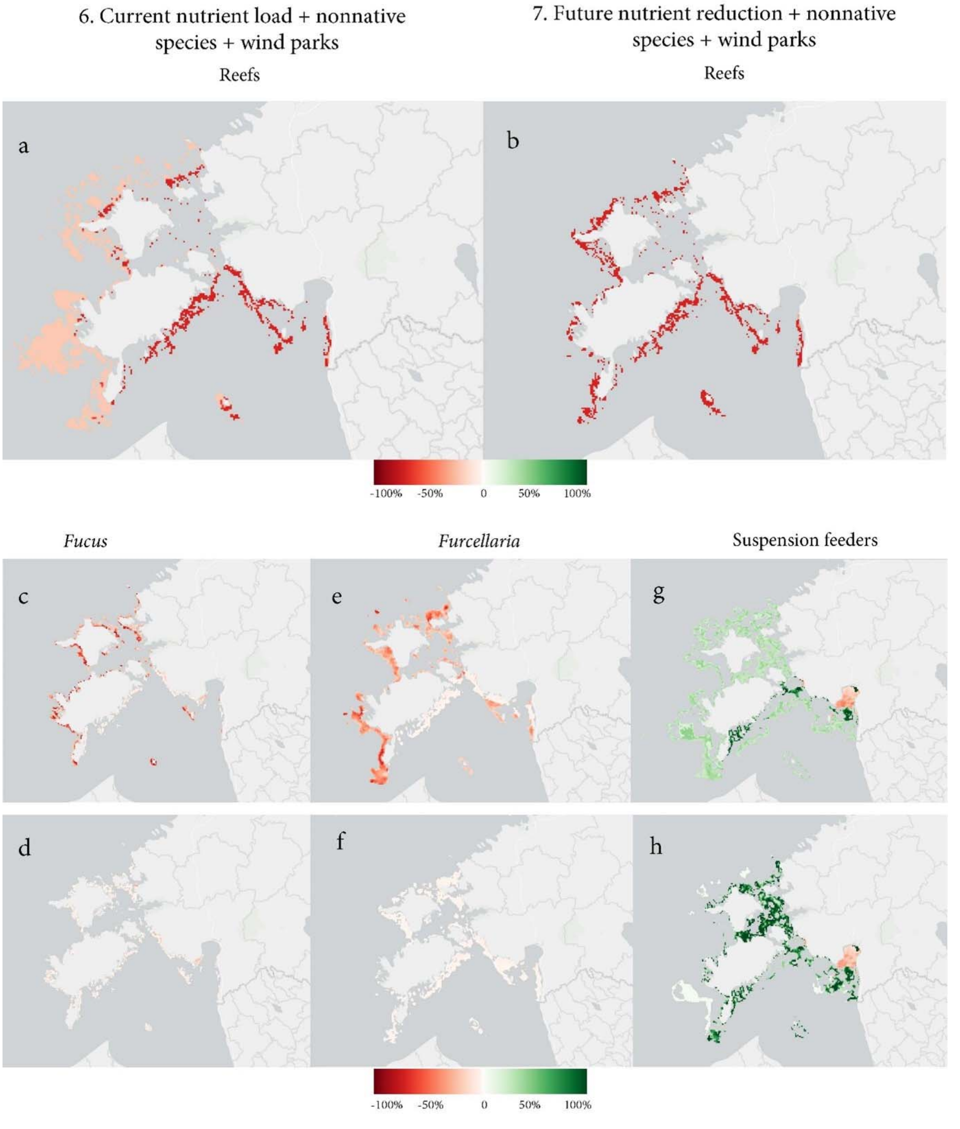

Figure 17. Habitat change comparing the combinations of current nutrient load + non-native species + wind park development versus 25% nutrient reduction + non-native species + wind park development scenarios. (a, b) show the difference in larger-scale reef environment. Differences in habitat change in associated habitat types are (c, d) in *Fucus vesiculosus* habitat, (e, f) in *Furcellaria lumbricalis* habitat, and (g, h) in suspension feeding mussels habitat (change in km^2 in a 1 km^2 cell), (**V**).

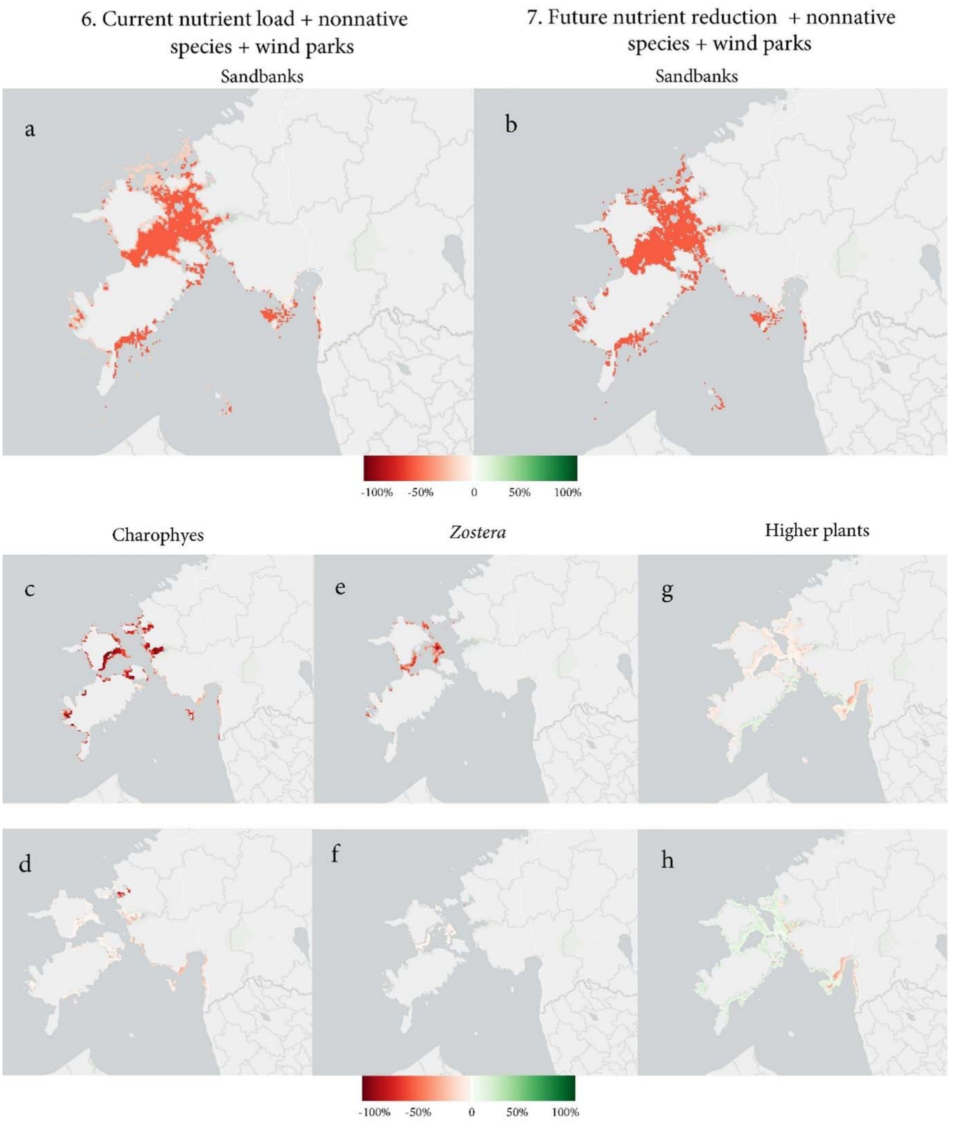

Figure 18. Habitat change comparing the combinations of current nutrient load + non-native species + wind park development versus 25% nutrient reduction + non-native species + wind park development scenarios. (a, b) show the difference in a larger-scale sandbank environment. Differences in habitat change in associated habitat types are (c, d) in Charophytes habitat, (e, f) in *Zostera marina* habitat, and (g, h) in higher plants habitat (change in km^2 in a 1 km^2 cell), (**V**).

Nutrient load is a manageable pressure that can and should be reduced. The results showed that reducing nutrient load by 25% together with the presence of non-native species and projected wind parks is a significant improvement for the marine environment. Based on our research, it is therefore highly encouraged for Estonia to follow the HELCOM nutrient reduction targets to conserve valuable marine environments (**V**).

3.3.4. Benefits, shortcomings, and future developments of the PW4B tool

The effectiveness of CEA to provide useful information centres on the availability of scientific knowledge and data on different nature assets and specific pressure effects. Uncertainty in the CEA takes two principal forms: first, the uncertainty of the nature asset assessment, and second, the uncertainty of the effect coefficient, i.e., that arising from the literature-based meta-analysis. Some lack of data and knowledge is due to poor mapping of marine habitats, e.g., coastal habitats are often better mapped than offshore habitats. Similarly, impacts of more traditional human pressures (e.g., nutrient loading) are better known than more recent activities (e.g., wind park development) (Dannheim et al., 2019). Importantly, our understanding of different interactive effects of human activities on different nature assets is likewise limited (e.g., Andersson, 2011; Wake, 2019). Experimenting with multi-stressors is a relatively new area of research and a great need exists for robust experimental work that is comparable and reproducible and that can generate ecologically meaningful results. Nevertheless, all these limitations can be easily alleviated if the frame of CEA assessment can readily accept new knowledge and data as they become available. In fact, measures of uncertainty serve two functions. The first function is straightforward, to provide planners and stakeholders with a quantifiable measure of confidence in any proposed strategy. The second function helps the developers of the PW4B tool to spot particular interactive relationships that demand further research in order to reduce uncertainty to more acceptable levels.

Benefits and uses of the tool:

The PW4B tool provides several benefits for its users. First, the nature and human activity layers are linked by an impact matrix that defines pressure-specific impacts (individual and synergistic effects) on different nature assets. The matrix is based on the best available scientific impact data linked through a meta-analytical frame (i.e., storing pressure and nature asset specific standardized effect sizes). Many other similar applications are limited to expert judgement on impacts. Moreover, the matrix quantifies both individual and synergistic effects of different human-induced pressures on ecosystem services. Many other applications succumb to complexity and disregard all interactive/synergistic effects despite of the known existence of multiple interactions in ecosystems (e.g., HELCOM, 2018b; Menegon et al., 2018b). These features enable PW4B to identify rapidly spatial conflicts between different human activities as well as to assess the CEA of different planning scenarios on nature assets. This tool has been developed to assist with maritime spatial planning but is also applicable in other fields. Importantly, when combining environmental impact of different human activities with the economic benefits of various management scenarios, the PW4B tool enables development of sustainable solutions to maximize the economic benefit gained from the use of marine resources with minimum damage to the environment. Second, the tool is dynamic, and users can upload novel information on nature assets and impact knowledge that automatically generates novel algorithms to quantify cumulative effects. Third, it is open source and therefore publicly accessible. Fourth, it incorporates key economic sectors with a variety of nature assets and their ecosystem services with which to quantify CEA assessments. The values of ecosystem services reflect provisioning, regulating and maintenance services. Fifth, the tool is versatile: users can choose input data on pressures and nature assets – both actual and theoretical. The tool has the potential for implementation regions beyond Estonia.

Shortcomings and limitations of the tool:

The PW4B tool is currently a work-in-progress and continues to rely on expert judgement on those pressure combinations currently lacking concrete data, but only until new information becomes available (e.g., Gunderson et al., 2016), after which the impact matrix is readily updated. Therefore, further development of the tool is needed e.g., to incorporate a broader set of nature values and ecosystem services and account for novel human induced pressures such as microplastic pollution. Some combinations of pressures still require more data in order to decrease uncertainty in model output. In addition, the 1 km^2 spatial resolution may be too large for some aspects of coastal management. The tool is likewise limited to Estonian sea space and may suffer edge effects from neighbouring countries and does not account for interactions (e.g., cascading food web effects) among different nature assets.

Potential for tool development:

The PW4B is a useful tool for planning and prioritizing the use of coastal areas, drafting development plans, and contributing to political decision making. However, the current tool can be enhanced to produce more accurate predictions and the associated added value. The latter is dependent on further basic research in order to reduce the uncertainty of CEA assessment to more acceptable levels. Such basic research may involve experiments targeting the effects of multiple novel stressors to the biota under current and future environmental conditions as well as improving knowledge base on spatial predictive modelling of nature values. It is judicious to make enhancements to validate concrete development plans.

To enhance the tool:

The most important improvement to the tool is regular updating of the model data, i.e., input data layers and information concerning impacts, and refinement to the model algorithms. This will result in enhanced predictive capacity and a reduction in uncertainty in particular regions, as well as the ability to measure model sensitivity and to stream-line modelling and calculation processes. By incorporating data from beyond Estonian sea space, the tool can remove edge effects and perhaps eventually encompass the entire Baltic Sea.

4. CONCLUSIONS

This doctoral study demonstrated that the knowledge and data availability are among of the main limitations of ecosystem-based marine management. However, these limitations can be alleviated by the implementation of spatial decision support tools (SDST) which link multiple data sources and innovative data-driven analyses. Geospatial information is one of the main requirements to carry out ecosystem-based marine management. Graphical representation of the distribution of ecosystem components and services they provide facilitates communication and discussion with stakeholders, which is improved by publicly available visualization tools. New web platforms or mobile applications create opportunities to reach a wider audience and acquire information. This is also linked to planning teams to be interdisciplinary, with sectorial involvement and ensuring public participation oriented to the actual ecosystem services beneficiaries on local and regional scales. SDST combine spatial and non-spatial data, the analysis and visualization functions of GIS, and decision models in specific domains, to find solutions to different problems and facilitate reaching compromises. Emergency responses and scenario-based modelling are important fields of application of SDST. SDST need to be user-friendly and information display should be simple and clear even if the algorithms behind are complex.

The concept of Real-time Collaborative GIS was effectively implemented under the Next-Generation Smart Response Web (NG-SRW) application. As an important advancement, this oil emergency response SDST linked real-time tracking and forecasting of oil spill positions to the sensitivities of the biota in the expected spilled area. By integrating the analysis and visualization of dynamic spill features, the benefits of potential response actions are compared to develop an appropriate response strategy. The web tool enables achieving common situational awareness between oil spill response decision-makers and other actors, such as merchant vessel and Vessel Traffic Service centre operators, which is essential to minimise the detrimental effects of oil spill. As such, this SDST enables response authorities to simulate better the complexity and dynamic behaviour of the systems and processes underlying environmental risk assessment and thereby undertake oil spill mitigation more effectively to protect the ecological and human values.

The developed by this doctoral study the PlanWise4Blue (PW4B) tool expands to a broader set of human action and provides decision makers with a tool to enable ecosystem-based planning and sustainable management of multiple maritime human activities. The tool incorporates an innovative methodology in which the assessment of cumulative effects is based on the causal links between different pressures and natural values based on quantitative knowledge published in the scientific literature and/or calculated from databases. Consequently, this methodology allows compilation in the calculation algorithms of most of the regional observations and experimental studies that demonstrate the separate and combined effects of different pressure factors on different natural values.

Importantly, this approach allows the databases to be updated, i.e., the calculation algorithm can be readily supplemented with new knowledge on pressures and their effects on natural values. PW4B tool was applied to analyse how different human activities would interactively affect nature assets concerning the Estonian Maritime Spatial Planning (MSP). As such, the PW4B tool allows knowledge from empirical marine science to be applied effectively in decision-making, to bridge the divide between science, policy and management, and to support sustainable maritime development.

Users can use the portal to estimate impacted areas and changes to natural assets caused by any combination of anthropogenic pressures. The PW4B tool can be used to predict individual and synergistic effects – both current and future – of a wide range of human activities and can be used regardless of scientific background. The tool was tested in the Baltic Sea region in coordination with the Estonian MSP process and using some plausible future scenarios. This test evaluated the combined effects of human activity such as fisheries, aquaculture, wind energy, mining and maritime transport sectors on nature assets such as selected seaweed, invertebrate, fish habitats, and bird and mammal species. The analyses showed that current Estonian maritime spatial planning options would result in a moderate loss of some nature assets and a significant gain of benthic suspension feeders. However, predicted losses in wind park areas could be mitigated if novel aquaculture activities such as mussel or macroalgal farming are established. The studied scenario analyses indicate that a business-as-usual attitude will cause permanent losses in benthic habitats due to the combined adverse effects of excessive nutrient input and non-native species in both soft and hard bottom habitats. Nutrient load is one of the strongest pressures. However, this is a manageable pressure that can and should be reduced. The scenario analyses showed that reducing nutrient load by 25% together with the presence of non-native species and projected wind parks is a significant improvement for the marine environment. It is therefore highly encouraged for Estonia to follow the HELCOM nutrient reduction targets to conserve valuable marine environments. These tests demonstrated how spatial planners can use the PW4B tool to minimize adverse environmental effects, suggest effective mitigation strategies, and attain sustainable planning solutions.

The capacity of modelling approaches to produce scenarios is a frequently reported strength. Scenario-based models should be implemented to explore effects and/or benefits of human activities to ecosystem services provision, and vice versa. Scenario analysis can be used to include society preferences of what future would they prefer and can improve transparency in decision-making processes. Further, the use of trade-off analysis techniques should be consolidated to better understand and communicate intra-sectorial environmental and socio-economic conflicts of planning solutions. Also, the integration of the ecosystem services concepts within global change phenomena such as climate change, can provide further advancement in the integration and provide novel insights into climate change adaptation strategies.

SUMMARY IN ESTONIAN

Ruumiliste otsustustugede arendamine võimaldamaks merede jätkusuutlikku majandamist

Ruumilised otsustustoe süsteemid ühendavad ruumilisi ja mitteruumilisi andmeid, geograafiliste infosüsteemide analüüsi- ja visualiseerimisfunktsioone ning temaatilisi otsustusmudeleid, et leida erinevatele probleemidele lahendusi ja hõlbustada kompromisside leidmist. Võrreldes traditsioonilise otsustustoe süsteemidega mängivad uudsetes otsustustugedes organisatsiooniválised andmed väga suurt rolli, sest asjakohaste väliste andmete kaasamine võimaldab mitmekesisemaid analüüse. Otsustustoed on hädavajalikud kriisiolukorras reageerimiseks ja erinevate stsenaariumipõhiste analüüside läbiviimisel. Nende kasutus peab olema mugav ning tulemuste esitusviis lihtne, isegi kui arvutusalgoritmid on väga keerukad.

Merede jätkusuutlikul majandamisel on selliste ruumiliste otsustustugede kasutus vältimatu, kuna andmete iseloom, osapoolte erilaadsus ja läbiviidavate analüüside mitmekesisus ei võimalda alternatiivsete lähenemiste kasutust. Vaja on luua otsustustugesid, mis näitlikustavad ruumiliselt inimtegevusi ja inimtegevustest põhjustatud keskonnamõjusid ning ökosüsteemi komponente ja nende poolt pakutavaid hüvesid. Selliste andmete ja analüüside avalik kättesaadavus hõlbustab arutelusid erinevate sidusrühmade vahel ning parandab sellistel aruteludel vastuvõetud otsuste kvaliteeti.

Doktoritööl oli kolm suuremat eesmärki: (1) anda ülevaade olemasolevate ruumiliste otsustustugede võimalustest Euroopa merede ruumilisel planeerimisel, (2) töötada välja uued kaasaegsed ruumilised otsustustoed võimaldamaks merede jätkusuutlikku haldamist ja (3) katsetada väljatöötatud otsustustugesid juhtumiuuringutes.

Olemasolevate ruumiliste otsustustugede funktsionaalsuse uurimisel käsitleti nende kontseptuaalseid (sh. eesmärgid, funktsioonid või kasutaja-arendajate kogukond), tehnilisi (sh. programmeerimiskeel, tarkvararaamistik, andmesisestus) ja praktilisi aspekte (sh. sidusrühmade kaasamine, väljatöötatud tööriistade rakendamine mereala ruumilise planeerimise protsessis). Erilist tähelepanu pöörati kumulatiivsete mõjude hindamise (CEA) võimalustele, milline võimekus on olemas kõikides uuritud otsustustugedes.

Doktoritöö raames töötati välja NG-SRW veebirakendus, mis võimaldab dünaamiliselt modelleerida naftalekke levikut ja seda visualiseerides hinnata võimalike reageerimismeetmete eeliseid, et kujundada sobiv reageerimisstrateegia. Veelgi enam, naftareostuse protsessi simulatsioon võimaldab naftatõrjumisega tegelevatel asutustel paremini mõista merekeskkonnas toimuvate protsesside dünaamikat ning seeläbi paremini juhtida naftareostustõrje tegevust. Veebipõhine tööriist võimaldab luua ühine olukorrateadlikkus naftareostuse tõrjega tegelevate otsustajate ja teiste osalejate, näiteks kaubalaevade ja laevaliiklusteeninduskeskuste operaatorite vahel, mis on oluline naftareostuse kahjulike mõjude minimeerimiseks.

Doktoritöö raames töötati välja ka teine veebipõhine otsustustugi, PlanWise4Blue (PW4B), millega on võimalik hinnata erinevate survetegurite kumulatiivset mõju mereelustikule. PW4B arvutusalgoritm tugineb peamiselt eksperimentaalsetele või vaatlusandmetele ning puuduva info korral lähtutakse mõjude hindamisel ekspertteadmistest. PW4B tööriista saab kasutada inimtegevuste eraldi- ja koosmõjude prognoosimiseks nii tänapäevaste kui ka tuleviku kliimamuutuste tingimustes. Portaali kasutajal ei pea olema loodusteaduslikku haridust.

Esimeses juhtumiuuringus katsetati PW4B tööriista Eesti mereala ruumilise planeerimise protsessis. Planeeringu käigus hinnati inimtegevuse, näiteks kalanduse, vesiviljeluse, tuuleenergia, kaevandamise ja meretranspordi sektorite kombineeritud mõju loodusväärtustele, sh. mõnedele merevetikatele, selgrootutele, kalade elupaikadele ning linnu- ja imetajaliikidele. Analüüs näitas, et praeguse Eesti mereala ruumiline planeerimisega kaasneks mõningate loodusväärtuste mõõdukas vähenemine ja märkimisväärne kasu filtreerivatele merekarpidele. Loodusväärtuste vähenemist saaks leevendada merre rajatud vetika- ja/või karbikasvatuste abil. Teises juhtumiuuringus kasutati PW4B tööriista, et prognoosida tõenäoliste majandamisstsenaariumide keskkonnamõjusid merepõhja elupaikadele. Läbiviidud stsenaariumianalüüsid näitasid, et praeguse olukorraga leppimine põhjustab püsivaid kadusid merepõhja elupaikades, mis on peamiselt tingitud liigsetest toitainete koormustest ja võõrliikide kahjulikest mõjudest erinevates mereelupaikades. Toitainete koormus on üks olulisem Läänemerd mõjutav survetegur. Kuid tegemist on hallatava survega, mida saab ja tuleb vähendada. Stsenaariumianalüüsid näitasid, et toitainekoormuse vähendamine 25% võrra (isegi võõrliikide ja kavandatud tuuleparkide olemasolul) toob kaasa merekeskkonna seisundi märkimisväärse paranemise. Sellest tulenevalt on väga oluline, et Eesti järgiks HELCOM toitainete koormuste vähendamise eesmärke, et säilitada ja parandada väärtuslikku merekeskkonda. Uuringute käigus läbi viidud stsenaariumianalüüsid näitasid ilmekalt, kuidas PW4B tööriist pakub mereplaneerijatele operatiivset otsustustuge võimaldamaks vähendada kahjulikke keskkonnamõjusid, teha ettepanekuid tõhusate leevendusstrateegiate kohta ja luua jätkusuutlikke planeerimislahendusi.

Töö tulemused julgustavad kasutama olulisemates otsustusprotsessides modelleerimisel põhinevaid stsenaariumarvutusi, et uurida inimtegevuse mõju ja/või kasu ökosüsteemi hüvede osutamisele. Stsenaariumianalüüse kasutades saame teada ühiskonna eelistusi selle kohta, millist tulevikku nad eelistaksid ning paraneb otsustusprotsesside läbipaistvus. Lisaks tuleks arendada metoodikaid, mis võimaldaks leida parimaid kompromisse keskkonnaalaste ja sotsiaalmajanduslike eesmärkide saavutamisel. Ökosüsteemi hüvede kontseptsioonide integreerimine globaalsete arengute, sh. kliimamuutuste konteksti, on PW4B portaali arendamise üks järgmisi perspektiivseid suundi, kuna pakub uudseid teadmisi ja lahendusi just kliimamuutustega kohanemise osas.

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PUBLICATIONS

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Scientific publications

Kotta, J., Fetissov, M., Szava-Kovats, R., Aps, R., Martin G., 2020. Online tool to integrate evidence-based knowledge into cumulative effects assessments: Linking human pressures to multiple nature assets. Environmental Advances, 2, 1–15.

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Veebipõhised otsustustoed, mere naftareostuse tõrje, survetegurite kumulatiivsete mõjude hindamine

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