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Design and Insights Gained in a Real-World Laboratory for the Implementation of New Coastal Protection Strategies

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Abstract: Novel strategies in coastal protection are needed to cope with climate change-induced sea level rise. They aim at the sustainable development of coastal areas in light of intensification and land use changes. A promising approach is the design of nature-based solutions (NbS), complementing the safety levels of technical infrastructure. However, NbS lack a widespread and large-scale implementation. To address this deficit, co-design concepts are needed that combine experiences from science and practice. This work presents and discusses the approach of a coast-specific real-world laboratory (RwL) addressing the inclusive design of ecosystem-based coastal protection. Strategies of RwLs are applied for the first time in a coastal context along the North Sea coastline in Germany. We found the concept of RwLs suitable for coastal transdisciplinary research, although adaptions in the spatial reference level or flexibility in location and time of experimentation are necessary. A profound actor analysis is indispensable to specify participatory processes and interaction levels. A criteria-based cooperative selection of RwL sites helps to reveal and solve conflicting interests to achieve trust between science and practice. Addressing site-specific characteristics and practitioners' needs, our coastal RwL provides a mutual learning space to develop and test NbS to complement technical coastal protection.

Keywords: coastal transformation; ecosystem services; transdisciplinarity; nature-based solutions; southern North Sea; Gute Küste Niedersachsen

1. Introduction

Intensification of economic activities, urbanization as well as changes in land and sea use impose increasing pressures and aggravate the state of coastal environments. Additionally, settlements and developments in coastal areas are increasingly imperiled by the impacts of climate change and sea level rise [1,2], exacerbating coastal squeeze [3,4]. Novel attempts and strategies that enhance coastal resilience are sought [5,6] as infrastructure development and implementation often impair (or even ignore) coastal ecosystems and simply compensate for the anticipated loss of biodiversity [7]. A promising approach to promote coastal resilience are nature-based solutions (NbS) that offer or even exploit services provided by ecosystems [8,9], e.g., wave attenuation [10,11], accretion of sediments or reduction of erosion naturally provisioned or supported by coral reefs, salt marshes, seagrass meadows or coastal dunes [12–16]. Further studies and experiences of NbS are provided and discussed, e.g., by Scheres and Schüttrumpf [17] on alternative plant coverage and its root systems stabilizing sea dikes or by Schipper et al. [18] on the ecological dimensions of beach and foreshore nourishments with marine aggregates, such as sand and gravel. Temmerman et al. [9] more recently reviewed and synthesized available knowledge taken from field-proven experiences of nature-based coastal protection measures to progress mitigation of coastal storm impacts and erosion. In research, NbS are obviously and increasingly seen as complementary elements to coastal infrastructure while enhancing safety levels and mitigating financial aspects of construction and maintenance [19–21]. Nevertheless, NbS still lack more widespread and large-scale implementation [9]. Some of the reasons that hinder an implementation are mainly the unquantified performances of NbS in the concert of varying coastal protection elements, unknown side effects and co-benefits, and broadly spread misbelief in NbS in contrast to hard coastal infrastructure [22]. Along the North Sea coastline, coastal protection operates in a dilemma. On the one hand, it is strictly regulated at the national, regional or municipality level, and the flexibility to test and experiment with novel protection elements is marginalized. On the other hand, there is a growing need and desire by some actors to find innovative and sustainable answers, and this is motivated by the pressing predictions of climate change-induced sea level rise, its acceleration towards the end of this century and the general long duration of planning processes of infrastructure projects. However, there are increasingly more windows of opportunity for sustainable solutions, as many of the existing coastal protection measures have to be upgraded in ongoing adaptation processes, strengthened, or even realigned to adapt to the impacts of climate change [3,4,6]. To foster the implementation of NbS within this process, the combination of different strategies [22] and participatory methods are increasingly applied and implemented in real-world contexts [23].

Transdisciplinary research modes by means of participation and extended collaborations between various actors (including scientists) unveil the potential to become involved and actively progress an innovative and demand-driven research process [24–26]. These processes can help to find practical solutions and initiate societal changes on the transformative path toward sustainable development. In this context, real-world laboratories (RwLs) have become increasingly popular as a novel transformative format for transdisciplinary sustainability research and are adopted for a growing range of topics [27]. So far, experiences have been gained in implementing RwLs, mostly in rather small-scale urban and neighborhood developments, e.g., addressing climate protection or adaptation, while dealing with questions of future-oriented mobility and energy supply [28–30]. This work has not yet found implementations of RwLs in coastal settings, and thus, for the first time, seeks to explore the benefits and challenges that coastal RwLs might have through a practical implementation at the Lower Saxonian North Sea coastline.

Some initial assessments have also been conducted to explore structures, concepts, and definitions of RwLs [31–34]. Being a "hybrid space" between scientific experimentation and the real living world and, thus, involving stakeholders in research approaches, RwLs signify a novelty helping to jointly design, test, and evaluate pathways and solutions to shape society. They promote broader as well as reflective thinking and structure transformation processes towards sustainable development [35,36]. It can be assumed that the structure of an RwL is suitable to address the lack of implementation of NbS as described above; nevertheless, adaptions for coastal specifics are indispensable and not yet demonstrated in realistic implementation scenarios.

Given the above-outlined lack of implemented demonstrators for RwLs in coastal settings, we aim with this work at designing and testing a coast-specific RwL approach; the RwL itself intends to strengthen and integrate NbS in coastal management, a true challenge in the context of formalized regulations, normative frameworks, stipulations, standards and guidelines, and thus to realize sustainable coastal protection and resilient coasts. The overarching aim is to advance the entire portfolio of ecosystem functions and services while safeguarding human settlement and enabling coastal livelihoods. A coast-specific RwL approach is developed to test and iteratively adjust potential solutions in co-design, co-production, and co-evaluation with a broad number and diverse spectrum of actors with different mandates, interests, and responsibilities. Actors with concerns in coastal strategies include water and coastal management authorities, nature conservation, and tourism experts, municipal and state authorities, federal government bodies and institutions, NGOs, and civil society.

This work presents and discusses a novel context-specific concept of a coastal RwL, illustrating our multi-year experiences in the inter- and transdisciplinary project "Gute Küste Niedersachsen" (GKN). Being the first RwL on the German North Sea coast, we discuss design stages, procedures, challenges, and initial findings on the implementation of a coast-specific RwL, as well as the selection and prioritization of experiment locations.

2. Methods, Procedures, and Challenges to Coast-Specific RwLs

The RwL approach is tightly connected to transdisciplinary research. Transdisciplinarity has been defined as "a reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge" [37] (p. 26). The conceptual model of transdisciplinary research has been refined in the last two decades and communicated in different process diagrams [37–39]. The main complement to (multi)disciplinary and interdisciplinary research is the active integration of societal actors into the production of knowledge and joint evaluation of the main outcome. RwLs use and complement this approach by targeted interventions, so-called 'real-world experiments' with rigorous scientific framing to explore new means of achieving transformative knowledge [40,41]. The concept by Wanner et al. [36] builds upon previous attempts and develops a cyclical framework for RwLs within transdisciplinary research, which comprises the three phases of co-design, co-production, and co-evaluation.

We adapted and iteratively modified this framework to harness its potential for transdisciplinary coastal research. To structure central parts and processes of a coast-specific RwL, we 1. defined constitutive characteristics of a coast-specific RwL, 2. identified actors and actor networks including co-evaluation, 3. developed a co-selection process for RwL sites and 4. validated the coast-specific RwL approach by elaborated success factors, using a specific sub-set of factors by Bergmann et al. [25].

2.1. Constitutive Characteristics of a Coast-Specific Real-World Lab

Constitutive characteristics of RwLs have been described and discussed in the literature, often in the context of mobility, energy transitions, or climate mitigation [25,42,43]. They are mainly based on transformative approaches to urban and neighborhood development. They are characterized by a transdisciplinary research mode and participation, scientific and societal co-learning, laboratory and model character with transferability of results, and experimental design with the normative aim of sustainability and transformation. These features and archetype elements may also apply or be easily adapted to an RwL that deals with questions of sustainable coastal management. For the real-world problem—to foster the design and implementation of NbS in coastal protection strategies—inter- and transdisciplinary approaches and experiences from science and practice partners are essential. E.g., coastal authorities and science partners need to exchange ideas about their goals, to collaboratively learn about the benefits and chances of NbS in coastal protection systems, and to develop knowledge on transformation requirements that may finally lead to the proof-of-concept of NbS in coastal protection strategies. This can mainly be achieved by exploring new means, testing solutions on-site, and interpreting results together to prove or falsify concepts of NbS. However, there are unique characteristics of the coastal setting that need to be addressed by a coast-specific RwL approach (Table 1).

Table 1. Characteristics of coastal settings to be addressed by a coast-specific real-world lab.

Coastal Characteristics	Requirements
Large spatial reference level in comparison to city districts and differences in environmental conditions	Selecting RwL sites carefully with regard to the diversity of environmental conditions and allowing for permanent contact/facility on site
Temporal scale of development, planning, and implementation of NbS measures that range in the order of decades	Presenting NbS elements of coastal protection in illustrations, visualizations, and visions of high quality that allow actors to perceive value without real construction action on the ground
Several communities or regional entities to be involved and a high number of relevant/concerned actors	Getting to know actors and their complex network, including decision-making processes, to enable broad-based and targeted collaborations
Low degrees of experimental freedom in terms of safety aspects (storm surge) and access (high tide, nature protection zoning)	Knowing constraints and being prepared to adapt location and time of experiments and (if necessary) the number of collaborators in experiments

The spatial reference level of any coastal protection scheme or strategy is far larger than, for example, a city district. To find the most suitable NbS compatible for a specific coastal environment, we experienced a dilemma: choose the greatest possible diversity of locations (transferability of results) or have a permanent coastal observation lab or facility on-site (real-world laboratory as an institution). On the North Sea coast, there are also significant differences in environmental conditions between, e.g., the barrier islands and the mainland coast. To address these differences and interlinked challenges, a multi-criteria process in collaboration of interdisciplinary science partners with local actors has been executed as a first step to elucidate and prioritize suitable locations for the RwL (see Section 2.3). Aside from the spatial dimension of a coast-specific RwL, the temporal scale is equally challenging, as implementations of novel NbS may, because of long-standing normative procedures, permitting processes and actor involvement on a considerable time scale, result in substantial, decade-long processes well beyond the lifetime of traditional research actions funded by governmental agencies. Such long-duration processes imply that on a level of actor engagement, illustrations, visualizations, and visions of high quality of the designed or invented novel coastal protection NbS elements are required to communicate and convey messages. Taking a wide variety of locations into account, we had to deal with a significant number of actors and intervention areas encompassing more than one community or regional entity alone. Using an actor and network analysis (see Section 2.2), key prerequisites for collaboration within an RwL context were examined and included in the approach. When planning and implementing experiments on the coast, it comes to comparatively low degrees of experimental freedom due to access or use restrictions. The main reasons for these restrictions and limitations are found in safety concerns or precautionary measures to avoid tentative damages to coastal protection infrastructure due to storm surges, in accessibility during high tide, and in protected zones for nature conservation. Thus, experiments with NbS had to be designed and realized in narrow guardrails concerning time, location, and number of collaborating participants. To finally counter the negative effects of these coast-specific challenges, we draw on the success factors of RwLs to recalibrate and improve our approach (see Section 3.3).

2.2. Actor Analysis

To meet the interdisciplinary requirements of the RwL from the beginning, a science team with researchers from seven disciplines has been compiled, covering engineering, social, and natural sciences. In several working group meetings, we discussed practical experiences of transdisciplinary projects within the science team [44–46] and concluded with a first sketch of a coastal RwL concept.

Transdisciplinarity within the RwL has been achieved by selecting relevant societal actors within the field of coastal management, primarily responsible for the design, construction, and maintenance of coastal protection infrastructure. All relevant actors were identified by undertaking a document analysis of responsibilities and strategies, policy recommendations and reports, as well as websites [47]. As a result of this analysis, a comprehensive list of national, federal, and local actors from different sectors influencing or influenced by coastal management was compiled. This list included practitioners, experts, and decision-makers in coastal protection, water management, nature conservation, tourism, and agriculture, as well as administration and politics. Based on this list, more than 50 actors have been initially informed about the intended coastal RwL, primary aims, and participation options.

After the initial analysis, 19 key actors were selected as interviewees for a Network Analysis (Appendix A). The social network data were collected through digital, semi-structured interviews using the Net-Map method, a participatory tool combining qualitative and quantitative data collection [48]. It is particularly suitable for capturing complex networks with diverse actors, including analyzing individual networks to identify the overall network structures. By applying the Net-Map method, formal and informal structures have been revealed, as well as mandates, responsibilities, and the decision-making power of relevant actors. Furthermore, cooperation and conflicts were visualized while mapping and facilitating co-creation and knowledge exchange. The resulting maps and attributes of the coastal actor network were used to substantiate the coastal RwL concept in terms of team and task definitions, communication strategies, and workflows.

2.3. Setting up the Spatial Context: Locations for the Real-World Lab

The collaborative selection of suitable candidates and prioritization of RwL sites were central tasks of the initial co-design phase and strictly necessary for the practical set-up of a coast-specific RwL. This endeavor was conducted parallel to the actor analysis and was structured in three distinct steps (Figure 1).

In the first step, we used the comprehensive list of national, federal, and local actors from different sectors (see Section 2.2) to select and contact key actors to indicate and discuss potential locations at the North Sea coastline of the federal state of Lower Saxony, Germany. In addition, and in reflection of indicated actor perspectives and demands, the research team first discussed potential locations for a coast-specific RwL in interdisciplinary workshops and compiled an assessment matrix. Thus, 15 specific coastal locations were initially pooled and discussed. These locations were assessed in the dimensions of 18 individual parameters addressing spatial, natural, and political aspects. For each of the 18 parameters, a gradual scale from 0–5 was applied, where 0 indicated "not applicable", while 5 defined "complete agreement".

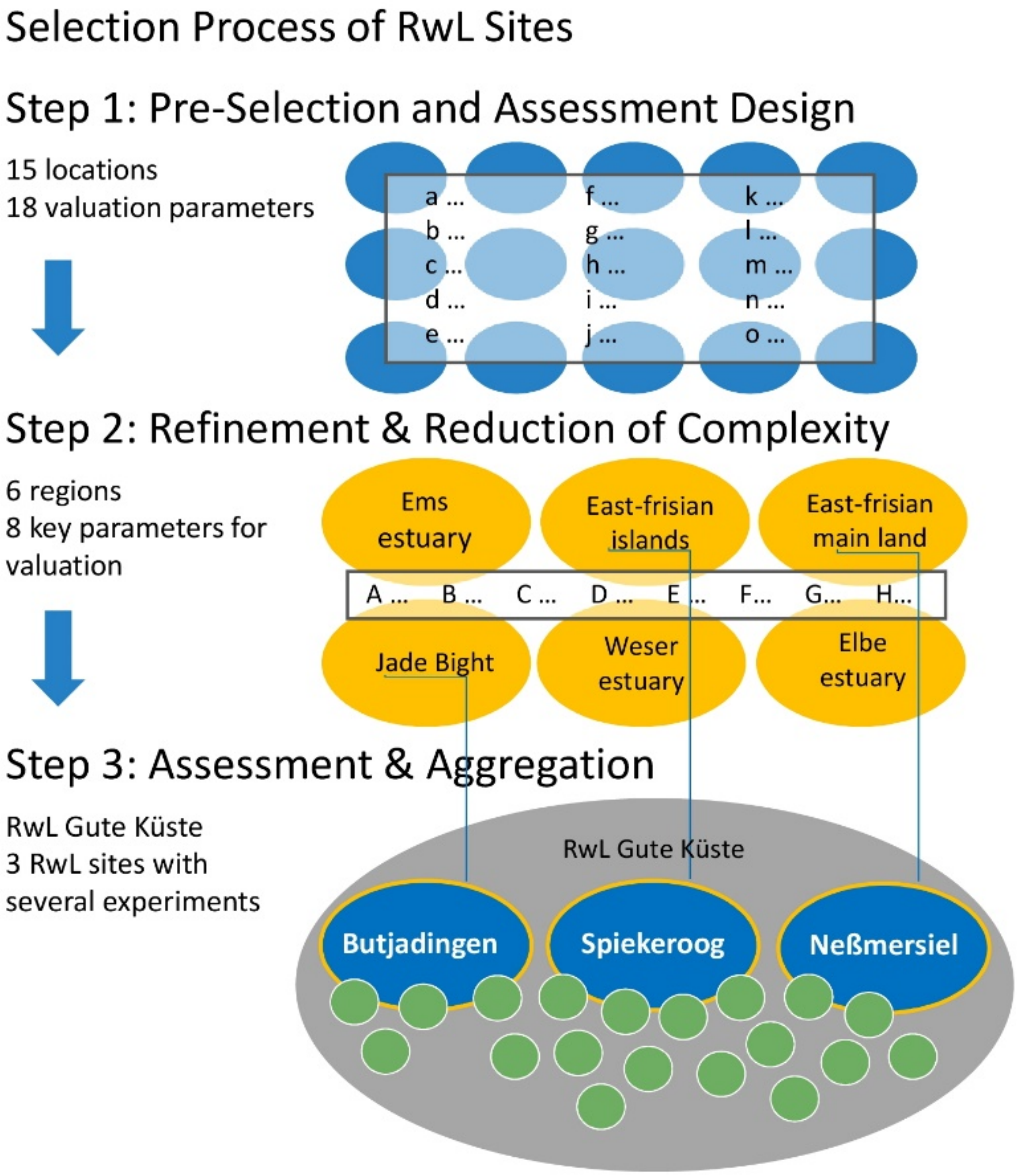

Figure 1. The selection process of sites for the real-world laboratory. The characters a to o represent the initial valuation parameters, while A to H stand for the final assessment parameters. RwL Gute Küste (Good Coast) is the name of our Real-world Lab including the three RwL sites Butjadingen, Spiekeroog and Neßmersiel.

Overall, the project's initial assessment of the potential locations and filling out the matrix was too time-consuming to be directly forwarded to involved actors for feedback and co-design. Therefore, in a second step, a workshop format was chosen to intensively discuss selection criteria and candidates for RwL locations regarding potential knowledge interests or targeting demands in novel coastal protection schemes. Participants of this workshop were all science partners of GKN and responsible actors from the Lower Saxony state authorities, the administration of the Lower Saxony Wadden Sea National Park, as well as other actors of Lower Saxony's coastal regions (e.g., national park visitor centers, dike associations, coastal research networks). At this stage, experiments were introduced as a key method of RwLs to investigate and try out innovative and sustainable NbS in coastal protection. The aim was to develop a shared understanding of experimental research and focus the selection process on possibilities for on-site experimentation to gain action-oriented knowledge.

As a result of the workshop's discussions, the research team condensed the 15 locations and 18 parameters into 6 regions to be assessed by 8 parameters. This was necessary to reduce the external workload, streamline the process and increase the overall chance for feedback to thus initiate the iterative process of co-design in subsequent stages of involvement. The 8 chosen parameters (Table 2) reflect and value the project requirements concerning the knowledge interest of science and practice as well as the implementation of joint experiments. Every parameter was assessed on a scale of 1–5, where high scores jointly correspond to preferred conditions for the intended RwL. For instance, in light of increasingly competing land use claims in the coastal zone and following the idea of co-design with multiple actors, regions with active conflicts would benefit more from RwL research and score higher (AP1). Similarly, AP2 assessed coastal regions with predominant hard protective infrastructure that incorporate a more significant potential for improvement of ecosystem services than natural systems.

Table 2. Real-world laboratory location matrix for evaluating coastal regions regarding their potential for transdisciplinary experimentation.

No.	Assessment Parameter	Assessment Scale
AP1	Existing conflicts/competing claims	1 = no conflicts; 2 = single claims; 3 = permanent overlapping claims; 4 = opposing claims; 5 = active (legal) conflict(s)
AP2	State of the coastal ecosystem	1 = natural dynamic system; 2 = restored area; 3 = managed area; 4 = dominant protective infrastructure; 5 = artificially constructed coastline
AP3	Exposure to coastal hazards	1 = no exposure; 2 = low/indirect hazard level; 3 = exposed area; 4 = increased hazard level; 5 = imminent danger
AP4	Logistics/accessibility/infrastructure	1 = own boat required/no infrastructure; 2 = ferry available; 3 = road access; 4 = public transport access; 5 = within walking distance
AP5	Scientific potential/previous studies	1 = (multiple) completed studies; 2 = preliminary studies available; 3 = axiomatic further research required; 4 = promising research perspectives; 5 = multiple open research questions
AP6	Transferability/role model character	1 = unique settings; 2 = results may be partially transferred to other sites; 3 = transferability for other German North Sea coastline sections; 4 = relevance for multiple European coastlines; 5 = role model for global application
AP7	Freedom of research/legal situation	1 = no access; 2 = non-invasive observations only; 3 = periodic invasive observations; 4 = permanent invasive experiments & observations; 5 = landscape and field experiments are freely configurable
AP8	Regional impact/visibility	1 = unknown and remote region; 2 = locally known location; 3 = regionally recognized location; 4 = trans-regionally known location; 5 = internationally recognized and well-known location

The exposure parameter (AP3) reflects the adjustment pressure on present coastal protection and, thereby, the need for actors to respond. Another parameter encompasses the logistic accessibility and local infrastructure (AP4), meaning how well the region is accessible for conducting scientific field research and transdisciplinary experiments, as well as the pre-existence of research infrastructure. The parameter "scientific potential/previous studies" (AP5) considers how far a region has been studied before or the design of an experiment has been done already. The project consortium set out to avoid regions already overwhelmingly researched by previous works. At the same time, preliminary studies and existent data series for the regions were screened to guarantee a minimum of information as a starting point. Parameter AP6, transferability/role model character, was defined to ensure a selection of sites representative of other coastal stretches rather than looking at unique coastal systems that hardly allow for the transfer of the knowledge gained. If, for example, there would be only one island along the coastline, it would not be a suitable site in terms of transferability for the remainder of the coast. Therefore, tidal barrier islands, mainland coast, and estuaries are predominant areas of interest for the coast-specific RwL. Especially, areas designated for being "restored" or altered during the project's run-time are of high interest as system states can be compared before and after.

The parameter AP7, "freedom of research/legal situation" addresses the regulation schemes expected in the respective regions. In areas with a high degree of urban development, it is more likely to encounter a reserved attitude towards experiments, which could potentially hamper the coastal protection level, ultimately endangering values and livelihoods. However, the opposite option would be an untouched natural protection zone with equally unequivocal limits, as human interference through transdisciplinary activities would foil the principle of natural dynamics. The parameter AP8 "regional impact/visibility" was chosen to ensure that scientific advancement in coastal protection was not made in secluded areas of no public interest, especially given the co-design character directly aiming at the interactive development of management concepts and research ideas with the interested public.

The matrix, compiled from Table 2, was filled in by the project team members and, in parallel, by the actors, but without insight into the preferences and choices of the other party. The results of the matrix assessments were aggregated, and potential RwL regions with the highest scores were taken for further consideration. It was observed that some participants had different specific aspects for single regions in mind and gave a range of scores. This was, in turn, regarded as an argument for further consideration.

Within the last step (see Figure 1 Step 3), research and practical questions, assigned experiments, and suitable candidate sites within the pre-chosen RwL regions were intensively discussed in a moderated online workshop to set priorities and mutual interest between researchers and actors. The parameters from the matrix in Table 2 were used as guidelines for the discussion. As a result, the final RwL sites were selected in an approach of co-design and used to refine target groups and cooperation structures.

3. Results: Design and Implementation of the Coast-Specific Real-World Lab Approach

3.1. Locations of Real-World Laboratory Sites

The assessment of potential RwL locations using the matrix compiled from Table 2 was filled in by science partners and actors and included actors in six potential regions; namely, these are (1) Ems estuary, (2) East Frisian islands, (3) East Frisian mainland, (4) Jade Bight, (5) Weser estuary and (6) Elbe estuary (Figure 2). The top-rated three regions were (2), (3), and (4). Within these three potential RwL regions, multiple field experiments and research sites were sketched and discussed with the involved actors. The comprehensive assessment matrix enabled researchers and actors alike to discuss conflicting interests and to make a reasoned selection of suitable sites. However, being in an area with high nature conservation status (Wadden Sea National Park), the options to obtain permits for accessing specific areas and conducting permanent experiments had a high impact on the selection of sites. As a result of this comparative assessment within the pre-chosen regions, three final RwL sites have been selected: (1) Spiekeroog, (2) Nessmersiel and (3) Butjadingen (Figure 2).

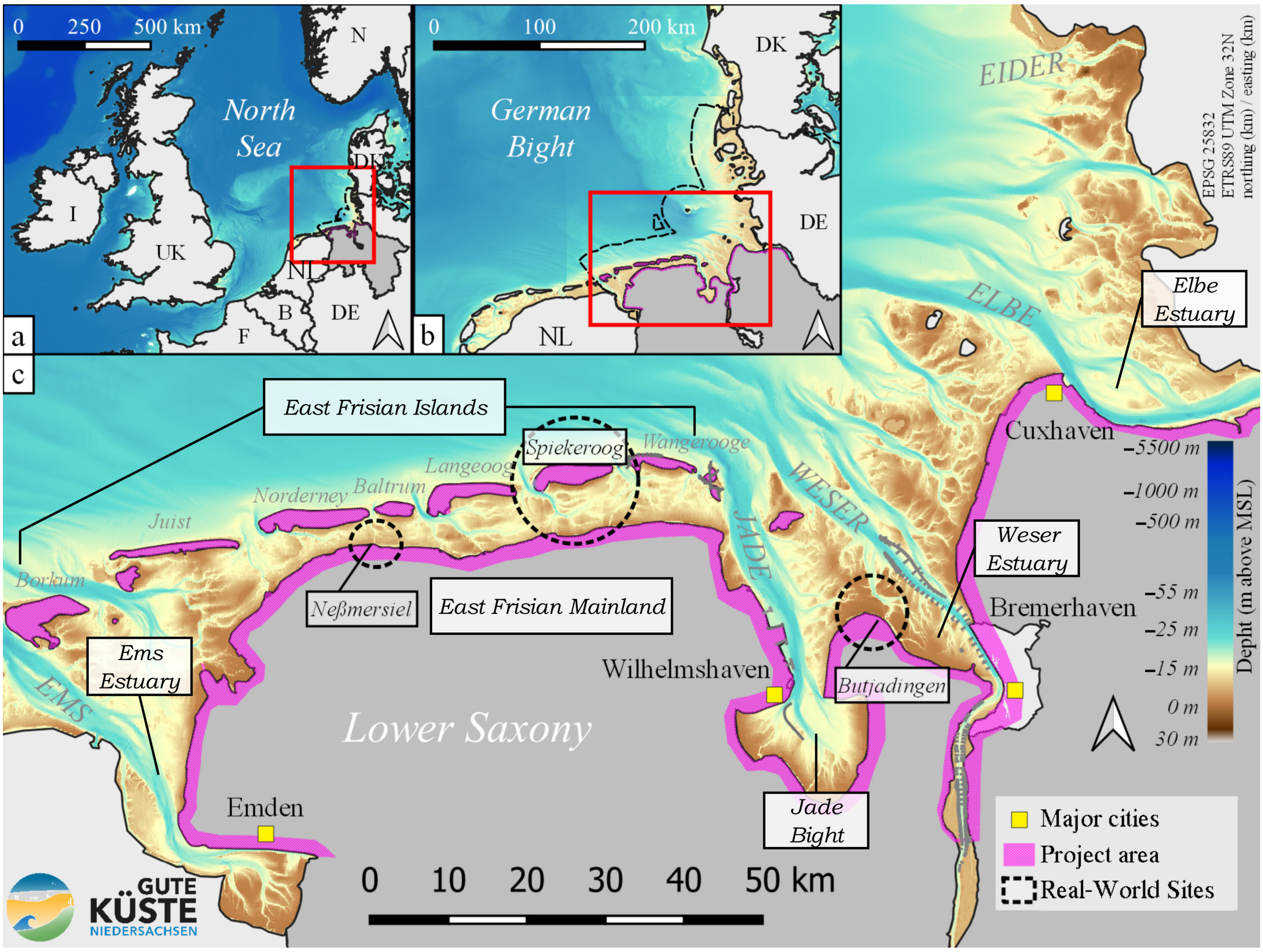

Figure 2. (**a**) Project site in northern Europe, (**b**) Coastline of Lower Saxony, northern Germany at the German Bight and (**c**) Potential RwL regions and final RwL sites at the North Sea coast of Lower Saxony (Germany) within the general project area (magenta). Data used in this map was made available by the EMODnet Bathymetry project, www.emodnet-bathymetry.eu, funded by the European Commission Directorate General for Maritime Affairs and Fisheries. The data originator(s) are the Federal Maritime and Hydrographic Agency of Germany, the United Kingdom Hydrographic Office, the British Oceanographic Data Centre, the Danish Hydrographic Office, Norwegian Hydrographic Service, Geological Survey of Ireland, IFREMER, MARINE GEOSCIENCES, and GEBCO.

The barrier island Spiekeroog is one out of seven East Frisian tidal barrier islands, stretching the coastline of Lower Saxony, with a solid pre-existing scientific and observational infrastructure [49] that compensates well for disadvantages in accessibility (access by ferry, no roads on site). The island features both hard protection infrastructure and large natural reservation areas with marginal intervention. Similar to other barrier islands worldwide, it forms the first line of coastal protection, which resulted in high scores for exposition and transferability as well as visibility due to the tourism activities. The second RwL site, Nessmersiel, was mutually chosen for the ongoing research activities; as it belongs to the East Frisian-mainland coast along the 720 km long dike line of Lower Saxony with a polder designated for future restoration during the project run-time with more locations to follow in the near future. With these construction works upcoming, fewer restrictions for in-situ field research based on existing zoning in nature conservation areas were anticipated, and excellent potential for transferable insights due to the chance of prior- and after-restoration experimentation. The third RwL site, Butjadingen, was chosen from the RwL region Jade Bight. It is a peninsula in the Weser estuary, representing estuarine conditions with a polder that has been restored in the recent past allowing for a hindcast assessment of coastal restoration work [50]. Estuarine conditions are a significant part of the overall German North Sea coastline, and thus, the surveyed actors felt the need for such a complex region to be included in the portfolio of research sites. The Butjadingen site features directly exposed dikes with high water levels and considerable wave attacks, areas with competing claims from agriculture and natural restoration, and some existing tourism infrastructure with a focus on coastal processes enhancing the visibility of field research.

3.2. Characteristics of a Coast-Specific Real-World Lab: Involved Groups, Collaboration Processes, and Workflows

Our jointly designed final approach of an advanced coast-specific RwL is visualized in Figure 3. The heart of the RwL approach to implementing new coastal protection strategies is the science-practice interaction space. Here, co-design, co-production, and co-evaluation processes take place and, thus, an iterative inter- and transdisciplinary integration and dissemination of ideas and results. Embedded in the science-practice interaction space are both the science team and the real-world sites. In terms of interdisciplinary collaboration, the science team brings together various disciplines and research backgrounds. It is responsible for experiment planning and implementation, coastal system analysis, interdisciplinary integration, and scientific dissemination. The real-world sites represent the geographical location of the RwL and the involved local actors. Transdisciplinary cooperation and actor engagement are embedded in an interactive, dynamic process that links to site-specific interests and needs. These requirements are addressed by conducting and adapting on-site experiments to derive and disseminate practical knowledge (e.g., on NbS). Partners from the real-world sites and the science team constantly reflect and integrate the experiment planning and results within the different co-phases in the science-practice interaction space.

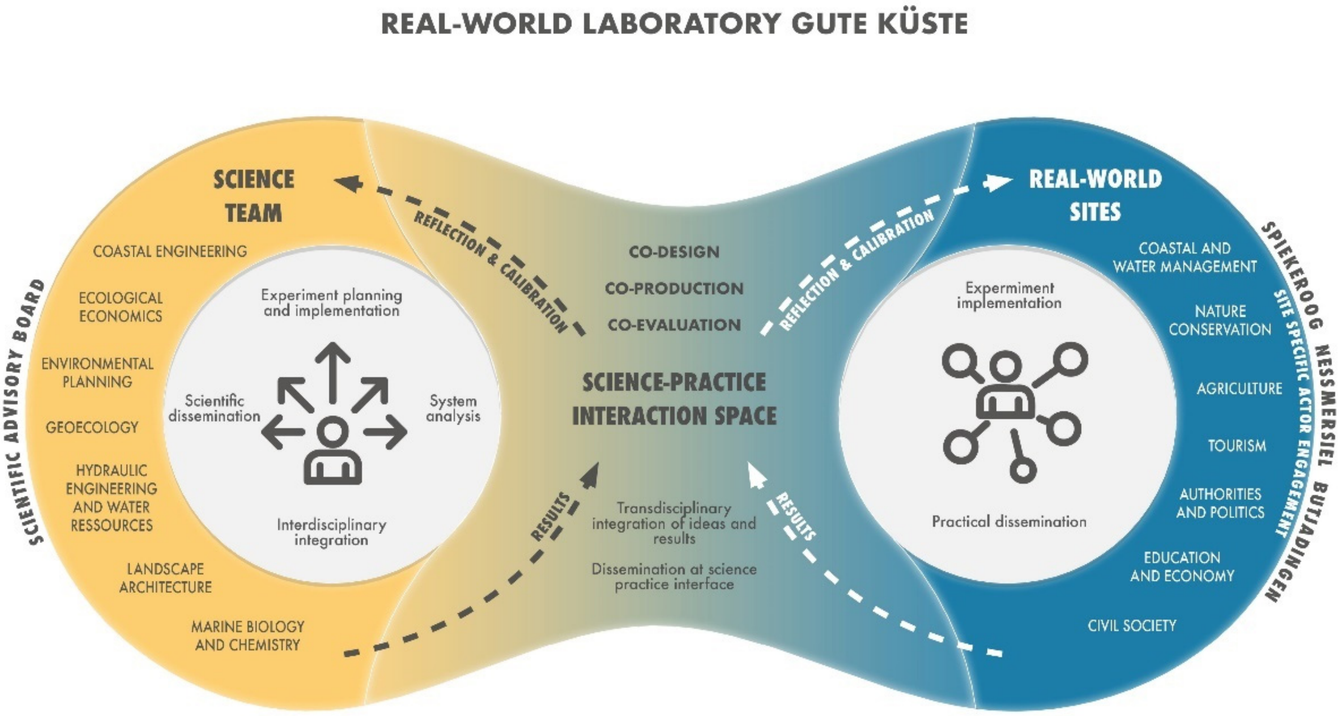

Figure 3. Design of the coast-specific real-world laboratory exemplified by the project "Gute Küste Niedersachsen" (schematic approach, graphics by Felix Brennecke and David Kreis).

In the following, we describe the coast-specific RwL approach exemplified by the project "Gute Küste".

The **science team** comprises researchers from seven disciplines, namely coastal engineering, ecological economics, environmental planning, geoecology, hydraulic engineering and water resources, landscape architecture, and marine biology and chemistry (Figure 3); these are organized in four interdisciplinary work packages: observation and analysis, ecosystem services, socio-ecological systems, and hydraulic and morphological modeling. Regular meetings of the work packages are complemented by the jour fixe of the science team and workshops to provide space for iterative interdisciplinary integration and mutual learning. The central task of the science team is the interdisciplinary coastal system analysis with field surveys to record and evaluate coastal ecosystem services and coastal protection measures, including field and lab experiments and system modeling. Additionally, socio-economic framework conditions are examined by assessing the cultural values of ecosystems and executing an actor-network analysis. During the regular meetings, research questions, experiment design, scientific results, and dissemination were discussed. In workshop formats, a common understanding of key aspects has been developed, as the involved researchers have different scientific backgrounds in terms of concepts and terminology. During the first phase, these workshops included, e.g., the interdisciplinary design of a customized ecosystem service classification and a set of criteria for the selection of sites for the RwL. The iterative and mutual learning process during these workshops led to a common terminology on ecosystem services in the multidisciplinary research team, the integration of different approaches for ecosystem analysis, and the consideration of specific requirements for field research. Initial drafts of the science team, e.g., site selection criteria or experiment design, were introduced and discussed with actors of the real-world sites to jointly elaborate them further. The experiments' feasibility was also secured during field visits and direct consultations with site-specific actors.

As per Section 3.1, the **real-world sites** of the RwL Gute Küste are Spiekeroog, Nessmersiel, and Butjadingen. At these sites, co-designed experiments are conducted, including the participation of actors and civil society. Involved actors belong to water and coastal management, nature conservation, agriculture, tourism, local and regional authorities and politics, education, and economy. This broad spectrum of different interest groups is necessary to secure a holistic RwL approach that incorporates the multi-faced requirements for a good coast. Permanent contact persons of the science team organized consultations and site visits to discuss specific on-site requirements and subsequently adapt experiments. Beyond this intense participation process, further actors and residents are informed, consulted, and involved through interviews, exhibitions, outdoor installations, and workshops, as well as broad local media coverage (press, social media, and TV).

The **science-practice interaction space** is the main interface for the inter- and transdisciplinary knowledge exchange and mutual learning in and between the three RwL sites. Here the methodological approaches from science and the implementation requirements of practice are brought together to elaborate transformative knowledge. In regular analog or digital meetings that encompass different methodological formats (such as qualitative and quantitative interviews, focus groups, or workshops) co-design, co-production and co-evaluation are explicitly implemented and supported through calibration and reflection with the science team and actors of the real-world sites. The designated tasks to be worked on in the interaction space emphasize the cyclical and iterative process of all co-phases. The coast-specific RwL and its science-practice interaction space can best be exemplified by example activities and procedures, as follows:

- In moderated science-practice meetings, criteria for selecting RwL sites have been elaborated (co-design); these were then transferred to an assessment matrix (co-production). Based on the matrix, the science team and actors decided on the real-world sites (co-evaluation).
- Scientists and actors alike contribute ideas for experiments. On the one hand, these experiments investigate the design or "how-to" of nature-based coastal protection

solutions. On the other hand, concrete solutions are tested experimentally at the RwL sites. In online meetings, science partners and actors elaborate on the experimental design for joint implementation (co-design and co-production) and thus pave the way for sustainable knowledge integration.

- The networks of involved actors have been conducted (co-design). Based on the individual networks, the overall network of each RwL site has been developed and verified in feedback interviews (co-production). Subsequently, the overall networks, their implications for decision-making processes and resulting needs and further steps have been discussed in focus group meetings with the interviewed actors from each site (co-evaluation).
- Through site visits and workshops, science partners and actors of the RwL sites transdisciplinary interpret and integrate the results of the coastal system analysis and NbS tests and evaluate the application and transfer options (co-evaluation).

Through the intensive and recurrent involvement and collaboration within the interaction space between the science team and actors from the real-world sites, a high level of inter- and transdisciplinary participation [51,52] is achieved with the meaningful influence of participants on and responsibility for the RwL (Figure 4).

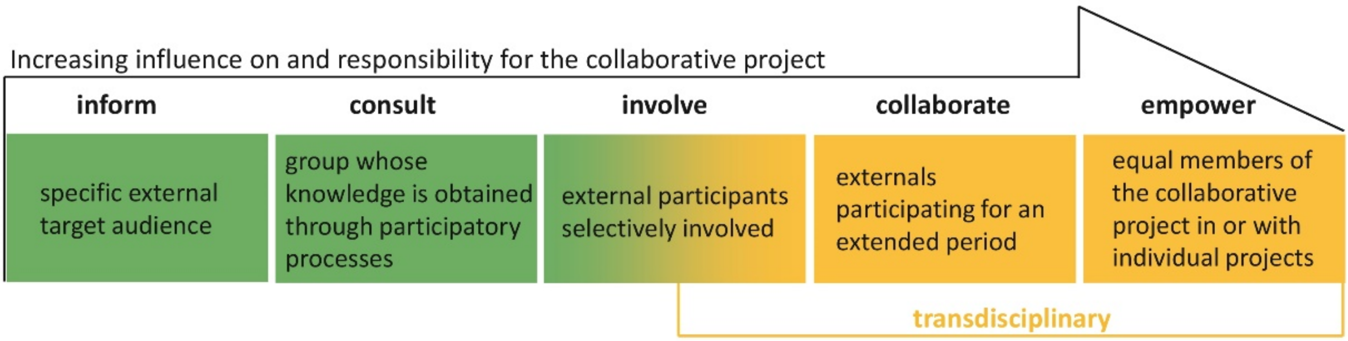

Figure 4. Transdisciplinary participation levels in the coast-specific RwL Gute Küste.

3.3. Validation with Real-World Lab Success Factors

During the implementation phase, we decided to do an intermediate evaluation by reflecting on our RwL against 11 RwL-success factors proposed by Bergmann et al. [25]. Table 3 shows that we already addressed most success factors, such as "Make use of the experimentation concept", "Develop a 'collaboration culture' between science and society", "Be attached to concrete sites" or "Provide research-based learning and reflection in RwL settings". At the same time, we saw possibilities for improvement for "Address the needs, interests, and restrictions of practitioners" or "Actively communicate" [25]. For these two dialogue-based success factors, we improved our communication (due to pandemic restrictions of Covid-19 for live meetings), particularly by using visual digital workspaces and online pin boards such as Mural or Padlet (www.mural.co; https://padlet.com, both accessed on 3 January 2023). In addition, we introduced an RwL logbook to document our consultations and agreements with societal actors.

Table 3. Real-world lab success factors and corresponding measures in the RwL Gute Küste.

Real-World Lab Success Factors	Real-World Lab Gute Küste: Measures
(1) Find the right balance between scientific and societal aims	We carefully discussed the different roles and expected outcomes between scientists and local actors in the starting phase and set up the organizational structure accordingly.

Table 3. *Cont.*

Real-World Lab Success Factors		Real-World Lab Gute Küste: Measures
(2)	Address the practitioner's needs and restrictions	Our main products of scenarios and guidelines for ecosystem-based coastal protection in the face of sea-level rise are timely and highly demanded by practitioners; they are highly visible and aim for long-lasting, transformative effects. We were unfortunately not able to include financial compensation for the practitioner's engagement.
(3)	Make use of the experimentation concept	We use different types of experimentation: In addition to the traditional disciplinary and interdisciplinary experiments, we also conduct transdisciplinary experiments such as the mapping workshop "Growing together" on Spiekeroog or "Coast-Snap" (UNSW Sydney 2023) as a citizen science approach in Butjadingen.
(4)	Actively communicate	The existing network between the scientific and societal actors was intensively tightened at the beginning of the RwL Gute Küste. We improved our communication (due to pandemic restrictions for live meetings), particularly by using visual digital workspaces and online pinboards.
(5)	Develop a 'collaboration culture'	The collaboration primarily happens in transdisciplinary experiments and joint workshops. Covid was a problematic issue in the first two years for the collaborative culture; the local actors were only partly involved in the co-design of the research application.
(6)	Be attached to specific sites	We have three clearly defined RwL sites with selected local societal actors. Workshops and regular attendance at these sites foster public attention.
(7)	Create lasting impact and transferability	Our project is still ongoing; thus, factual statements on the impact are limited. We aim at transferable guidelines applicable for ecosystem-strengthening coastal design beyond Lower Saxony´s North Sea coast and addressed this, e.g., by selection parameters for the RwL sites.
(8)	Plan for sufficient time and financial means	With five years, the RwL Gute Küste is already longer than the usual three-year funding period for research projects. However, a funded pre-phase for co-design would have been helpful, while regular planning and permitting processes for coastal infrastructure measures have even decadal time frames.
(9)	Adaptability	We have intensive discussions about the character of the RwL and adapted the relation between the whole RwL and the RwL sites; the scientific partners have regular meetings with the scientific advisory board, which lead to adaptations afterward, e.g., the character of the transdisciplinary experiments. Workflows and participatory formats were reflected and adapted to meet the demands of researchers and societal actors (e.g., a mixture of workshops, bilateral meetings, logbook of actor contacts)
(10)	Research-based learning	Students (and societal actors) are actively involved in experimental and transformative research processes; we had an exhibition of related student work in the National Park House of Spiekeroog, which also serves as public education. In general, by integrating the societal actors into the discussion of scientific work, research-based learning on the side of society is achieved.
(11)	Recognize dependency on external actors	We calculated buffer time for approval processes to conduct experiences which often take longer than expected. Changes of mayors had more or fewer consequences in two of the three RwL sites.

4. Discussion

Implementing sustainable, safe, and ecosystem-friendly coastal protection strategies that cope with or compensate for the impacts of climate change require new and proactive approaches. These approaches and derived strategies need to be scientifically proven and broadly accepted by coastal authorities and other responsible actors to enable integration in guidelines and actions. The above-described and developed coast-specific RwL provides an excellent approach to pursue these targets by testing solutions on-site under various conditions and demands which allows interpreting results together with science and practice incorporating a framework of continuous and mutual learning. However, the specific coastal characteristics have required novel adjustments to the RwL concept, neither incorporated in previous RwL attempts nor discussed in the pertinent literature.

We have abandoned the spatial reference level of previous RwLs with a focus on single rather small-scale areas in favor of a higher site diversity in our coastal RwL; see some of the more recent RwLs on (sub-)city-scales such as Zurich [53] or Stuttgart [54]. Our approach to multiple and regional RwL sites has, for the large spatial extent of the RwL, disadvantages in terms of pooling activities and resources and, thus, poses challenges in terms of permanent local presence and institutionalization. At the same time, the choice and set-up of our three RwL sites have allowed us to address site-specific requirements in the respected coastal zone, e.g., the RwL team can move to other locations within the RwL sites if unforeseen or sudden challenges arise regarding accessibility, access of permits (see also permitting issues mentioned in [55]) or implications from storm events. In addition, experimental findings of the tested solutions already cover multiple coastal and environmental conditions, e.g., barrier island coastlines or estuarine conditions, allowing for a broader and easier transfer of findings and results to progress science communication and means for decision-making.

Since transferability is a major concern and success factor of RwLs, we also made it a chief parameter for site selection, based on an intentionally initiated discourse, following an extensive dialogue and finally resolved consensus between science and practice. However, the co-design process of this parameter-based site selection also brought to light conflicting meanings and interpretations of the parameters commonly found to be relevant. Thus, we introduced the RwL location matrix, which supported the discourse relating contradicting viewpoints to each other and customizing parameter expressions. Although this was not effortlessly resolved and needed at least several months to emerge within the consortium, it helped structure the selection process and create transparency and, in the end, trust and acceptance among the various actors in science and practice.

Some of the chosen valuation parameters for the site selection represent these contradictions; here, we exemplify this ambiguity by using the parameters "freedom of research/legal situation" and "regional impact/visibility". Here transdisciplinary theory and coastal reality partly collided or emerged as obstacles to be tackled: To conduct transdisciplinary research with a high level of societal participation, sites with a high visibility and public awareness for adaptions of coastal protection are needed. In parallel, densely populated areas are strictly regulated in terms of coastal protection to save settlements and livelihoods and preserve elements at risk. Thus, we partly had to choose RwL sites that have only medium visibility but allow for permanent or periodic transdisciplinary experimentation. The RwL consortium also tried to avoid regions and sites that are already intensively researched to avoid an overload of residents or administration. Nevertheless, a minimum of logistic accessibility and infrastructure is necessary and often only provided at sites with prior research activities. The East-Frisian Island Spiekeroog is a good example: In early discussions of science partners and key actors, it became clear that societal actors have already encountered several research projects (visible in good observational infrastructure) and are eager to learn to know about new research. Nevertheless, societal actors were often interested in joint activities if major concerns, such as sufficient communication in terms of information flow and participation, are secured.

In the last decade, the involvement of a broad range of actors in coastal research increased [56–58]. Similar to studies executed by Groen et al. [59] and Jordan et al. [60], results of the SNA reveal that coastal management is locked in traditional thinking and biased attitudes among sectors exist, e.g., between authorities and NGOs in nature conservation and actors in agriculture as well as coastal protection. Such formation of sectoral clusters and skepticism against innovative ideas hampers open-minded discussion and thus limits knowledge exchange in terms of conventional and ecosystem-based measures in coastal protection. At the local level of the RwL sites, informal communication is important and practiced in coastal protection and maintenance. On this level, linkages and knowledge exchange between actors are intense, whereas communication on higher authoritative levels (e.g., the federal level) is limited. The coastal network is characterized by a strong multiplexity of formal and informal relationships, which derives from different types of linkages between the actors. Multiplexity can support the diffusion of information in a network [61], but close ties can also inhibit the influx of novel information and confine the development of innovative ideas [62,63]. Understanding interactions in the coastal network on local and regional levels allows our RwL team within the science-practice interaction space to specify and organize participatory processes and to incorporate actors on different vertical and horizontal levels of interaction and exchange. Thus, we foster mutual knowledge exchange on NbS with and between actors to reduce skepticism and to facilitate the beneficial integration of ecosystem services in coastal management strategies [61,64,65].

At present, such a systematic approach of ecosystem-based coastal management and NbS in combination with a coast-specific RwL is a very innovative way forward. We address the obstacles to a more widespread implementation of NbS by enabling mutual observations and quantifications in the field, jointly evaluating and reflecting on trade-offs and co-benefits. However, this approach has neither been widely accepted nor fully implemented on the German North Sea coast, so that we cannot draw on best practice examples or ready-made solutions, yet. Rather, we recommend stimulating transdisciplinary knowledge exchange, experimental thinking, and co-learning to bring together and subsequently intertwin actor experiences with the latest scientific knowledge and outcomes elaborated in the RwL before we can define and test NbS strategies along coastlines. Since there are no established coast-specific RwLs so far, our design approach of the RwL was rather science-driven at the beginning, and relevant actors had to be motivated and activated to share their valuable knowledge to adapt coastal protection strategies. In the sequel, we have experienced an appreciation of various participating actors concerning the input from science which stipulated further discussions and led to new ideas for joint interventions. To take another step forward with large-scale implementation of NbS, more efforts are needed to validate quantified performance in other sites, to observe the robustness and adaptability of NbS, and to overcome disciplinary barriers, e.g., by addressing vertical decision-making structures in coastal actor networks.

We strongly believe that the developed structure and utilized processes in our approach, e.g., the actor analyses or the site selection criteria, can be methodologically transferred to other coastal areas in terms of the generic framework. However, some adjustments might be required, e.g., site selection parameters could change if geographic conditions are different, only urban or only remote coastal areas are considered, or areas where there are no constraints for observations and experiments. In terms of actor engagement and co-learning, short distances and cross-regional collaboration among actors are beneficial and worth considering in anyhow. Therefore, smaller RwLs with only local impact and learning spaces might be useful, which have shortcomings in transferability but better chances in (on-site) institutionalization and practical implementation of means.

5. Conclusions and Outlook

This work describes for the first time a coast-specific RwL approach by systematically illustrating the iterative and cyclic processes of co-design, co-production, and co-evaluation in defining new strategies and measures in coastal protection. We point out unique characteristics of coastal settings and demonstrate methods to address the interlinked challenges by continuous exchange and mutual learning between science and practice, such as joint actor network analysis or cooperative selection processes for RwL sites. We have shown how to carefully structure and operationalize the transdisciplinary process for a coast-specific research agenda, focusing on sustainable, ecosystem-enhancing coastal protection strategies. Three years into the RwL experience of a large interdisciplinary science team, we strongly recommend remaining very open and flexible for adjustments to the RwL in terms of (rather unexpected) obstacles and reserving sufficient time for discussion and iterations to enforce transparency, to build trust and to create acceptance across all RwL participants.

The goal of our RwL approach is to stimulate and promote transformative knowledge on NbS in coastal protection and bring about empowerment to coastal actors to progress transformation. Acting spatially explicitly, with a high level of participation, while respecting the ideas, knowledge, and interests of practitioners, our coastal RwL provides experimental and learning space to develop and test new measures leading to the compilation of NbS and technical coastal protection.

Working in parallel on three RwL sites, co-learning between different locations and regional transfer is already being implemented. Moreover, the integration of NbS for resilient and future-oriented management practices in coastal protection guidelines can be mainstreamed as a role model to influence and initiate further implementation plans at the German North Sea coast and beyond. The transfer of knowledge and science communication will also be addressed by practical recommendations for implementation jointly developed with actors and citizens, which in the medium term could be incorporated into the General Plan for Coastal Protection of Lower Saxony (Generalplan Küstenschutz [66]) and into existing regulations and recommendations (e.g., The European Floods Directive [67], Marine Strategy Framework [68].

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Appendix A

Table A1. Key actors interviewed for the social network analysis.

Sector	Institution	Level
Coastal protection	Wesermarsch district association of water and soil associations	Regional
Nature conservation	BUND e.v.	Local
Agriculture	Dike shepherd	Local
Spatial/regional planning	Planungsgruppe grün	Local
Coastal protection	Drainage association Norden	Local
Coastal protection	Dike association Norden	Local
Nature conservation	County Aurich, department of building regulations, planning and nature conservation	Regional
Administration/politics	County Aurich, climate management	Regional
Administration/politics	Municipality Dornum	Local
Agriculture	Farmer	Local
Tourism	Tourismus GmbH Gemeinde Dornum	Local
Coastal protection	Lower Saxony state agency for water management, coastal protection and nature conservation	Local
Nature conservation	National park house	Local
Administration/politics	Municipality Spiekeroog	Local
Tourism	Nordseebad Spiekeroog GmbH	Local
Education	Hermann Lietz-School Spiekeroog	Local
Nature conservation	Lower Saxony Wadden Sea national park authority	Regional
Coastal protection	Lower Saxony state agency for water management, coastal protection and nature conservation	Regional
Agriculture	Dike shepherd	Local

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