D4.3 Guidelines for building adaptation-through-restoration pathways (tested at Pilots)

27/09/2024

WP4 – Task 4.3

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REST-COAST

Large Scale RESToration of COASTal Ecosystems through Rivers to Sea Connectivity

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Preface

The REST-COAST Project (Large scale RESToration of COASTal ecosystems through rivers to sea connectivity) is an EU Horizon 2020 research project (Grant agreement No. 101037097) whose overall goal is to address with effective and innovative approaches and tools the key challenges faced by coastal ecosystem restoration across Europe. The approach chosen for this project will deliver a highly interdisciplinary contribution, with the demonstration of improved practices and techniques for hands-on ecosystem restoration across several pilot sites, supported by the co-design of innovative governance and financial arrangements, as well as an effective strategy for the dissemination of results.

Work Package 4 (WP4) focuses on the development of scalable adaptation-through-restoration plans (for each pilot of REST-COAST) based on adaptation pathways that incorporate ecosystem services (ESS) and biodiversity value (BDV) from NBS building blocks. It is envisaged that these plans will be suited for upscaling restoration in coastal systems worldwide, supported by the global scale analysis of coastal risks, costs and governance performed in WP 2/3/5. Deliverable 4.3 aims at providing guidelines for building adaptation-through-restoration pathways, based on NBS and technical measures that deliver ESS and BDV gains, tested and validated at the Pilots.

When using the adaptation pathway guidelines, it is important to apply them with flexibility to accommodate the specific needs and contexts of individual pilots. While it is recommended to follow the methodology in Chapter 2—'Generic Stepwise Approach'—to develop pathways, pilots should view these methods as flexible rather than rigid, to fit their unique restoration goals, timelines, environmental and social conditions. Chapter 3—'Restoration Pilots'—serves as a reference to provide insight from three pilots with pilot-specific approaches to build the pathways. The guidelines should be seen as a dynamic tool that can evolve based on feedback, local stakeholder input, or new scientific data, ensuring that each pilot tailors its pathway to address local uncertainties, opportunities, and challenges.

Summary

The adaptation pathway approach has been increasingly used as a powerful tool to support decision-makers to manage uncertainties and adapt strategies over time. It can help with preparing a long-term adaptation plan with clear visions and prioritizing strategies and measures through easily understandable graphic representations. The underlying approach focuses on identifying, appraising, and sequencing adaptation measures through quantitative inputs based on models and scenarios and qualitative inputs through participatory approaches with stakeholders. This guideline document outlines a structured, step-by-step methodology for guiding coastal restoration efforts through sequencing adaptation measures into pathways to achieve near- and long-term objectives. Six main steps are elaborated: 1) Understanding the current situation; 2) Defining the policy objectives; 3) Identifying possible adaptation strategies and measures in the pathway; 4) Determining early warning signals and tipping points of adaptation measures; 5) Generating the adaptation pathway map; and 6) Evaluating pathways with multi-criteria analysis. The generic methodology is designed to be flexible, allowing adjustments based on new information and evolving conditions regarding climate change and/or socio-economic developments, which is crucial for effective long-term planning in dynamic coastal environments. Both quantitative (data-driven) and qualitative (expert judgement and stakeholder participation) approaches are illustrated to develop the narratives of adaptation (through restoration) trajectory and assess the performance of pathways. Building on the Dynamic Adaptive Policy Pathways (DAPP) framework and tailored to the scope of REST-COAST's focus on coastal restoration measures, this guideline emphasizes the impact of adaptation measures on the biophysical performance of ecological systems. Along this trajectory, the definition of tipping points and the evaluation of effectiveness have been adapted to align with this focus, integrating findings from the modelling work in WP2. The pathways are structured to meet specific policy objectives, aligned with different strategies, while also providing a roadmap for scaling up restoration efforts.

This deliverable is produced in close cooperation with many other work packages within REST-COAST, which provides valuable input for several steps. We use modelling findings (WP2) to suggest early warning signals and tipping points of pathways, as well as the evaluation of effectiveness regarding ESS and BDV delivery. We apply the scorecard methodology (M4.2) to process Finance (WP3) and Governance (WP5) indicator data for evaluating pathway alternatives. The methodology is tested and validated with three pilots in this deliverable – the Wadden Sea (Ems-Dollard) pilot, the Venice Lagoon pilot, and the Ebro Delta pilot (WP1). The other pilots within REST-COAST have been applying this methodology to develop their pathways towards upscaling and implementation plans, which will be included in Milestone 19 'Visualization of complete adaptation pathways with multi-scale impacts and accompanying narratives for climate scenarios for the pilot (due M42)'. It has shown that this methodology is generally applicable in coastal restoration practice, by addressing differences regarding data collection and analysis, climate and environmental risks, biophysical and socio-economic conditions, and coastal management policy regimes.

List of abbreviations

ESS	Ecosystem services
BDV	Biodiversity value
FP	Food provisioning
CCR	Climate change regulation
WQP	Water quality purification
RFR	Reduction of coastal flooding risk
RCE	Reduction of coastal erosion risk
NBS	Nature-based Solutions
VSM+E	Visions-Strategies-Measures and Enablers and barriers of restoration efforts
DAPP	Dynamic Adaptive Policy Pathways
EWS	Early warning signal
TP	Tipping point
SLR	Sea level rise
SDG	Sustainable Development Goals
MCA	Multi-criteria analysis
KNMI	Koninklijk Nederlands Meteorologisch Instituut
IPCC	Intergovernmental Panel on Climate Change
SSP	Shared Socioeconomic Pathways
BaU	Business as Usual
WP	Work package

Glossary of key terms

Adaptation pathway: Sequences (or portfolios) of measures over time to achieve a set of pre-defined objectives under uncertain and changing future conditions. It provides a framework to explore multiple options, assess trade-offs, and make decisions that can be adjusted as new information becomes available (Haasnoot et al., 2013; Werners et al., 2021). The **adaptation pathway map** is the graphical representation of a set of adaptation pathways.

Solution space: The space within which opportunities and constraints determine why, how, when, and who adapts to climate risks. The solution space is shaped by biophysical, cultural, socio-economic, and political-institutional dimensions at a given moment in time (Haasnoot et al., 2020a).

Policy objectives: The packages (or complete selection) of policy objectives as guiding principles to achieve all described futures (visions).

Adaptation strategies: Clusters of time-dependent adaptation measures, offering actions that outline how a region or sector intends to achieve policy objectives in both spatial and temporal scopes. A Strategy usually encompasses a broad range of (more specific) measures to achieve specific policy objectives (e.g. biodiversity or coastal protection).

Adaptation measures (for coastal restoration): The basic units of construction or composition of coastal restoration efforts that contribute to the delivery of ecosystem services and the biodiversity status of the area, to reduce vulnerability to climate change. Measures can be either Nature Based Solutions (NBS) or technical interventions, that can function alone or put together in synergy with each other for upscaling. In Deliverable 4.2, NBS measures are referred to as NBS Building Blocks which are bounded by/limited with the key biophysical and socio-economic parameters of coastal restoration sites (Arslan & van Loon-Steensma, 2024).

Projects: Practical, field-based initiatives that involve direct physical interventions to enhance or restore coastal environments.

Early warning signal (Adaptation signal): The adaptive plan requires an associated monitoring system, describing signposts to monitor and related signals that indicate the necessity to implement the next actions. A signal is given if the observed value of a signpost or a combination of signposts reaches a specified critical value (Haasnoot et al., 2018).

Adaptation tipping point (Threshold): An adaptation tipping point is reached when the magnitude of change is such that the system no longer can meet its objectives, and new actions are needed to achieve the objectives (Kwadijk et al., 2010).

Biophysical tipping point: In REST-COAST, the policy objectives are related to the delivery of sufficient ESS and BDV, and decision making is about whether a certain level of changes in the biotope areas and the impact on their ESS and BDV is acceptable. We refer to the biophysical tipping point as the critical threshold at which ecological systems undergo significant changes (e.g. ecological degradation) that can hinder restoration efforts.

Pilots: Specific, real-world sites where innovative coastal restoration and adaptation strategies are tested and implemented. These pilot sites serve as experimental grounds to validate, demonstrate, and refine approaches to large-scale coastal restoration.

1 Introduction and background on the adaptation pathway approach

1.1 Why do we need the adaptation pathway approach for policy support?

Policy making has been facing deep uncertainty due to the lack of knowledge towards uncertain futures and the range of potential impacts such as from climate change. In this regard, adaptation plans are needed to specify actions to be taken to deal with challenges in both the near- and long-term futures. The exploration of adaptation pathways is an essential part in the process of developing adaptation plans. **Adaptation pathways are sequences (or portfolios) of actions over time to achieve a set of pre-defined objectives under uncertain and changing future conditions** (Haasnoot et al., 2013; Werners et al., 2021). Pathways are part of a policy and planning framework, which incorporates recurring cycles of evaluation of multiple criteria with monitoring to track both policy implementation and any changing conditions. In the context of changes and responses, as discussed by Wise et al. (2014), adaptation pathways are viewed more as an ongoing process rather than a final outcome. The goal is to identify and implement responses that will provide benefits across a range of possible future scenarios.

Developed by Deltares and Delft University of Technology, the **Dynamic Adaptive Policy Pathways (DAPP)** approach has been widely applied as a policy making support tool to deal with the changing conditions such as climate, environmental risks and socio-economic circumstances under deep uncertainty (Walker et al. 2013; Haasnoot et al., 2024). Adaptation pathway planning explicitly addresses decision making over time as conditions change. It provides decision makers with an adaptation roadmap presenting alternative policy pathways (sequences of actions), which makes policy-makers aware of the 'solution space' - the space within which opportunities and constraints determine why, how, when, and who adapts to climate risks (Haasnoot et al., 2020a), and helps to break adaptation into manageable steps over long timescales (i.e. > 50 years), starting with flexible near-term actions to avoid investing too much or too early, or locking in investments. The DAPP approach is built upon the notion that decisions are made over time in dynamic interaction with the system of concern and cannot be considered independently (Haasnoot et al., 2013).

The adaptation pathway approach has been applied worldwide (Haasnoot et al., 2024). It was applied to develop a long-term tidal flood risk management plan for London and the Thames Estuary (***Thames Estuary 2100 Adaptation Pathway Project***), which is followed by New York City and New York State in the municipality's ***climate action strategy*** in response to Hurricane Sandy (Rosenzweig & Solecki, 2014). In Australia, adaptation pathways are being piloted for coastal flooding risks by engaging stakeholders through '***Enabling Adaptation Pathways initiative'*** (Siebentritt & Stafford Smith, 2016), and New Zealand has proposed guidance for coastal adaptation using a similar approach (***The Coastal hazards and climate change guidance***) (Lawrence et al., 2018). The initial application of Adaptation Pathways in the Netherlands formed part of the ***Dutch Delta Programme's adaptive delta management*** approach, aiding in the formulation of flood risk and freshwater availability strategies into the future. It has since assisted with the exploration of long-term adaptation strategies for extreme sea level rise in the Netherlands, among many other applications (van Rhee, 2012). The adaptation pathway approach is presently being widely applied within several of Horizon Europe's Mission Adaptation projects, such as '***Pathways2Resilience***', supporting the development of transformational adaptation strategies across European regions and is incorporated as part of this project's Regional Resilience Journey; '***RISES-AM***' assessed the impacts of future sea-level rise and the effectiveness of a wide range of adaptation strategies and measures, as well as barriers to implementing adaptation at local, regional and global scales. Furthermore, the adaptation pathway approach has also been applied to better preserve European's cultural heritage from hazards and risks, such as in the ***ARCH project*** (Zorita et al., 2023).

1.2 How to develop adaptation pathways step-by-step?

Literature broadly outlines the key steps common in nearly all adaptation pathways approaches with minor variations in the sequence of several steps (Bosomworth et al., 2018; Bosomworth & Gaillard, 2019; Butler et al., 2016; Coulter, 2019; Haasnoot et al., 2013). These steps include: 1) Understanding the current situation; 2) Defining the policy objectives; 3) Identifying possible adaptation strategies and measures in the pathway; 4) Determining early warning signals and tipping points of adaptation measures; 5) Generating the adaptation pathway map; and 6) Evaluating pathways with multi-criteria analysis (Figure 1). The first two steps can be referred to as the 'decision context' for pathway development in the DAPP approach (Haasnoot et al., 2019). Chapter 2 will elaborate on these six steps with a generic methodology to show how to develop adaptation pathways step-by-step. **Pathways can be designed quantitatively using models and/or qualitatively based on expert/stakeholder assessment** (Haasnoot et al., 2024). The quantification process can happen in different steps, such as defining policy objectives, determining tipping points and evaluating the effectiveness of measures. It is important to note that **these steps are to be applied in an iterative process.** It is necessary to **review and adjust the pathways as new information and feedback become available** (Figure 2).

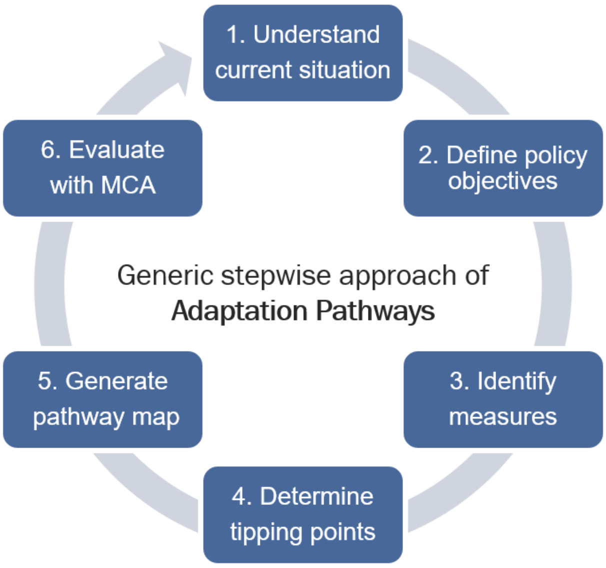

Figure 1: Generic stepwise approach of adaptation pathway development [1]

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[1] The outlined steps are based on the DAPP (Dynamic Adaptive Policy Pathways) approach and other pathway frameworks but exclude the stages of implementation and monitoring. This exclusion is primarily due to the scope of the REST-COAST project so that the focus of this guideline is on developing the pathway itself. However, recommendations on implementation and monitoring will be covered in D4.4, which will focus on a scalable plan for adaptation through restoration to bridge the implementation gap.

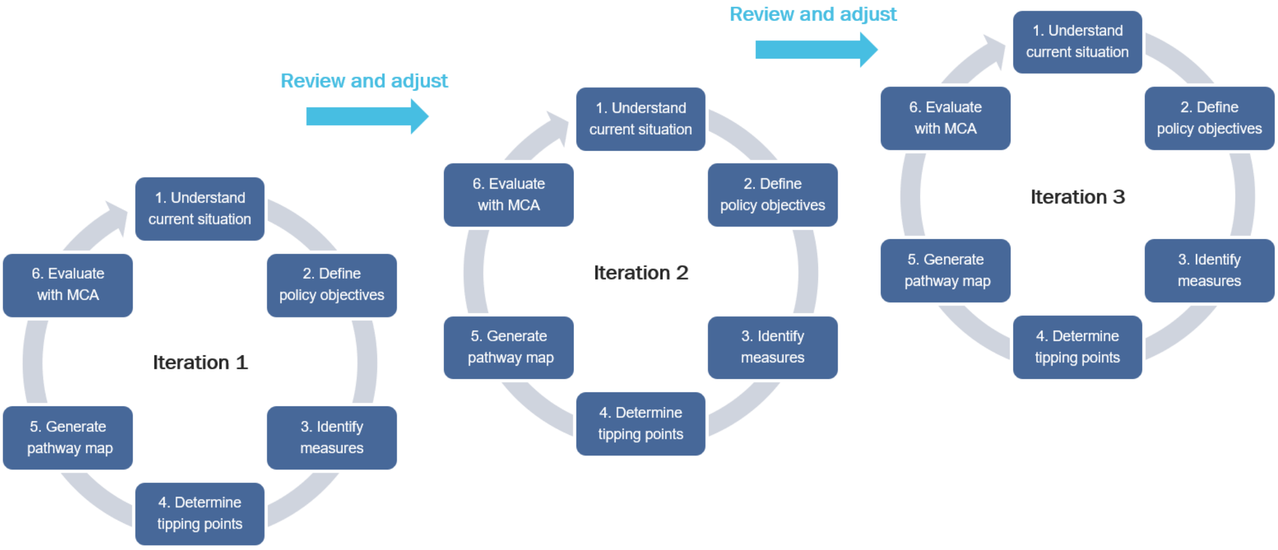


Figure 2: Iterative process of adaptation pathway development

2 Generic stepwise approach

2.1 Understanding the current situation

The first step of the pathway approach is to understand the current system including the system characteristics, and potential constraints in future situations. This step aims to describe 'the problems' or challenges and diagnose approaches to address it that are fit for purpose (at this point in time) (Haasnoot et al., 2019; Bosomworth et al., 2015).

The underlying premise of adaptation planning is that current practice - or 'business-as-usual (BaU)' - will not be sufficient to adapt to environmental and societal challenges such as climate change in the future. In preparing an adaptation pathway, this should be explicitly discussed and determined to ensure that policy objectives are aligned with the understanding of biophysical and socio-economic BaU. Business-as-usual scenarios have long been considered an essential point of reference in policymaking, planning, and investment – a baseline to compare alternative scenarios, or a starting point for analysis of a system. It has been stressed by the UN at the 2023 SDG Summit that the BaU model of development has resulted in dangerous levels of pollution, climate change and biodiversity loss, and has failed to eradicate poverty and inequality. Therefore, new adaptive and sustainable actions in a broader system perspective are urgently needed to deal with current and future challenges, while BaU is no longer an option in policy.

As detailed in D4.1 (Baptist et al., 2024), each pilot has created biotope maps using the EUNIS classification system. Furthermore, homogeneous rank scores of ecosystem services (ESS) and biodiversity value (BDV) indicators are assigned to each EUNIS habitat. We recommend using this information as a reference to describe the current situation as decision context and establish policy objectives of each pilot, such as maintaining biotype area or enhancing ESS and BDV in the near term and long term.

2.2 Defining policy objectives

The pathway development is based on the identification of the objectives, constraints, and uncertainties that are relevant for decision-making. The uncertainties are used to generate an ensemble of plausible futures.

These futures are compared with the objectives to see if problems arise or if opportunities occur. Objectives (and clear targets) are essential for developing adaptation pathways because they define the scope and limits of the issues or systems being addressed. This determines if and when any adaptation thresholds or limits may occur and thus when adaptation is needed. From this analysis, near-term and long-term policy objectives are identified to be the guiding targets of the adaptive plan with specific measures. In practice, as the project's vision broadens in scope and time ('the solution space'), the pathways tend to become more general, focusing on strategic planning. Conversely, a narrower and near-term vision results in more specific pathways that are better suited to guide individual decisions and operational planning, taking into account the specifics of the area considered (Siebentritt & Stafford Smith, 2016). **Setting up specific and measurable goals can help decision makers to assess their policies and make feasible plans accordingly**. To do so, it is essential to **establish and coordinate a multi-disciplinary working group that effectively leverages its expertise alongside local and regional governmental resources for attaining consensus on integrated visions to tackle existing and future challenges.**

It is recommended to **do a 'gap analysis' for setting up clear, specific and measurable policy objectives**. Gap analysis in policymaking is a method used to identify the differences between the current state of policies and the desired outcomes or goals. It involves assessing existing policies to determine where they fall short in addressing certain issues or achieving specific objectives. The process helps policymakers pinpoint areas that require improvement, additional resources, or new strategies to bridge the gaps (Chen et al., 2016). By understanding these deficiencies, policymakers can develop more effective plans to meet their objectives and improve overall policy performance.

2.3 Identifying possible adaptation strategies and measures

The adaptation measures are used as the basic elements for the assembly of potential adaptation pathways (a sequence of measures or portfolio of measures), that can be presented in an adaptation pathway map (Haasnoot et al., 2020a). In REST-COAST, adaptation measures refer to the basic units of construction or composition of coastal restoration efforts that contribute to the delivery of ecosystem services and the biodiversity status of the area, to reduce vulnerability to climate change. Measures can be either Nature Based Solutions (NBS) or technical interventions, that can function alone or put together in synergy with each other for upscaling. In Deliverable 4.2, NBS measures are referred to as NBS Building Blocks which are bounded by/limited with the key biophysical and socio-economic parameters of coastal restoration sites (Arslan & van Loon-Steensma, 2024). For example, saltmarsh restoration is an essential measure in coastal management that positively contributes to ESS and BDV. Adaptation strategies are clusters of time-dependent adaptation measures, offering actions that outline how a region or sector intends to achieve policy objectives in both spatial and temporal scopes. A Strategy usually has a specific focus (e.g. biodiversity or socio-economics) and encompasses a broad range of (more specific) measures that are more-or-less similar in the way they affect the region.

As a preparation for this, we have identified a clear storyline in the **VSM+E table** (Visions, Strategies and Measures of restoration efforts as well as Enablers and barriers that facilitate or hinder the efforts), from the overarching vision to sub-visions, strategies, projects and measures (see the Glossary of key terms). It's important to note that, in WP4 we mainly refer to biophysical measures (both NBS and technical interventions on the ground) that contribute to ESS and BDV, while in WP3 and WP5 financial and policy actions are considered enabling factors, paramount for implementation of measures. In some cases it might be necessary to include **a phasing plan of measures** in the pathway map when policy objectives shift over time, such as **implemented measures**, **planned measures**, **upscaling measures** and **new measures**. Each phase can be considered a checkpoint for the re-assessment and update of the pathways. This is often the case in transformation pathways. In the Wadden Sea pilot for example, where the number and total area of restoration projects needs to scale up, it turned out to be useful to set upscaling objectives per phase (see the example of the Wadden Sea pathway in Section 3.1.5). Here **upscaling refers to the process of expanding or replicating successful smaller-scale restoration projects to larger areas or more extensive ecosystems based on the policy objectives, feasibility study, impact assessment and landscape characteristics of the new target area**.

2.4 Determining early warning signals and tipping points of adaptation measures

Adaptation Tipping Points (ATP) are a key concept in DAPP. **An adaptation tipping point is reached when the magnitude of change is such that the system no longer can meet its objectives, and new actions are needed to achieve the objectives** (Kwadijk et al., 2010). Both biophysical (Bosomworth et al., 2015) and socio-economic conditions (Van der Brugge & Roosjen, 2015) determine if an adaptation measure can be implemented, or that another measure fits in more easily. An example of a biophysical tipping point is when an estuarine salt marsh cannot retreat because of geological or infrastructure constraints, and becomes permanently inundated under sea level rise scenarios. While the former salt marsh area may transform into a different habitat, its loss will lead to a decline in critical ecosystem services that the salt marsh previously provided, such as coastal protection, carbon sequestration, and habitat for wildlife. A socio-economic tipping point can be the public resistance to certain measures or the lack of funding for plan implementation. In REST-COAST, we mainly refer to the biophysical tipping points in the pathway map, while the socio-economic aspect is assessed with the multi-criteria analysis, by addressing the enablers and barriers of governance indicators as well as financial aspects. Socio-economic conditions might change over time, so they can 'tip' from a constraint to an enabling factor, opening up new pathways. In REST-COAST, the policy objectives are related to the delivery of sufficient ESS and BDV, and decision making is about whether a certain level of changes in the biotope areas and the impact on their ESS and BDV is acceptable. In this context, we use biophysical tipping points to suggest adaptation tipping points, while the management conditions (e.g. finance and governance enablers and barriers) are used to evaluate the pathways based on the four main criteria defined in Section 2.6.1.

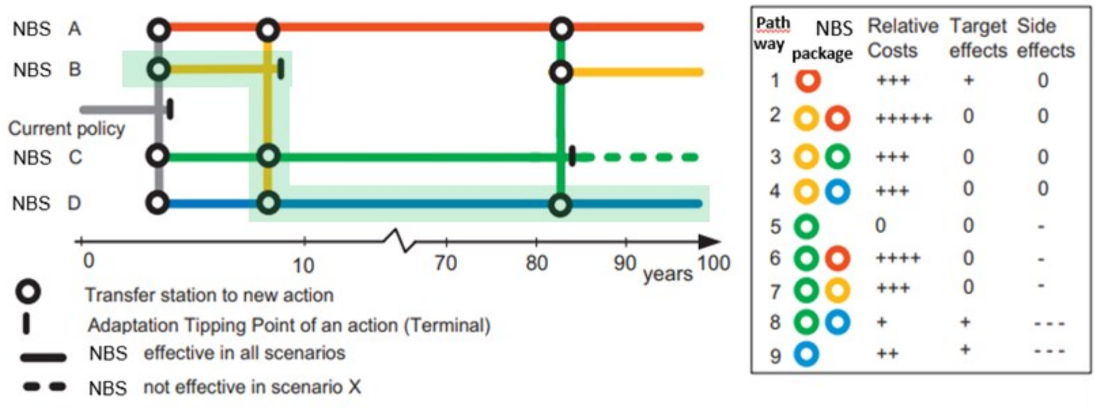
To prepare for actions when approaching tipping points, it is essential to recognize the **early warning signals (adaptation signals)** (Haasnoot et al., 2018) when a system changes to a point where existing measures should be reviewed, and new measures should be implemented. An early warning signal should occur before a tipping point being reached, so decision-makers can act upon it in a timely fashion (Siebentritt & Stafford Smith, 2016). Early warning signals are difficult to identify and to act upon. For example, sea level rise might reach a point where a large storm could destroy infrastructure. The early warning is the sea level rise reaching a level at which a management decision needs to be made. While the damage has not occurred yet, action should be taken in order to prevent the tipping point when there is actual failure of the system or it has exceeded its acceptable level or risk (i.e. infrastructure).

There are two approaches to define the biophysical early warning signal and tipping point for each measure – the quantitative approach and the qualitative approach.

In the quantitative approach, **we define the biophysical tipping point as 'the critical threshold at which ecological systems undergo significant changes (e.g. ecological degradation) that can hinder restoration efforts' (Lenton et al., 2008)**. In REST-COAST, we quantify these critical thresholds by using model projections of natural systems (i.e., biotopes) under different climate scenarios and restoration measures. ESS scores of measures are calculated based on changes to ESS supply compared to a baseline scenario to identify tipping points and early warning signals. Specifically, it focuses on determining when a restoration measure loses its acceptable level of effectiveness in terms of ESS supply and needs to be replaced or supplemented by another measure. ESS values are presented as rank-scores, derived from comparisons between different scenarios over time. For the Wadden Sea pilot, we propose that any decrease in ESS scores in a given year should be seen as an early warning signal (e.g. 2020: 0, as it is the reference year, 2030: +0.1, 2050: -0.2, then the early warning signal appears between 2030 and 2050), while a decrease of 0.5 unit in the overall ESS score for a given scenario compared to a baseline situation can be considered a tipping point (e.g. 2020: 0, 2030: +0.1, 2050: -0.2, 2100: -0.6, then the tipping point is between 2050 and 2100). This score, obtained from the methodology developed by Baptist et al. (2024) and further refined in Milestone 4.2 (Cobacho et al., 2024), identifies tipping points by quantifying changes in biotope coverage and ESS provision. For example, a 1-point reduction on the tipping point scale indicates a loss of over 245,000 hectares in the habitat of 'Faunal communities on full salinity Atlantic littoral coarse sediment'[2] due to a measure such as 'facilitating natural deposition'. In line with policy objectives that mandate no loss of existing habitats as a result of restoration (Section 3.1.2), early warning signals can be triggered by any negative value, indicating a reduction in ESS supply. Additionally, the threshold for these early warnings and tipping points is flexible, allowing different pilots to adjust them according to their specific policy objectives and pilot needs. Similarly, pilots that will not produce biotope maps, can use this line of thinking to set a suitable threshold based on their direct ESS metrics results (Marijnissen et al., *in preparation*). Additionally, the biodiversity value (BDV) of the biotopes affected by the measures could be used as a threshold for the tipping points. The BDV approach can also be used to assess the measure's effectiveness in preserving and/or improving local biodiversity by its impact on red list habitats (endangered and vulnerable) (IUCN, 2024) present in the pilot area.

The qualitative method for assessing early warnings and tipping points in adaptation pathways involves using expert judgement, stakeholder input, and existing literature to identify potential indicators and thresholds for system vulnerabilities. This method is crucial when quantitative data or biophysical models are insufficient or unavailable. Qualitative indicators can be identified from literature and adapted to the local context. For instance, a decline in the presence of key species or increased storm frequency could serve as early warning signals. It is important to engage experts and stakeholders to gather insights on the system's vulnerabilities, uncertainties, and thresholds that may signal the need for new actions. This includes consulting ecologists, engineers, policymakers, and local communities who have deep contextual knowledge of the area, through various forms of workshops, interviews, or focus groups.

2.5 Generating the adaptation pathway map (iterative process)



Adaptation Pathways Map

Scorecard pathways

Path way	NBS package	Relative Costs	Target effects	Side effects
1	🔴	+++	+	0
2	🟡 🔴	+++++	0	0
3	🟡 🟢	+++	0	0
4	🟡 🔵	+++	0	0
5	🟢	0	0	-
6	🟢 🔴	++++	0	-
7	🟢 🟡	+++	0	-
8	🟢 🔵	+	+	- - -
9	🔵	++	+	- - -

Figure 3: Example of an adaptation pathway map visualized by the pathway generator (Source: Haasnoot, Deltares)

An adaptation pathway map visualizes different possible sequences of measures (as defined in Step 3) to achieve specific policy objectives (as defined in Step 2) under various scenarios. Tools like the Pathways

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[2] https://eunis.eea.europa.eu/habitats/30266

Generator (http://pathways.deltares.nl) support the development of adaptation pathways by integrating expert and stakeholder input with insights from literature or model-based assessments. In this example (Figure 3), starting from the current situation (with current measures), objectives begin to be missed after four years, so then an adaptation tipping point is reached. Following the grey lines of the current plan, one can see that there are four options – NBS measures. Measures A and D should be able to achieve the objectives for the next 100 years in all scenarios. If Measure B is chosen, a tipping point is reached within about five more years; a shift to one of the other three measures (A, C, or D) will then be needed to achieve the objectives. If Measure C is chosen after the first four years, a shift to Measure A, B, or D will be needed after approximately 85 years (following the solid green lines). All the different sequences of measures in time result in a range of adaptation pathways. In this case, 9 pathways have been identified with all the combination options of measures. **We recommend pilots to combine pathways that align with the same policy objective / strategy so as to evaluate the pathways with specific criteria, such as the effectiveness of objectives (ESS and BDV) as well as finance / governance enablers and barriers.**

The timing of an adaptation tipping point is scenario dependent. This way a plan can be easily adapted in case of new information on changing conditions such as new (climate) scenarios; in which case only the timing of measures needs to be adapted. The concept also helps to stress-test current strategies and identify when new adaptation is needed. Scenarios are used to project possible futures under a range of conditions, especially regarding climate change and socio-economic developments. Scenarios are present in the X axis of the pathway map indicating the changing conditions, for example, sediment availability and sea level rise. There are two ways to generate pathway maps: condition-based (Figure 4) and time-based (Figure 5).

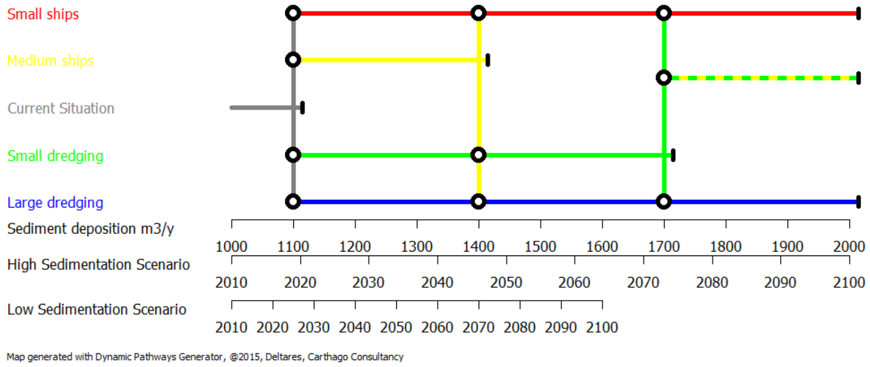

Figure 4: Condition-based: Using adaptation tipping points based on the conditions under which a policy fails. Scenarios are then used to assess the timing of the tipping points. e.g.: sediment volume; sea level rise (Source: Haasnoot, Deltares).

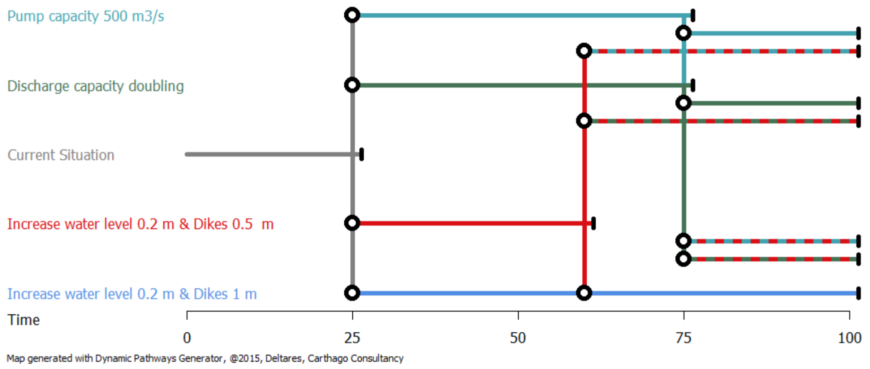

Figure 5: Time-based: Using the timing of adaptation tipping points determined from an analysis of different scenarios. e.g. 100 years (Source: Haasnoot, Deltares).

Visualizations of the pathway map can differ to meet the specific needs of pilots. More exploration of pathway visualizations will be the focus of MS19 'Visualization of complete adaptation pathways with multi-scale impacts and accompanying narratives for climate scenarios for the pilot (due M42)'.

2.6 Evaluating pathways with multi-criteria analysis

The final step is the evaluation of pathways. We developed a general evaluation framework for the main assessment criteria and scoring methodology including the following five parts. In the evaluation of pathways, it is crucial to consider the specific conditions and capacities of each pilot, particularly in terms of data collection and priorities. This flexibility allows for adaptation to the unique context of each pilot project.

1. Identify criteria to assess the consequences of each option.
2. Organize these criteria by grouping them into high-level and lower-level objectives within a hierarchy.
3. Evaluate the expected performance of each measure against the criteria by assigning scores.
4. Calculate overall scores by combining and averaging scores to determine an overall value for each pathway.
5. Review the results to ensure they align with assumptions, repeating steps if necessary.

2.6.1 Multi-criteria analysis

Multi-Criteria Analysis (MCA) provides a structured approach to assess various alternatives and prioritize multiple options based on a set of criteria. It is particularly useful when decisions involve complex trade-offs between different objectives or when qualitative and quantitative factors need to be considered together, often with a high degree of uncertainty (Belton & Stewart, 2002). When alternative pathways are developed following the previous steps, it is important to evaluate the performance of each pathway to support decision making, whether certain measures are feasible or prioritization is needed with limited budget and time. A multi-criteria analysis with a scoring strategy is applied to evaluate the pathway alternatives. Similar to the pathway design, the evaluation can be done quantitatively using models, or qualitatively relying on expert-judgement using scorecards, or through various forms of stakeholder engagement.

Within the scope of REST-COAST, four main criteria are identified as key for evaluating pathway alternatives: **Effectiveness**, **Feasibility**, **Cost**, and **Flexibility** (Singh et al., 2021; Van der Brugge & Roosjen, 2015; Haasnoot et al., 2020b). These four main criteria are further developed into sub-criteria that are aligned with the indicators developed by other work packages within REST-COAST - WP4.1 ESS scoring, WP3 Finance indicators and WP5 Governance indicators. The definitions and scopes of these criteria are summarized in the table (Table 1).

Table 1: Multi-criteria based on ESS, BDV, Finance and Governance indicators

Criteria	Sub-criteria	Description	Indicators
Effectiveness (in ESS & BDV delivery)	Reduction of coastal erosion risk (RCE)	Whether the measure contributes to slowing down the process of coastal erosion.	Reduction of coastal erosion risk (RCE)
	Reduction of coastal flooding risk (RFR)	Whether the measure contributes to reducing flood risks.	Reduction of coastal flooding risk (RFR)
	Water quality purification	Whether the measure contributes to decreasing turbidity by removing	Water quality purification (WQP)

	(WQP)	nutrients and other pollutants in the water.	
	Climate change regulation (CCR)	Whether the measure contributes to climate change regulation such as carbon sequestration.	Climate change regulation (CCR)
	Food provisioning (FP)	Whether the measure contributes to food provisioning for ecosystems, e.g. fish abundance and composition.	Food provisioning (FP)
	Biodiversity value (BDV)	Whether the measure contributes to enhancing the biodiversity of species.	Biodiversity value (BDV)
Feasibility	Technological feasibility	Whether the required technologies and associated human administrative resources are developed and available.	● Technical and organisational feasibility; ● Experimentation and learning
	Institutional feasibility	Whether institutional support is available, such as governance, institutional capacity and political support.	● Inclusive decision-making; ● Strategic vision, learning and direction; ● Coordination and coherence; ● Capacity and skills; ● Devolution
	Legal feasibility	Are there known legal and regulatory barriers?	● Governance structure and legal alignment; ● Tenure rights
	Sociocultural feasibility	Whether the measure typically finds acceptance within existing socio-cultural norms, utilise diverse knowledge systems including indigenous and local knowledge.	● Diversity of knowledge, cultures and institutions; ● Grievance and conflict resolution (trust); ● Drivers of change: urgency + liveability / wellbeing; ● Accountability; ● Leadership
Cost	Total cost	Present value of all costs of the NBS over the project lifecycle. This includes: pre-construction costs (such as design and feasibility studies), construction costs, operational costs and maintenance costs.	● Total cost
	Public funding ratio	The ratio of public funding sources. The higher ratio could indicate the less willingness of the decision maker in approving the project. More private funding sources could enable the project to be sustained in the long term.	● Public funding ratio
	Funding gap	Total cost minus funding secured. The gap could be shown in absolute monetary terms, or in percentages (e.g. 75% is secured, 25% is still open). Funding secured includes both	● Funding gap

		transfers received (grants, donations), as well as revenues generated from the NBS.	
	Cost-effectiveness	The non-monetary value delivered by an ESS of a NBS divided by the investment and maintenance costs (also called value for money).	● Cost-effectiveness
Flexibility		The relative ease by which a policy can be adapted to changing circumstances. Policies can be adjusted or switched to other measures, while the policy objectives will still be achieved.	

2.6.2 Scoring methodology

To effectively evaluate adaptation pathways, a robust scoring methodology based on the multi-criteria analysis (MCA) is essential. This approach allows for the comprehensive assessment of various adaptation measures by systematically considering multiple criteria, as explained in 2.6.1. By assigning scores to each criterion, this methodology facilitates the comparison of diverse adaptation measures, ensuring that decision-makers can prioritize actions that offer the most balanced benefits and trade-offs across different dimensions. The scoring methodology of the four main evaluation criteria is summarized below and detailed in ‘M4.2 First application of generic scorecard methodology’ (Cobacho et al., 2024).

Effectiveness

For the criterion of ‘Effectiveness’, the score is used to assess the performance of each measure in the delivery (increase or decrease) of ESS and BDV (Singh et al., 2021). Determining the ‘effectiveness’ of each measure can be approached through two different methods: the biotope maps and the direct system metrics[3]. Both methods stem from WP2 (Marijnissen et al., *in preparation*), and further information on the methodology for effectiveness calculation can be found in M4.2 (Cobacho et al., 2024).

The implementation of a restoration measure in a given scenario can vary in effectiveness depending on its impact to ecosystem service provisioning. Additionally, depending on policy objectives, the biodiversity value of an area of interest can also be used to assess effectiveness. This is particularly important when aiming to preserve endangered and vulnerable habitats present in the pilot area, as detailed in D4.1 (Baptist et al., 2024) and based on the IUCN Red List of Endangered species (IUCN, 2024).

Feasibility

The implementation of restoration projects is not always feasible. Feasibility is defined as ‘the degree to which measures (projects) are considered possible and/or desirable’. To understand what facilitates adaptation, feasibility is assessed across four dimensions: technological, institutional, legal and socio-cultural feasibility (Singh et al., 2020). In REST-COAST, feasibility is associated with previously defined Governance indicators based on the IUCN Governance Framework adopted in WP5 (see Appendix 1) (Springer et al., 2021;

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[3] The direct metrics route involves simulating future scenarios through numerical modelling of the system. These modelling exercises conducted by WP2 are meant to provide additional insights using a series of predetermined biophysical indicators that correspond to different REST-COAST ecosystem services.

Van Buuren et al., 2018). Two scale level governance indicators are defined to highlight the different levels of relevance – (higher) pilot/region level or (lower) project/measure level. This categorization is based on different impact indicators at different scale levels, discussed and acknowledged by pilots. Enablers and barriers for each governance indicator are used to assess if the measure is feasible or not. Barriers and enablers are weighted against each other – dominance of enablers means a positive score while dominance of barriers generates a negative score.

Cost

From the comprehensive list of financial indicators developed by WP3 as part of Deliverable 3.3 (Johannessen et al., 2024), we have selected a subset that provides the most relevant information for evaluating the pathways: 'total cost', 'public funding ratio', 'funding gap' and 'cost-effectiveness'. In selecting these indicators, we also considered factors such as (limited) measurability and data availability, as well as the (lack of) potential for data collection at later stages across the various pilots. This resulted in a more simplified approach in which the score of the total cost is assessed based on a relative comparison with other measures – negative score means more costly for that measure (per ha, per year) in the lifetime of the measure; Both 'public funding ratio[4]' and 'funding gap' are assessed as follows: <20%: +2, 20%-40%: +1, 40%-60%: 0, 60%-80%: -1, >80%: -2; 'cost-effectiveness' is used to assess the relative costs (investment and environmental costs) and effects (e.g. reduction in ESS as well as social benefits such as well-being and other social functions) of each measure.

Flexibility

Flexibility refers to the relative ease by which a policy can be adapted to changing circumstances (Mens et al. 2012). Flexibility is seen as a key quality of robust policies in the sense that policies can be adjusted, may be implemented sooner or later, or can be switched to other measures, while the original policy objectives will still be achieved. We use expert judgement (usually by decision makers) to estimate the level of flexibility.

As shown in Table 2, each adaptation measure is assessed semi-quantitatively with a five-point scoring methodology between -2 and +2 for all the sub-criteria for assessing the impact of the measure on each sub-criterion: -2: major negative impact; -1: minor negative impact; 0: neutral or no obvious impact; +1: minor positive impact; +2: major positive impact.

The next step is pathway scoring of the four main criteria that are used to assess pathway alternatives (Table 3). Each pathway is scored by averaging the individual scores of each measure in a pathway. For example, if Pathway 1 consists of measure 1, 2, 3, and 4 then the individual scores of these four measures are averaged to be the score of pathway 1. In this way, the pathway scoring is simplified but **the interdependence and trade-offs between measures need to be addressed**. Similar to the methods for defining early warning signals and tipping points, there are two approaches to assess these criteria and sub-criteria: the **quantitative approach with data-driven assessments** and the **qualitative approach with stakeholder-led assessments**. Data-driven assessments typically use indicators like environmental impact or economic performance, drawing from models, statistical studies, or site-specific testing to directly evaluate the effectiveness and performance of measures. Stakeholder-led assessments, often conducted through participatory workshops, relying on qualitative analysis informed by expert knowledge and experience. It fosters consensus on

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[4] While this scoring method suggests that a higher public funding ratio results in a lower score, it doesn't imply that a higher proportion of public funding is inherently negative. The impact depends on the primary objective of the measure. For example, flood defense is typically prioritized by the government and thus often heavily funded by public sources. On the other hand, farmland raising may attract more private funding to engage local stakeholders, making the funding balance context-dependent.

adaptation plans by integrating diverse perspectives, such as the socio-institutional acceptability of adaptation measures. It enhances understanding of the broader context and interconnections between climate adaptation and environmental risks, while also promoting stakeholder dialogue and cohesion (Zorita et al., 2023).

Table 2: Measure scoring

Criteria	Sub-criteria	Measure (scoring -2 to +2)										
		A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3
Effectiveness	Reduction of coastal erosion risk (RCE)											
	Reduction of coastal flooding risk (RFR)											
	Water quality purification (WQP)											
	Climate change regulation (CCR)											
	Food provisioning (FP)											
	Biodiversity value (BDV)											
	AVERAGE											
Feasibility	Inclusive and effective decision-making											
	Recognition and respect for tenure rights											
	Capacity and skills											
	Technical and organisational feasibility											
	Leadership											
	Experimentation and learning											
	Governance structure and legal alignment											
	Diversity of knowledge, cultures and institutions											
	Strategic vision, learning and direction											
	Coordination and coherence											
	Grievance and conflict resolution (trust)											
	Drivers of change											
	Devolution											
	Accountability											
	AVERAGE											
Cost	Total cost (e.g. per ha / per year)											
	Public funding ratio											
	Funding gap											
	Cost-effectiveness											
	AVERAGE											
Flexibility	Flexibility											

Table 3: Pathway scoring

Criteria	Pathway 1	Pathway 2	Pathway 3
	e.g. A1+A2+A3+A4	e.g. B1+B2+B3+B4	e.g. C1+C2+C3
Effectiveness	AVERAGE(A1:A4)	AVERAGE(B1:B4)	AVERAGE(C1:C3)
Feasibility	AVERAGE(A1:A4)	AVERAGE(B1:B4)	AVERAGE(C1:C3)
Cost	AVERAGE(A1:A4)	AVERAGE(B1:B4)	AVERAGE(C1:C3)
Flexibility	AVERAGE(A1:A4)	AVERAGE(B1:B4)	AVERAGE(C1:C3)

3 Restoration pilots (Wadden Sea, Venice Lagoon and Ebro Delta)

3.1 Wadden Sea

3.1.1 Understanding the current situation

Figure 6: Current situation of Ems-Dollard (source: Ems-Dollard 2050 Programme)

The Wadden Sea, a UNESCO World Heritage Site, is renowned for its expansive tidal flat system and largely intact natural dynamics (Gadsden et al., 2022). It is a critical habitat for migratory birds, providing foraging grounds, stopover points during seasonal migrations, and nesting sites. Conservation of the Wadden Sea is a shared responsibility across the Netherlands, Germany, and Denmark. The region consists of interconnected tidal basins, each featuring unique elements such as salt marshes, tidal flats, gullies, barrier islands, and ebb-tidal deltas. The Ems-Dollard represents one of the final remaining fully functional estuaries of the Netherlands in which saltwater gradually transitions into freshwater (Vroom et al., 2024). The estuary was formed around the 14th-15th century as a result of storm surges. In the centuries that followed, large areas around the Ems-Dollard have been drained to form polders, which has resulted in the loss of intertidal areas and habitats (Talke & de Swart, 2006). Due to regular dredging and resuspension, the low energetic regions where mud can settle and consolidate in periods of calmer conditions (i.e. the marshes and upper tidal flats) were converted to polders. The turbidity level of the waters of the Ems-Dollard has increased, resulting in decreasing ecological carrying capacity and biodiversity (Van Maren et al., 2016). An additional stressor for the Ems-Dollard estuary is sea level rise (SLR). Salt marshes are particularly vulnerable to SLR, which in severe cases can lead to marsh submergence or 'drowning' (Vinent et al., 2021). Freshwater availability is another critical concern, with the growing threat of seawater intrusion exacerbated by both SLR and land subsidence (Talke & de Swart, 2006). Without intervention to mitigate saltwater encroachment (which could occur within the next decade in some areas), many agricultural lands in the region will likely become unsuitable for farming due to increased soil salinity (Ems-Dollard 2050 Programme).

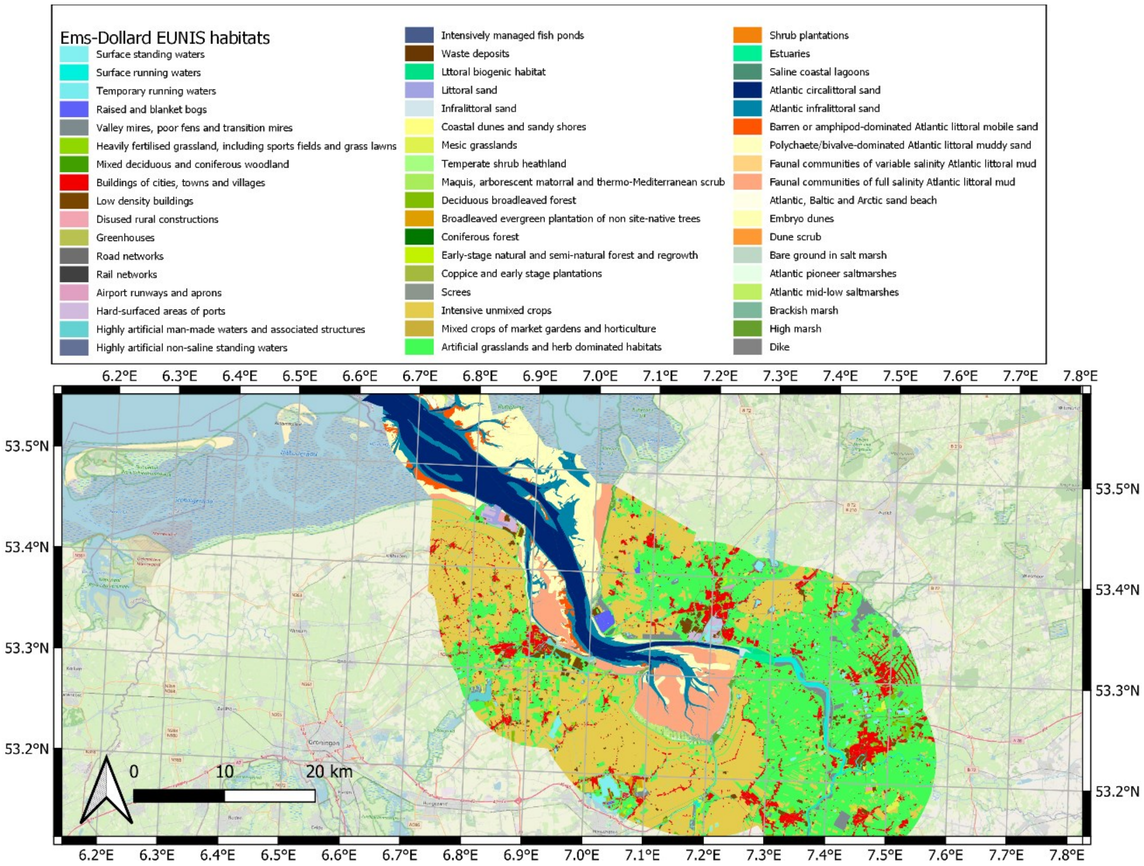

Figure 7: EUNIS habitat map showing the biotopes present in the Ems-Dollard estuary (Baptist et al., 2024)

The EUNIS habitat map of the Ems-Dollard estuary, as shown in Figure 7 was produced in Deliverable 4.1 (Baptist et al., 2024) and can be used to inform the future review of policy objectives. Deliverable 4.1 identified the biotopes present in the Ems-Dollard pilot site, assigning each biotope values for ecosystem services (ESS) and biodiversity value (BDV). Given that one of the main policy goals for the Ems-Dollard pilot site is to prevent degradation of existing biotopes (Section 3.1.2), D4.1 provides a baseline for evaluating future policy effectiveness. This evaluation can be guided by monitoring spatial changes in biotopes, reflecting the impact of restoration measures and climate change.

3.1.2 Defining policy objectives

In the Wadden Sea pilot, the long-term policy objective (overarching vision) is '**Ecology and Economy in balance**', as stated in the ***Ems-Dollard 2050 programme*** (ED2050) (Figure 8): 'In 2050, the Ems-Dollard is a robust and resilient estuary with fitting dimensions and natural dynamics, healthy habitats and smooth transitions, natural turbidity and sufficient food at the base of the food chain.' The multi-year adaptive program Ems-Dollard 2050 was initiated in 2016, in which the government and the regional stakeholders structurally work together on the ecological improvement of the Ems-Dollard through projects, measures and research. The programme is part of the ***Agenda for the Wadden Area 2050*** and included in the ***Wadden Implementation Agenda 2021-2026***.

Figure 8: Projects in the Ems-Dollard 2050 Programme

The Ems-Dollard 2050 programme has highlighted three policy objectives:

- Reducing turbidity (20-50% reduction in turbidity in the central area of the estuary) by removing at least 1 million tons of fine sediment (dry matter) annually;
- Expansion of natural habitats (approx. 600-2000 ha along the shores);
- Adapting to climate change, especially preventing any losses in the area of existing habitats and associated ecosystem service value, due to sea level rise or other climate-related impacts.

Although the Ems-Dollard 2050 programme has stressed the ultimate goal of improving the ecological value of the Wadden coast and its estuarine environment, two other policy objectives are of equal importance to achieve the vision of ‘Ecology and Economy in balance’. These two additional objectives are:

- Enhancing flood safety - resilience against climate change induced sea level rise and storm events;
- Enhancing agricultural productivity.

3.1.3 Identifying possible adaptation strategies and measures

In the policy agenda, the **Groeidelta (Growing Delta) Programme** – led by the Province of Groningen as an initiative plan of the Ems-Dollard 2050 Programme, has been recently signed to specify the adaptation strategies and measures for the coming decade (2027-2037). We have identified three main strategies (or three pillars) based on the Groeidelta Programme that aligns with the overall vision of **‘Ecology and Economy in balance’** (Figure 9). Each strategy has been further developed with several hands-on pilot projects. Each project includes one or more measures (NBS and technical interventions) (see Annex 1). Near- and long-term strategies and measures are needed to achieve the policy objectives. Although these three main strategies are developed in parallel with separate funding arrangements, they are still very much interdependent on each and have to be implemented together to achieve the overarching objective. For example, farmland raising (Strategy A) and coastal protection (Strategy B) are all dependent on the sediment extraction and reuse.

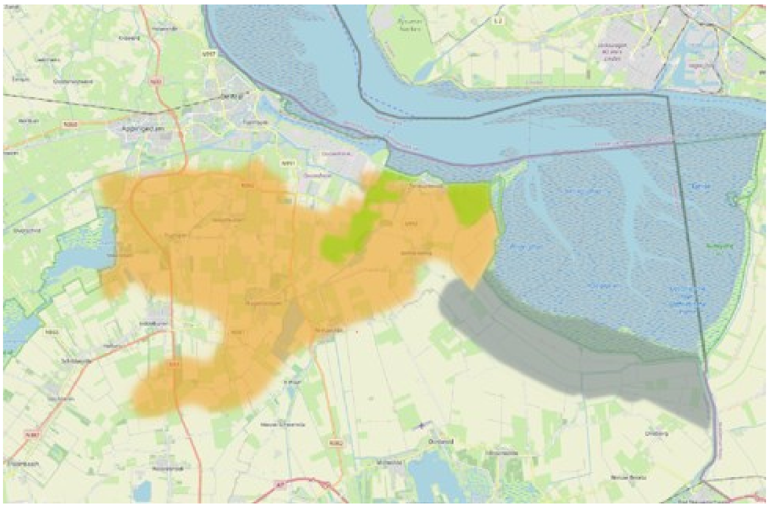

Figure 9: Areas for farmland raising (orange shade), clay ripening for the Dollard dike reinforcements (grey shade) and the natural silt trap (green shade) (Source: Groeidelta)

Strategy A. Agricultural productivity by farmland raising

To address the challenges posed by sea level rise and saltwater intrusion, the first strategy involves reusing sludge from the Eems-Dollard (sediment suspended in the water column) as material to raise low-lying agricultural land. Sludge was first applied to an agricultural plot of approximately 4 hectares near Borgsweer in 2021 (Ems-Dollard 2050 Programme). This project demonstrated that sludge from the Ems-Dollard is effective in raising low-lying soils, which supports agriculture in coastal areas. The approach has gained interest and support from over 30 local farmers. The concept has been developed for a target area of around

300 to 500 hectares, and the VLOED[5] exploration suggests that up to 3000 to 5000 hectares in the region could potentially be raised using this method, contributing to the creation of climate-resilient coastal agriculture (Figure 10).

Figure 10: Project 'Vloed' (www.eemsdollard2050.nl)

Measures of Strategy A:

- M-A1 Sediment removal (from harbor)
- M-A2 Farmland raising with local sediment (near term goal: 300-500 ha)
- M-A3 Farmland raising with other sources (long term goal: 3000-5000 ha)
- M-A4 Aquaculture and salt-tolerant agriculture

Strategy B. Coastal protection by sediment reuse

In the province of Groningen, there is a significant demand for clay to reinforce primary and regional flood defenses (A. Vos, *personal communication*). Typically, clay for such projects is sourced from river areas, which incurs high transport costs and CO_2 emissions. Additionally, suitable clay for dike construction is becoming increasingly scarce and expensive in the Netherlands. The Clay Ripening (Kleirijperij) and the Wide Green Dike (Brede Groene Dijk) (Figure 11) demonstration projects, conducted between 2018 and 2022, explored the feasibility of maturing sludge from the port of Delfzijl and the Breebaart polder into clay, and using matured dredged material from the Ems-Dollard as dike clay. Both projects confirmed that dredged material from the Ems-Dollard can be matured efficiently, making it a viable building material for dikes. This approach promotes more sustainable soil management and enhances circularity within the national dike reinforcement program. The near-term goal is to reinforce the 15km Dollarddijk, with a long-term goal of application along other sections of local flood defences.

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[5] VLOED refers to Verbetering Landbouwgronden door Ophoging met slib uit de Eems-Dollard (Improvement of agricultural land by raising it with silt from the Eems-Dollard).

Figure 11: Project 'Wide Green Dike' (www.eemsdollard2050.nl)

Measures of Strategy B:

- M-B1 Facilitating natural deposition
- M-B2 Clay ripening
- M-B3 Biodiverse dike reinforcement (near term goal: 15 km Dollarddijk; long term goal: dike extension)
- M-B4 Other measures for coastal protection (e.g. traditional dikes with asphalt)

Strategy C. Natural restoration by sediment capture

The third strategy aims at restoring natural dynamics by creating a culvert in the sea dike which allows for a controlled inundation of the area behind the primary barrier driven by tidal regimes, as shown in the Twin Dike (Dubbele Dijk) project (Figure 12). The natural process of sedimentation driven by the deposition of suspended particles carried by the controlled tide will enable low-lying coastal areas to naturally rise over time, keeping pace with expected sea level rise. This approach fosters the development of a dynamic coastal landscape, providing a gradual transition between freshwater and saltwater environments. Moreover, the design of this area offers the chance to establish breeding bird islands, surrounded by water channels, ensuring protection from land predators. The focus for this measure is on the region between Delfzijl and Termunten, the part of the coast with lowest elevation and rapidly subsiding lands. This area also marks the beginning of the Groote Polder development, which will allow for the natural expansion of sludge collection across several hundred hectares. The Groote Polder represents the first step towards scaling up these efforts.

Figure 12: Project 'Twin Dike' (www.eemsdollard2050.nl)

Measures of Strategy C:

- M-C1 Tidal area restoration (with culvert in the sea dike and saltmarsh within the dike)
- M-C2 Saltmarsh outside the dikes (near term goal: 300 ha new habitat area; long term goal: 600-2000 ha new habitat area)
- M-C3 Nesting islands

3.1.4 Determining early warning signals and tipping points of adaptation measures

Corresponding with the three strategies described in Section 3.1.3., this section aims to identify the quantitative indicators for a set of five measures through a literature study on the Ems-Dollard estuary. This set consists of the following measures: A2 Farmland raising with local material, B2 Clay ripening, B3 Biodiverse dike reinforcement, C2 Saltmarsh outside the dikes and C3 Nesting islands. In the end, using the acquired metrics, early warning signals (EWs) and tipping points (TPs) can be identified that will inform the adaptation pathway. The outcomes from the literature review are summarised in the table displayed in Appendix 2.

After thorough examination of the literature, it becomes apparent that **sea level rise (SLR)**, **saltwater intrusion** and **freshwater availability** are key indicators to be translated into the adaptation pathways. How these trends progress into the future has been tackled in the KNMI'23 report on climate scenarios. The climate scenarios presented by the KNMI'23 are a translation from the projections by the IPCC, but do show some differences in how exactly these are communicated. To give an example, the low range opted for by the KNMI coincides with the SSP1-1.9 and SSP1-2.6 scenarios formulated by the IPCC. Similarly, the high range refers to the SSP3-7.0 and SSP5-8.5. Another important consideration is that the KNMI'23 displays local data rather than global data. Nevertheless, the local data may be synonymous with global trends regarding climate change implications.

Regarding Strategy A. Agricultural productivity by farmland raising, SLR, saltwater intrusion and freshwater availability are key challenges that need to be addressed. Among which, the risk for saltwater intrusion is one of the most pressing issues for agricultural production (Deltares, 2023). Seepage with high salinity content is one of the causes for damage to crops. Particularly soils containing sand layers are most likely to experience saltwater intrusion. In such instances, reducing this risk requires a precipitation lens of at least 100 mm of freshwater and thickness of at least 1.25 m (Sweco, 2022). Mainly in drier periods (Apr-Sept), soils run the risk of becoming more saline due to higher evaporation levels. If the precipitation lens amount and thickness fall below these numbers, saline groundwater may seep into the root system of crops, thereby hindering their water uptake. In addition to the minimal depth and thickness of the precipitation lens, another critical factor indicating potential damage is the chloride concentration in seepage groundwater. Specifically, when **chloride concentration levels exceed 1 g/L**, the risk of salt stress in plant root systems increases (Deltares, 2023). This risk is especially prevalent in scenarios that predict higher overall temperatures and drier years (KNMI, 2023; Deltares, 2023). The measures of 'sediment removal (A1)', 'clay ripening (B2)', 'farmland raising with local material (A2)', and 'biodiverse dike reinforcement (B3)' show strong inter-dependency between each other as A2 and B3 rely on reusing the local material produced by A1 and B2, which suggests that their EWS and TPs are also related. It is important to note here that the clay ripening process is strongly dependent on the salinity level. More specifically, **the salinity content of the clay to be applied should not exceed 4 g/L/NaCl** (Ecoshape, 2022). Going beyond this level will render the clay inappropriate to be used for application on dikes (Technische Adviescommissie voor de Waterkeringen, 1996). The salinity level of clay is also relevant for agriculture. Therefore, it is recommendable to desalinize the clay before considering applying the material for farmland raising (Sweco, 2022). Another option is to investigate the potential of growing more salt-tolerant crops.

As part of Strategy B. Coastal protection by sediment reuse, measures such as 'clay ripening (B2)' and 'biodiverse dike reinforcement (B3)' return. As with farmland raising, the clay ripening process is also shown to depend on changes in **freshwater availability**. More specifically, the capacity for clay ripening may decrease in periods with a **precipitation deficit** as the clay must be flushed with freshwater as part of the ripening process to reduce NaCl concentrations. As the KNMI'2023 projections show, precipitation deficits are most likely to occur in the summer period running from April through September. Therefore, in order to facilitate the clay ripening process, one should carefully examine the season in which to conduct clay ripening. Preferably in seasons with a minimal precipitation deficit.

In the end, throughout the clay ripening process, mixing freshwater with salt water was not found to have any significant effect on declining salinity levels. But the mixing did result in the desired clay plasticity necessary for dike reinforcement (Ecoshape, 2022). For the subsequent measure 'biodiverse dike reinforcement (B3)', local material to be used for dike construction is dependent on a total of nine criteria (Technische Adviescommissie voor de Waterkeringen, 1996):

1. Clay must have an erosion class of II or I
2. Consistency index of at least 0.6
3. Local material has to be naturally deposited
4. Max. sand content of <63 µm
5. Organic matter <5% after hydrogen peroxide treatment
6. Lime content <25%
7. Salinity content <4 g/L/NaCl
8. No significant admixture of rubble nor gravel (sand content <40%)
9. Only slight to no discoloration of clay material

Lastly, Strategy C. Natural restoration by sediment capture with measures 'saltmarsh outside the dikes (C2)' and 'Nesting islands (C3)'. In both measures, the SLR is a prominent challenge. Generally, the rate of SLR is projected to increase under future scenarios (KNMI, 2023). More specifically, under RCP2.6 a projected increase in SLR is estimated in the range of 0.25-0.41 m, for RCP4.5 this range is estimated to be 0.27-0.52 m and in the most extreme scenario (RCP8.5), this range is estimated to be 0.36-0.76 m for the Wadden Sea alone (Vermeersen *et al.,* 2018). In relation to measure C2, salt marshes require sediment deposits as per inundation, which allows them to grow along with the rising sea level (Kirwan and Megonigal, 2013; Bunzel *et al.,* 2021; Leuven *et al.,* 2019; Kirwan *et al.,* 2016; Temmerman *et al.,* 2003). Although salt marshes can benefit from flooding, excessive periods of flooding can negatively impact the vegetation (e.g. plant growth and its productivity) and nesting potential of birds. In addition, to maintain growth in relation to SLR is only possible when the sea level does not rise too quickly, hence allowing salt marshes to increase in elevation by sediment deposition. A key threshold value to consider here for the Ems-Dollard case is a **SLR rate between 10-50 mm/y** (Kirwan *et al.,* 2016). Salt marshes can generally survive these rates, but exceeding this threshold value may present a permanently flooded plain, causing a loss of saltmarsh habitat. With respect to the measure 'Nesting islands (C3)', SLR and change in storm frequency are key indicators (Erwin *et al.,* 2006). **Seasonality of inundation** here may also add to the vulnerability, since marsh flooding during the nesting period in July, may impact the success rate of the offspring's survival. As is the case for measure C2, longer periods of inundation will cause degradation, which in the long-term may impact nesting habitats as the vegetation composition is altered.

Now that the biophysical indicators have been established, it is important to see if and when early warning signals or tipping points may be reached for their respective pathways. Important to note here is that the KNMI'23 scenarios predict an overall **increasing trend for SLR**, **temperature**, **saltwater intrusion risk** and occurrence of **extreme weather events** alternated with periods of **extensive droughts** (KNMI, 2023). With respect to the measure 'farmland raising with local sediment (A2)', a hotter and drier trend can be detected, which ultimately influences the ability of precipitation lenses to block the saline groundwater seepage (Deltares, 2023). Another trend that can be detected is for freshwater availability. The delta scenarios indicate that for 2050 and 2100, water shortage occurrence may increase as a result of climate change (e.g. SLR, more evaporation due to higher temperatures, etc.). In addition, less space will become available for freshwater production (RIVM, 2023).

Starting with the SLR, **no EWS nor TP can be pointed out for the measure 'saltmarsh outside the dikes (C2)'**. The modelling exercise demonstrates that suspended sediment concentrations will continue to increase throughout the period up until 2100. As concluded in Fagherazzi *et al.* (2012) and Kirwan *et al.* (2016), such increased sediment input will result in **natural accretion of the saltmarsh that is able to withstand SLR** even in the most extreme scenario (SSP585). Hence, the saltmarsh is projected to expand in light of increasing SLR scenarios rather than drown. For the other cases, pinpointing the exact EWS and TP remains complex as well. For instance, in determining future freshwater availability, one has to balance the freshwater amount against evaporation rates, riverine discharge and precipitation amounts (RIVM, 2023). Each of these factors contains different variables or show rough estimates that are not compatible. A similar observation can be made for measure 'Nesting islands (C3)'. In this case, the estuary's morphology (e.g. depth of the mouth), sediment supply and SLR play an important role as these variables affect the tidal range (Leuven *et al.,* 2019). Since these parameters differ per coastal ecosystem, it is hard to generalise future projections for this range. Therefore, it is important to consider the spring tides or storm frequency by means of Northwestern wind directions. According to the KNMI'23 report, Northwestern wind directions are indicative of storms.

3.1.5 Generating the adaptation pathway map

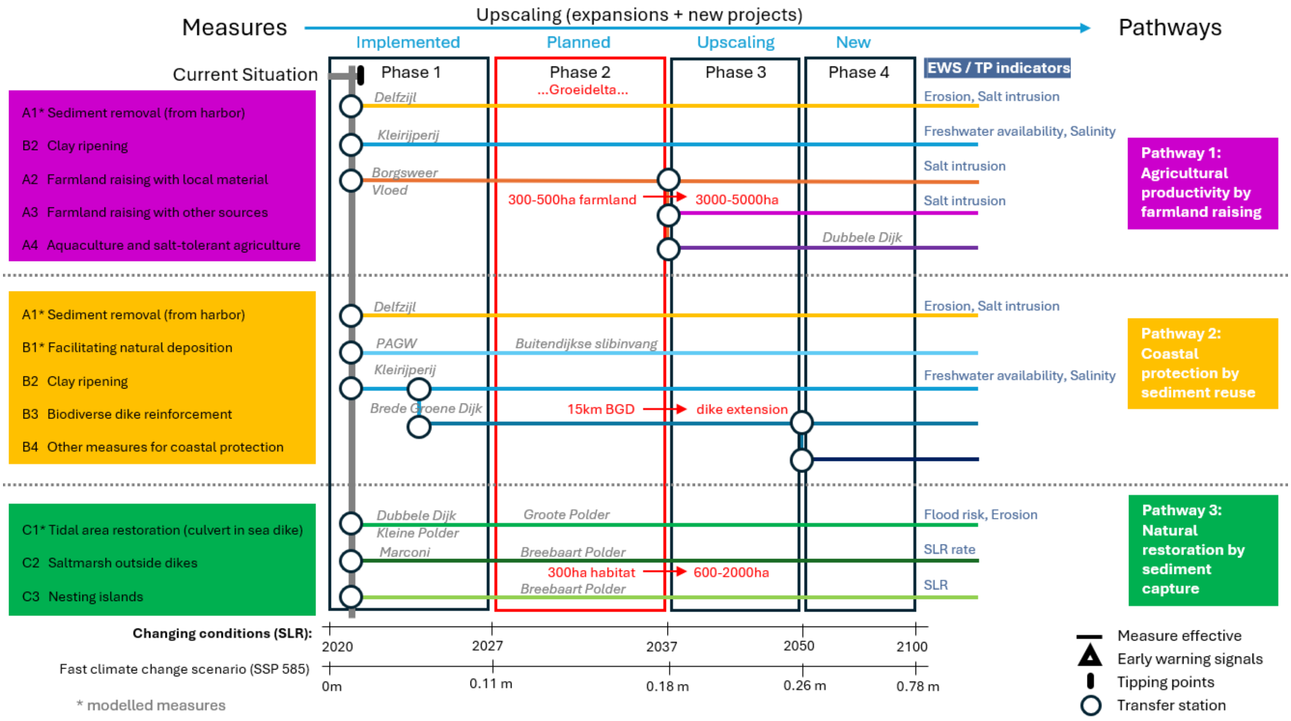

Figure 13: The adaptation pathway map of Ems-Dollard, with a condition-based scenario of SLR

Three pathways have been formulated based on three distinct strategies, each differing primarily in their policy objectives (see 3.1.3) (Figure 13). The adaptation process is structured into four phases, illustrating the progression of measures over time to meet these objectives: Phase 1: implemented measures; Phase 2: planned measures; Phase 3: upscaling measures; Phase 4: new measures (when existing measures are not sufficient to achieve adaptation objectives anymore). Each phase is associated with a certain percentage of the policy objectives being met, ultimately aiming for 100% achievement in the long term. Phase 2, highlighted in red, coincides with the Groeidelta programme, with some restoration goals extending into Phase 3 through the scaling-up of measures. Several hands-on projects are listed for each measure (in grey) that can lead to potential upscaling. We combine a timeline with a condition-based scenario in the X-axis, by referring to the SLR under fast climate change scenario (SSP585). Various climate change indicators can be mapped, such as sea-level rise, which is crucial for assessing the effectiveness of saltmarshes and nesting islands. Other indicators, like freshwater availability, storm frequency, and salinity, are more relevant for identifying early warning signals and tipping points associated with other measures.

Table 4: Overview of quantitative values for assessing tipping point and early warnings derived from the Baptist et al. (2024) methodology.

Measure name WP2	Measure name WP4	Climate scenario	2030	2050	2100
Extraction Delfzijl	A1 Sediment extraction from harbour	SSP585	0.38	1.27	1.34
Brushwood Groynes	B1 Facilitating natural deposition		1	1.55	0.83
Groote Polder	C1 Tidal area restoration		0.85	1.87	0.89

Based on model simulations, no biophysical early warning signals or tipping points were detected, as all measures proved effective in supporting ESS and BDV, although the effectiveness of B1 and C1 becomes less after 2050 (Table 4). A literature review of each measure, aligned with projected climate scenarios, indicates that they are expected to remain functional until 2100, continuing to meet policy objectives that are set in the Ems-Dollard 2050 Programme (Appendix 2). Consequently, all measures are represented as effective in the pathway map. However, key indicators for potential early warning signals and tipping points beyond 2100 are illustrated. Additionally, some transfer points within each pathway (e.g., from A2 to A3 and A4; from B2 to B3 to B4) indicate a sequential implementation of measures, enhancing their effectiveness through a phased approach.

3.1.6 Evaluating pathways with multi-criteria analysis

Using the multi-criteria analysis methodology, as detailed in M4.2 First application of generic scorecard methodology (Cobacho et al., 2024), we have evaluated and assigned scores for each criterion across the various measures (see Table 5). The 'Effectiveness' of some measures (A1, B1 and C1) is scored based on ESS changes (as of 2050 compared to 2020). The criteria of 'Feasibility', 'Cost' and 'Flexibility' are scored based on several semi-structured interviews with experts from the Province of Groningen. It is important to note that the Groeidelta Programme has adopted a 'blended finance' model in which several restoration measures are grouped into overarching strategies and the financial data is only available at the strategy (pathway) level. Therefore, all measures within each pathway are scored identically for the sub-criteria of 'cost'. By examining the three pathways against four criteria (Table 6), we can derive several insights.

Table 5: Measure scoring

Criteria	Sub-criteria	Measure (scoring -2 to +2)										
		A1*	A2	A3	A4	B1*	B2	B3	B4	C1*	C2	C3
Effectiveness	Reduction of coastal erosion risk (RCE)	+0.52	N/A	N/A	N/A	+0.63	N/A	N/A	N/A	+0.76	N/A	N/A
	Reduction of coastal flooding risk (RFR)	+0.42	N/A	N/A	N/A	+0.58	N/A	N/A	N/A	+0.69	N/A	N/A
	Water quality purification (WQP)	+0.52	N/A	N/A	N/A	+0.63	N/A	N/A	N/A	+0.76	N/A	N/A
	Climate change regulation (CCR)	+0.52	N/A	N/A	N/A	+0.63	N/A	N/A	N/A	+0.76	N/A	N/A
	Food provisioning (FP)	+0.52	N/A	N/A	N/A	+0.63	N/A	N/A	N/A	+0.76	N/A	N/A
	Biodiversity value (BDV)	+2	N/A	N/A	N/A	+2	N/A	N/A	N/A	+2	N/A	N/A
	AVERAGE	+0.75	N/A	N/A	N/A	+0.85	N/A	N/A	N/A	+0.96	N/A	N/A
Feasibility	Inclusive and effective decision-making	+1	+1	+1	+1	-1	+1	-1	+1	+1	-1	+1
	Recognition and respect for tenure rights	+1	+2	+2	+1	-1	+1	+1	+1	+1	-1	+1
	Capacity and skills	0	+2	+2	+1	+2	+2	+2	+2	+2	+2	+2
	Technical and organisational feasibility	-1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
	Leadership	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1

	Experimentation and learning	+1	+1	+1	+1	+1	+1	-1	+1	+1	+1	+1
	Governance structure and legal alignment	0	0	0	0	0	0	0	0	0	0	0
	Diversity of knowledge, cultures and institutions	0	0	0	0	0	0	0	0	0	0	0
	Strategic vision, learning and direction	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
	Coordination and coherence	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
	Grievance and conflict resolution (trust)	0	0	0	0	0	0	0	0	0	0	0
	Drivers of change	0	0	0	0	0	0	0	0	0	0	0
	Devolution	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
	Accountability	+2	+2	+2	+2	+2	+2	+2	+2	+2	+2	+2
	AVERAGE	+0.57	+0.93	+0.93	+0.79	+0.57	+0.86	+0.57	+0.86	+0.86	+0.57	+0.86
Cost	Total cost (per ha)	0	0	0	0	0	0	0	0	0	0	0
	Public funding ratio	-1	-1	-1	-1	-2	-2	-2	-2	-2	-2	-2
	Funding gap	-2	-2	-2	-2	+2	+2	+2	+2	+2	+2	+2
	Cost-effectiveness	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	AVERAGE	-1	-1	-1	-1	0	0	0	0	0	0	0
Flexibility	Flexibility	-2	-1	-1	+1	+1	0	-2	+1	-1	+1	+1

Table 6: Pathway scoring

Criteria	Pathway 1	Pathway 2	Pathway 3
	avg. (A1+B2+A2+A3+A4)	avg. (A1+B1+B2+B3+B4)	avg. (C1+C2+C3)
Effectiveness	+0.75	+0.8	+0.96
Feasibility	+0.82	+0.69	+0.76
Cost	-0.8	-0.2	0
Flexibility	-0.6	-0.4	+0.33

Effectiveness

The effectiveness score of the measures and pathways is based on the ESS and BDV scores under the high climate change scenario (SSP585) in 2050 compared to the baseline conditions of ESS and BDV in 2020. The year 2050 was chosen to provide a mid-term evaluation, as long-term projections are more uncertain, and to align with the objectives of the Ems-Dollard 2050 programme. The positive effectiveness values for the modelled measures (A1, B1 and C1) and all pathways are primarily due to the projected expansion of biotopes in the pilot area resulting from restoration measures. This expansion leads to increased contributions to ESS and BDV, as larger areas of these biotopes enhance biodiversity and the provision of ecosystem services. The biotope expansion is specifically driven by the growth of marshes and the infralittoral zone in response to restoration measures, a process accelerated by sea level rise. The complex sedimentary dynamics behind this marsh expansion are influenced by a number of interacting physical factors in the Ems-Dollard estuary, which are discussed in detail in Deliverable 2.3 (Marijnissen et al., *in preparation*). The other measures that are not modelled are marked as data not available (N/A). To allow comparison between pathways with the same method, we didn't use other (qualitative) methods for assessing the effectiveness of other measures.

Feasibility

All measures show similarly positive scores in terms of governance indicators regarding feasibility, which represents a strong capacity and skills, social engagement and governance structure in both horizontal (across sectors) and vertical (international, national, regional and local) levels. Farmland raising shows a slightly higher score due to the higher involvement of local residents and strong interests from the farmers. By comparing three pathways, pathway 1 scores slightly higher, bolstered by robust societal support and a participatory approach to farmland raising, particularly among local communities. In contrast, the other two pathways follow a more top-down approach with non-negotiable objectives, such as enhancing flood resilience through dike reinforcement.

Cost

Due to the 'blended finance' model adopted by the Groeidelta Programme, several restoration measures are grouped into overarching strategies and the financial data is only available at the strategy (pathway) level. Therefore, all measures within each pathway are scored identically for the sub-criteria of 'cost'. Three strategies (A, B and C) have the same estimated budget (100 million euros for each strategy) in the coming 10 years between 2027 and 2037. Therefore, the relative total cost score is 0 (neutral in comparison to each other). Funding of Strategy B and C are 100% secured with all public funding sources, while Strategy A has only 20% funding secured with more involvement and potential involvement of private funding. The measures are scored according to the scoring criteria (in Section 2.6.2). For the moment of this report, cost-effectiveness is not yet clear. We expect to update when data becomes available. By averaging the measure scores for each criteria, pathway 1 scores negatively due to financial constraints. Specifically, farmland raising has a significant funding gap of 80%, whereas the other two pathways are fully funded, primarily through public sources. To advance Pathway 1, more private funding sources need to be secured.

Flexibility

Certain measures within the pathways are less adaptable due to their fixed objectives and constraints imposed by other functions - for example, sediment removal and dike reinforcement. Measures dependent on external factors, such as farmland raising with local materials, show lower flexibility, as they rely on sediment availability, quality, and land use regulations. Consequently, Pathway 1 demonstrates the least flexibility compared to the other two pathways.

3.2 Venice Lagoon

3.2.1 Understanding the current situation

Since its foundation, the Venetian Republic considered Venice and its lagoon as a single entity, and Venice as the centre of a wide and productive commercial and residential system that should be carefully preserved in all its components (Deheyn & Shaffer, 2007). From a hydrodynamic point of view the lagoon is a micro tidal basin; within which the major wind systems - i.e. Bora and Scirocco - significantly impact the hydrodynamics and morpho-dynamics of the lagoon, with seasonal wind-storm events exerting a prominent morpho-dynamic control over decadal to centenary timescales (Carniello et al., 2009; Finotello et al., 2023; Janowski et al., 2020). The dynamic interaction between the morphology and the hydrodynamics creates a complex mosaic of coastal environments, including saltmarshes, seagrasses, wetlands, mudflats, islands, and ponds (Carniello et al., 2009; Ravera, 2000; Rova et al., 2022).

Over the last centuries, the hydrodynamics of the lagoon were severely affected by anthropogenic interventions - including the diversion of the major rivers, dredging of navigable channels and the construction of the jetties, extensive land reclamation, human induced subsidence - which subsequently critically impacted the lagoons' morphological evolution (Finotello et al., 2020, 2023; Solidoro et al., 2010). Therefore, the Venice Lagoon is at risk of losing a substantial amount of characteristic habitats (Figure 14A), inevitably resulting in biodiversity loss and the depletion of ecosystem services.

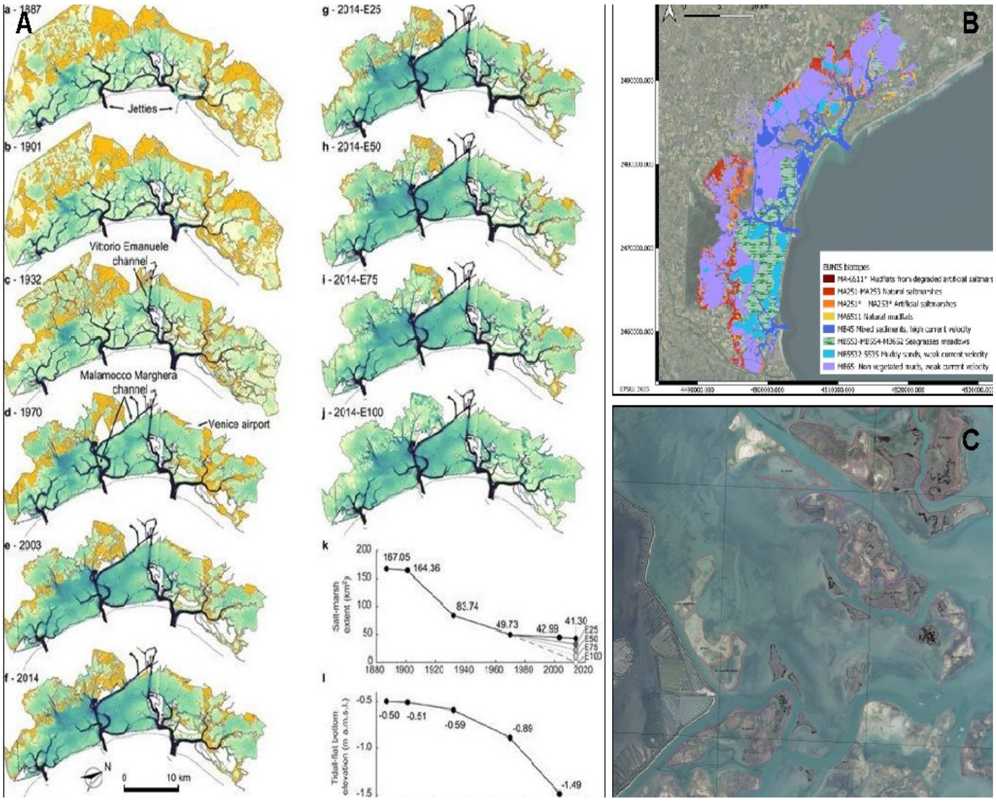

Figure 14: Understanding the current situation: A) change in the distribution of saltmarshes and mudflats between 1887 and 2014 (Finotello et al., 2023); B) EUNIS habitat map displaying the current distribution of biotopes; and C) REST-COAST focus area displaying the degradation of the saltmarshes and their proposed perimeter for restoration.

In the early 70s the national and local governments started to systematically address the safeguarding of Venice and its lagoon, including the introduction of the Special Law of Venice by the Italian government. These rules define objectives, the procedures for achieving them and the responsibilities of the various subjects implementing the interventions. The difficulty with this required restoration of the lagoon environment is establishing the baseline, the choice of establishing a reference period is scientifically difficult but rather practical for decision-making. Although various possible suggestions for a baseline were included in different policy documents, no quantifiable baseline has been officially accepted. Therefore, the current situation (i.e., the BaU) in this study is considered to be the EUNIS map (Figure 14B) developed in 2023 under the scope of the REST-COAST project, representing the 'current' mosaic of habitats found in the Venice Lagoon.

3.2.2 Defining policy objectives

The possible futures of the Venice Lagoon seem to involve the conservation of its quality, identity and functionality, being this unique system not only governed by civilizational choices but also by precise laws (Bonometto, 2003), and natural processes. The authorities of the Venice lagoon [6] have a long history of maintaining the state of the Venice lagoon and preserving its natural resources (Solidoro et al., 2010). Since the first Special Law of Venice, in 1973, the preservation of the ecological and physical unity of the lagoon was explicitly set as an objective and became a commitment of many institutional and non-institutional subjects (Bonometto, 2003). In the current morphological plan for Venice, that is an instrumental tool for the lagoon management, the strategy for recovering its ideal status under hydrological, morphological and biological perspective is based on the analysis of the system state and the prediction of its possible behaviours in relation to different scenarios. As such, various focus points have been identified, including maintaining an adequate intertidal surface according to morphological principles; the vivification and confinement of areas in relation to their residence time and hydrodynamics; and protecting and restoring typical lagoon habitats, biodiversity and species. Rather than quantifying the long-term goal of the lagoon, this morphological plan provides a framework in which the accumulated knowledge regarding restoration and interventions are updated every 10 years [7]. This updated assessment, based on literature, pilot studies, and expert knowledge, then underlines the new interventions and their locations according to the suitability of these locations in line with those changes generated through the past interventions.

By lack of an existing description of a ‘desired future’ on the 21st of February 2024, the REST-COAST Venice pilot team synthesised a desired future for the Venice Lagoon based on legislation, previous discussions with the CORE-PLAT and research inquiries: *‘A system that is in morphological balance, delivers ecosystem services and support biodiversity, safety and health, resilience of the socio-ecological system, and economic viability’.*

3.2.3 Identifying possible adaptation strategies and measures

Since the 1990s a variety of mitigation and adaptation interventions have been implemented, including: Sistema Mo.S.E., Piano di Azione per il Clima del Comune di Venezia, Piano Europa and Piano Morfologico. Simultaneously, various LIFE projects have been implemented, e.g., LIFE SeResto, LIFE VIMINE, LIFE Refresh, LIFE BARENE, and LIFE Forestall. The restoration works conducted as part of the mitigation and adaptation interventions implemented since the 90s range from the excavation of canals to the reconstruction of tidal flat and salt marshes, to re-naturalisation of lagoon areas, to interventions on subtidal bottoms to reduce wave shear stress and increase consolidation through seagrass transplantation (Tagliapietra et al., 2018), but also include technical interventions such as the Mo.S.E. [8] or sand engines. Based on these past projects, a set of sub-visions and underlying strategies have been defined by the REST-COAST pilot team. Each of these strategies can be associated with various measures, and during the knowledge gathering of the past projects over 30 measures were identified (detailed in the VSM+E table) (Annex 2). It is evident that the Venice Lagoon has a long history of restoration and conservation, and to provide an adequate level of detail the measures

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[6] It should be noted that the PROVV. OO. PP. will be replaced by the Lagoon Authority in the near future, and that this will have an influence on the future restorations as it will allow for the alignment of various restoration activities that are currently executed in a more fragmented manner.

[7] The past piano morfologico has not been accepted, and while the measures studied as part of the REST-COAST project have been approved, there is currently no quantitative number available for the planned interventions.

[8] Mo.S.E. (Modulo Sperimentale Elettromeccanico).

relevant for the restoration upscaling have been aggregated [9] (Figure 15) and are detailed in Sections 3.2.3.1, 3.2.3.2, and 3.2.3.3.

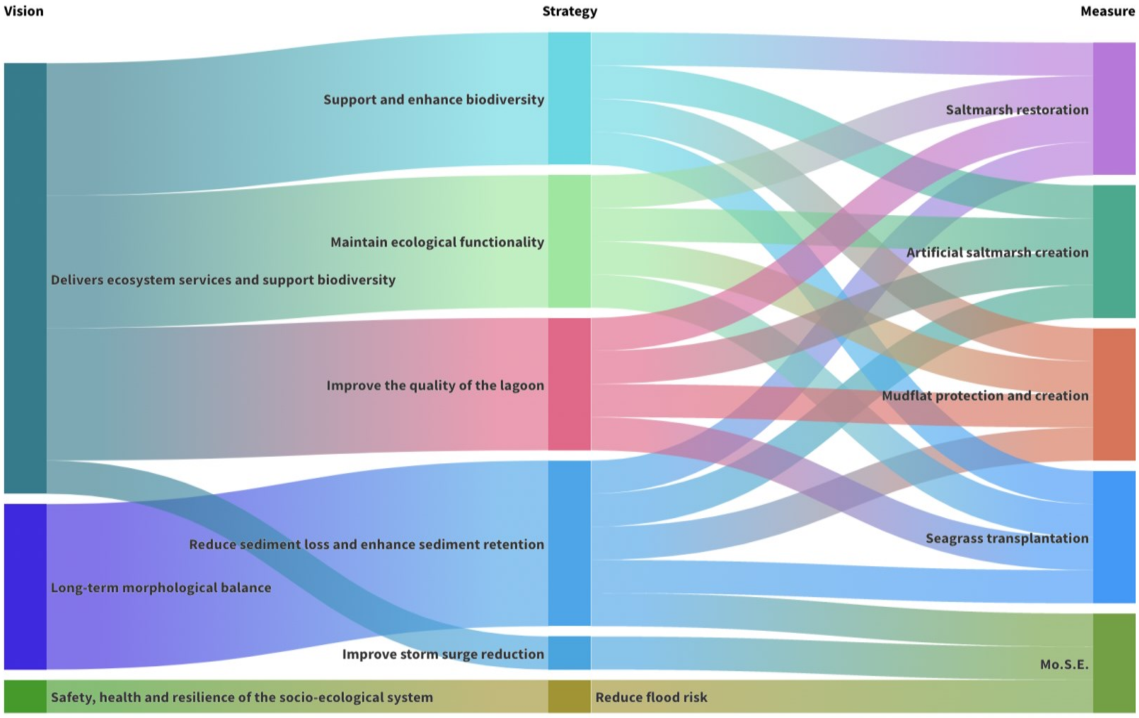

Figure 15: Relationship between the three main visions, six primary strategies, and aggregated measures; while the full elaboration of visions, strategies and measures included in the VSM+E table (see Annex 2).

3.2.3.1 Artificial morphological structures: Saltmarsh and mudflat construction and protection

So far, 1600 ha of new artificial mudflats and saltmarshes have been created in the Venice Lagoon (Figure 16). These results are significant for the saltmarshes, equal to 27% of the natural marshes and recovering 30% of the marshes lost since the 1930s (Tagliapietra et al., 2018). The reconstruction of saltmarshes has various functions, including the reduction of sediment loss, the protection of existing morphological structures, the reduction of fetch, and supporting ecological functioning (Consorzio Venezia Nuova et al., 2016). Therefore, these interventions align with various strategies to reach the desired future for the Venice Lagoon. The construction of saltmarshes has been based on pragmatic techniques, essentially following two phases: i) the creation of the contermination perimeter; and ii) the refilling of the enclosed area with dredged sediments of good chemical status. This pragmatic approach is anything but simplistic, including a variety of modules often used in combination based on the pressures affecting the area of implementation (Tagliapietra et al., 2018). The types of boundaries for achieving the contermination are determined based on the conditions (especially waves and wind) with the main kind of modules being timber piles, brushwood fascines, gabions, bags, rolls and mattresses made of, and filled with, different materials, such as polymeric fibres, natural fibres, stones, brushwood, and shells (Tagliapietra et al., 2018). Subsequently, the perimeter

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[9] This selection has been made based on the alignment of these measures with the REST-COAST project objectives and allowed the Venice pilot team to dive deeper into the evaluation of these measures for the adaptation pathways.

is refilled with sediment until an initial altitude of 0.7 – 0.8 m above mean sea level is reached, which in the medium to long term will compact and consolidate to the optimal height, 0.3 – 0.4 m above mean sea level.

Figure 16: Restoration site and visualisation of restoration techniques and materials, including burghe, mattresses, piling and removal of non-saltmarsh vegetation (source: Provv. OO.PP.)

The construction of mudflats, allowing for the dissipation of waves and protection of the seabed and saltmarsh edges, involves the creation of boundaries and pouring dredged materials (Consorzio Venezia Nuova et al., 2016). For the boundaries, during the executive project, different solutions are selected based on their exposure, including temporary boundaries, mattresses and huts filled with stones, and 'burghe' made from biodegradable materials filled with shells (Brotto, 2011). The boundaries are protective elements of various types, including 'burghe' and geogrid mattresses, commonly also used for the creation of saltmarshes. The different combinations of the elements correspond to the need to adapt the border structures to the trend of the seabed, and keep the height of the structure fixed (Brotto, 2011). For simplicity, in the drafted adaptation pathways the Venice pilot team considers saltmarsh restoration, artificial saltmarsh creation, and artificial mudflat construction while neglecting the specific techniques and materials used during the implementation of the measure (further research regarding this aspect is needed).

3.2.3.2 Seagrass transplantation

Seagrass transplantation has been carried out in by various Lagoon authorities over the past 30 years, including small scale transplantation experiments by the City of Venice in 1992 – 1997, various restorations through transplantation by the Venice Water authority, transplantation of *Zostera noltei* in shallow marsh ponds by the IUAV and Consorzio Thetis in 1994, explanting seagrass sods to donor sites between 1996 and 1997, and LIFE SeResto (2012 – 2017) aiming to recover the ecological status through widespread seagrass transplantation (Tagliapietra et al., 2018). The transplantation in the Venice lagoon has been conducted with *Cymodocea nodosa*, *Zostera marina*, and *Nanozostera nolteii* has proven to have a substantial positive outcome and provided insights in the different methods for different morphological and sedimentological areas. Seagrass transplantation was conducted according to two methodologies, manual and non-manual (Brotto, 2011). The intervention technique involved the use of a reduced number of clods, with advantages in terms of costs and impact on donor sites, making the restoration action applicable on a large scale (Berto et al., 2019). In defining the intervention strategy, the presence of natural seagrasses can lead to various intervention-approaches, including: concentrate transplants where an embryonic process of prairie development is underway, to encourage and accelerate their growth, or considering that transplants have a function of triggering the process of rapid diffusion thanks to the conspicuous production of seed (Sfriso et al., 2017). The options require a small removal of material from the donor site, and usually does not cause a disturbance to the transplant site. In these areas, in fact, if the intervention were successful, the presence of seagrasses would favour the improvement of environmental quality (sediment stability, water transparency), triggering a positive feedback process to the benefit of the ecological quality of the site (Sfriso et al., 2017).

3.2.3.3 Mo.S.E.

The Mo.S.E. is an engineering project which was implemented as part of combined measures for the defence of Venice and the lagoon ecosystem from high waters. The principal objectives of the Mo.S.E. are defence from high waters, defence from storm surges. The Mo.S.E. itself consists of 4 mobile barriers located in the lagoon inlets (i.e., Lido, Malamocco, and. Chioggia). These barriers are made up of 78 independent mobile gates, represented by hollow structures made of steel and filled with air to make them buoyant. When the Mo.S.E. system is operational, the gates are raised from the bottom of the inlets and are capable of temporarily separating the lagoon from the sea and defending Venice from ‘Acqua Alta’. The Mo.S.E. is expected to protect Venice and the lagoon from tides up to 3 metres high and from a rise in sea levels up to 60 cm over the next 100 years.

3.2.4 Determining early warning signals and tipping points of adaptation measures

Identifying tipping points can be complex and time-consuming, requiring advanced modelling and statistical approaches, as well as the exploration of their interactions. Therefore, it should be clarified that in this work the tipping points for the Venice Lagoon in Table 7 are reported only where available from previous literature or ongoing studies. Where they have not been previously calculated or estimated, the tipping point values are not reported, considering only the drivers and factors that are capable of influencing the trajectory of the system, following the framework proposed by WP4.

Table 7: Early warning signals and tipping points of measures implemented in Venice

Measures	Early warning signals (biophysical)	Tipping points (biophysical)[10]
Saltmarsh restoration & artificial saltmarsh creation	Sea level in relation to the saltmarsh elevation, to be estimated through future research.	The most relevant factors that are causing the disappearance of the morphological structures are the strong deficit between the sediments entering and leaving the lagoon, the rise of sea level, the lowering of ground level, the progressive rarefaction of the halophilous and hygrophilous vegetation. Sediment availability < 20 mg/L (Fagherazzi et al., 2013; Gedan et al., 2011).

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[10] The focus on SLR while ignoring for instance wave-wind characteristics is related to the fact that in a medium-long time-scale SLR is superimposing the impacts of the others and can thus be considered the primary driver of the hydrodynamic processes.

Artificial mudflats protection and creation	Sea level in relation to the mudflat elevation, to be estimated through future research.	Sea level rise & Sediment availability.
Seagrass transplantation	EW in relation to water quality not currently available	Water quality: turbidity, light availability, water temperature; nutrient concentrations; Limited tionitrophilic macroalgae; Maximum temperature <25 – 27 degree; Water speed and currents
Mo.S.E.	Sea level rise approaching 60 cm	The MOSE can protect Venice and the lagoon from tides up to 3 metres high and from a sea level rise of up to 60 centimetres over the next 100 years.

The maintenance of the morphological structures of the Venice lagoon would require the achievement of a dynamic equilibrium condition between incoming and outgoing sediments, both in the current condition and considering possible future sea level rise (Consorzio Venezia Nuova et al., 2016). This should also consider the decrease in fluvial sediment input due to the diversion of rivers in the 16th century as well as the reconfiguration of the jetties last century (D'Alpaos et al., 2024). Under current conditions, saltmarsh equilibrium is possible since the reduced suspended sediments is sufficient and sea level rise is below the threshold beyond which vegetated saltmarshes would disappear (Consorzio Venezia Nuova et al., 2016; Marani et al., 2007). However, this might change in the future, since future coastal hazards will be mostly dictated by rising sea levels (Finotello et al., 2023), and the sediment feeding the saltmarshes seems to be derived mainly from the eroding and deepening mudflats. However, with the absence of small scale process studies providing mechanistic insight in the tipping points of saltmarsh erosion and expansion it is difficult to provide a long-term trend and evolution of the saltmarshes (Bouma et al., 2016) and mudflats in the Venice Lagoon.

Sea level rise causes saltmarshes to move away from a static equilibrium (Neijnens et al., 2021), can negatively impact saltmarshes if the rate of vertical and lateral accretion is insufficient, might expose habitats to invasive species and erosion, and it could increase habitat fragmentation (Hudson et al., 2021). Modelling studies suggest that saltmarshes reach a tipping point when a critical rate of sea level rise is exceeded, beyond which the vegetation-induced sedimentation cannot keep up with sea level rise (Neijnens et al., 2021). And although this value has not yet been calculated for the Venice Lagoon does indicate an important consideration for the development of adaptation pathways. The behaviour of habitats in the coastal zone depends very much on the availability of sediments in relation to driving forces such as sea level rise and wave activity (Hudson et al., 2021). Marshes ability to trap and retain sediments make them resilient to erosion, and allow for the maintenance of an equilibrium elevation relative to the tidal frame (Hudson et al., 2021). Detailed sediment budgets can inform models and help assess the long term fate of coastal wetlands, where stable marshes are generally characterised by a consistent input of external sediments which are regularly mobilised (Fagherazzi et al., 2020). However, the lagoon sediment budget indicates a general tendency of sediment loss through the inlets of an overall value of 3.8×10^5 m^3/yr (Defendi et al., 2010). Riverine sediment input into the lagoon has almost completely been eliminated, and the reconfiguration of the tidal inlets (i.e., Malamocco, Lido, Chioggia) has significantly reduced the sediment resuspension by wave breaking in the surf zone, thus limiting the marine sediment influx (Sarretta et al., 2010; Tambroni & Seminara, 2006). Moreover, the delivery of sediments onto saltmarsh platforms during storm events represent a significant (>70%) sedimentation annual source (Fagherazzi et al., 2020), and the newly introduced Mo.S.E. could therefore interfere with sedimentation and subsequent saltmarsh resilience (Tognin et al., 2021).

Seagrasses are structural elements that represent one of the most important indicators of quality and stability of the lagoon environment (Brotto, 2011), and the presence of natural recolonisation represents a useful indicator of the reduction of pressures and the establishment of suitable conditions (Sfriso et al., 2017). The past decline of seagrasses can be mainly attributed to the optimum temperature of growth for species, where values above 25° C strongly increase the retreat and mortality of Zostera marina (Curiel et al., 2021). Moreover, the growth of sods is positively correlated with salinity, light availability and inversely to suspended particulate matter and nutrient concentrations (Sfriso et al., 2019). While water speed and currents (Tagliapietra et al., 2018), as well as waves due to boats can adversely impact the seagrasses and their growth. These conditions are relevant to consider, both as early warnings or tipping points as well as for the implementation of the interventions and their success.

3.2.5 Generating the adaptation pathway map

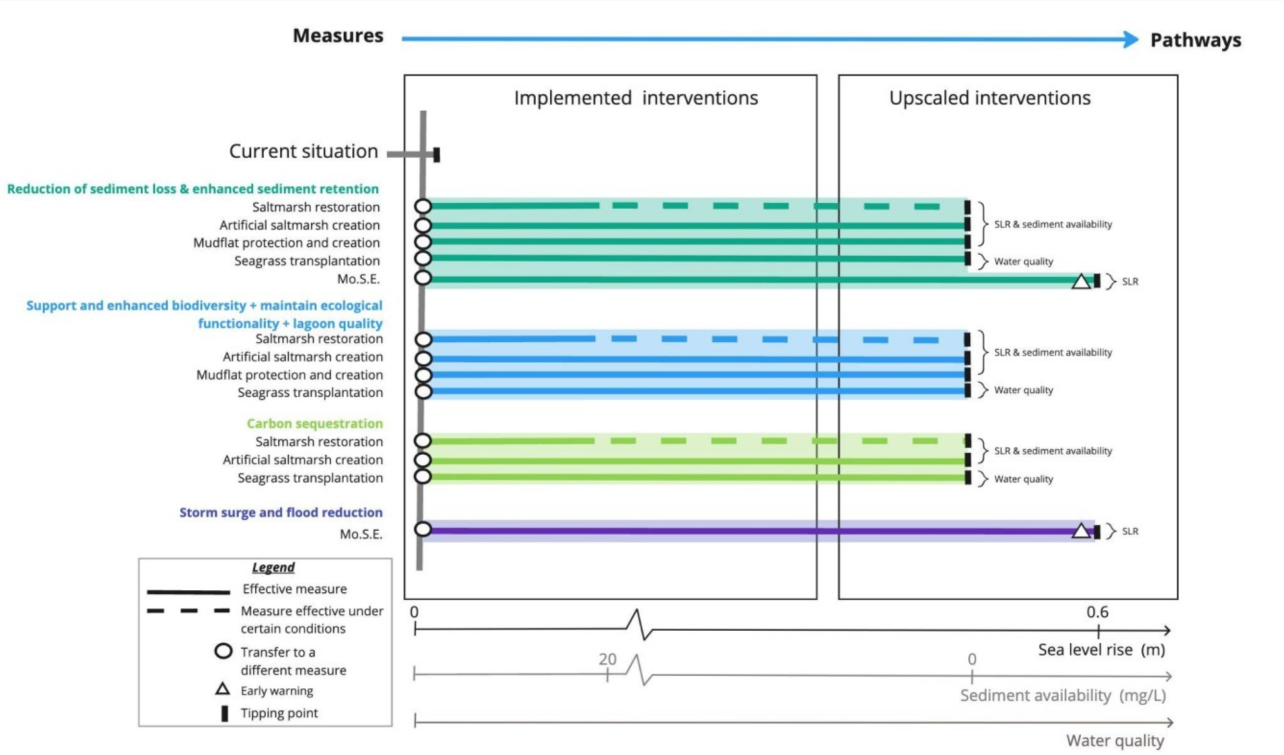

Figure 17: Adaptation pathways for the Venice lagoon, displaying the already implemented measures [11] in relation to various strategies, while leaving room for the future upscaling as this will be defined at a later stage in collaboration with the CORE-PLAT

In the Venice lagoon, the adaptation pathways are related to the upscaling of restoration to reach the desired future (Section 3.2.2). Considering the long history of interventions in the Lagoon, these adaptation pathways rely on the knowledge related to these past measures. Within the REST-COAST project, the upscaling plan is aimed at evaluating the possibility of restoring 1600 hectares of artificial salt marshes and mudflats. However, it should be noted that at this point in time, there is no lagoon wide restoration plan in place and the upscaling as described in REST-COAST for the Venice Lagoon does not provide a full holistic adaptation plan due to its relative narrow focus on artificial saltmarshes and mudflats. The visualised pathways (Figure 17) instead display the various aggregated interventions categorised according to their ability to contribute

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[11] The Mo.S.E. is the only measure that has not only been considered in the already implemented measures but also the upscaling, as this interventions will continue to be functional considering sea level rise up to 60 centimetres over the next 100 years, protecting the lagoon from tides up to 3 metres high.

to the four specific strategies, as identified in Section 3.2.3, and tipping points (Section 3.2.4), with limited consideration of possible future upscaling and sequencing. The drafted pathways reflect those measures implemented in the past in relation with the identified strategies rather than the sequential implementation of measures to achieve said desired future. Each of these measures has the potential to be implemented in the future, if the conditions remain favourable, and as such could support the upscaling of restoration in the Venice Lagoon. However, at the time of writing this deliverable their extent and implementation timeline remain uncertain. The only exception to this uncertainty is the Mo.S.E., which will remain operative in future adaptation plans considering sea level rise up to 60 centimetres over the next 100 years, protecting the lagoon from tides up to 3 metres high.

An in-depth discussion is expected together between the Venice pilot team and the CORE-PLAT to refine the different strategies, measures, and tipping points. This discussion is necessary to better understand the desired future not only from a theoretical point of view, but to make it tangible by exploring the possible spatial and temporal implementation of measures. Additionally, this inquiry will be supported by modelling activities (e.g. complementing the SHYFEM model with a vegetation module to explore the influence of saltmarsh vegetation on water quality, and developing a bayesian decision network to explore the influence of restoration on the provisioning of regulating ecosystem services in the Venice lagoon) to quantify the NBS effectiveness. All this will help build a better understanding of the performance of the different measures, both in isolation as well as combined into pathways.

3.2.6 Evaluating pathways with multi-criteria analysis

Each of the pathways is evaluated based on a set of sub-criteria in relation to the different measures, allowing for the evaluation of the different pathways relevant to each other in terms of effectiveness, feasibility, cost and flexibility (Table 8). This scoring has been done by the Rest-coast Venice pilot team by expert judgement through using a divergent Likert scale, where the lowest score (-2) represents the most negative influence, and the highest score (+2) represents the most positive influence on the assessed factor potentially achieved by the considered measures. The middle of the scale (namely, the score 0) is therefore referring to no effect or no influence. According to this approach, all the measures have been evaluated on a scale going from 'Very detrimental' to 'Very effective' for the effectiveness in fostering ecosystem services; from 'Very poor' to 'Very high' for the evaluation of feasibility, participation and engagement, and inclusiveness; and finally from 'Very wasteful' to 'Very cost-effective' when evaluating the performance of the implemented measure also considering the implementation costs as well.

Table 8: Measure scoring

Criteria	Sub-criteria	Measure (scoring -2 to +2)				
		A. Saltmarsh restoration	B. Artificial saltmarsh creation	C. Mudflat protection and creation	D. Seagrass transplantation	E. Mo.S.E.
Effectiveness	Reduction of coastal erosion risk (RCE)	+2	+2	+2	+1	0
	Reduction of coastal flooding risk (RFR)	+1	+1	+1	0	+2
	Water quality purification (WQP)	+2	+1	+1	+2	-1
	Climate change regulation (CCR)	+2	+1	+1	+2	-1
	Food provisioning (FP)	+2	+1	+2	+1	-1

	Biodiversity value (BDV)	+2	+1	+1	+1	-1
	AVERAGE	+1.83	+1.17	+1.33	+1.17	-0.33
Feasibility	Inclusive and effective decision-making	0	0	0	0	0
	Recognition and respect for tenure rights	0	0	0	0	0
	Capacity and skills	+2	+1	0	+1	+2
	Technical and organisational feasibility	+2	+1	0	+2	+2
	Leadership	0	0	0	0	0
	Experimentation and learning	+1	0	0	+2	N/A
	Governance structure and legal alignment	-1	-1	-1	-1	-1
	Diversity of knowledge, cultures and institutions	+1	+1	+1	+1	+1
	Strategic vision, learning and direction	+1	+1	+1	+1	1
	Coordination and coherence	-1	-1	-1	-1	-1
	Grievance and conflict resolution (trust)	-1	-1	-1	-1	-1
	Drivers of change [12]	N/A	N/A	N/A	N/A	N/A
	Devolution	-1	-1	-1	-1	-1
	Accountability	-1	-1	-1	-1	-1
	AVERAGE	+0.15	-0.08	-0.23	+0.15	+0.08
Cost	Total cost (per ha)	N/A	N/A	N/A	N/A	N/A
	Public funding ratio	N/A	N/A	N/A	N/A	N/A
	Funding gap	N/A	N/A	N/A	N/A	N/A
	Cost-effectiveness	N/A	N/A	N/A	N/A	N/A
	AVERAGE	N/A	N/A	N/A	N/A	N/A
Flexibility	Flexibility	+1	0	N/A	+2	0

Generally the measures pertaining to the restoration and creation of habitats in the Venice lagoon score well in terms of effectiveness. In particular the restoration of saltmarshes is considered to provide a wide range of ecosystem services. The created saltmarshes score slightly lower which might be attributed to biophysical differences such as sediment characteristics or elevation. Mudflats, if vegetated, provide a wide range of services and in particular provide nursery habitats and protection to fish species. Moreover, it might be noted that the particular purpose of each measure might influence the effectiveness, highlighting in particular that the restoration and creation of artificial saltmarshes in the Venice lagoon serve to enhance biodiversity

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[12] Drivers of change was extensively discussed, but as pilot team we decided that this indicator should be split into two aspects: awareness (2) and change - or effective strategies for achieving change (0), while also noting that there are various factors affecting this scoring such as age or as well as the occurrence of adverse events.

through bird nesting and reducing invasive species, limit the loss of sediments, attenuate waves, and restore general ecological functioning. Mudflats on the other hand are mainly protected and restored as a way to protect salt marshes through attenuating waves, and seagrass transplantation is often executed with water quality improvements and biodiversity in mind, but often also altering hydrodynamics and reducing erosion.

It should be noted that since the measures included in this evaluation are those that have already been implemented in the past it was unfeasible to provide details about the funding gap. The majority of the measures implemented in the past have been funded by public money, either provided by the state or acquired through European projects. However, for saltmarsh restoration additional financial details were provided considering the following: planning phase (13% of the total cost of the works), restoration of the perimeter of saltmarshes (362 euros per linear metre), refilling of the saltmarshes (19 euro per m^3), and monitoring (2900 per hectare of saltmarsh). These estimated costs are related to the regional price list for 2023. To these values a 20% must be added to consider the increased cost of materials registered in 2024 (see regional price list for 2024 https://prezziario.regione.veneto.it/), and more details are included in Deliverable 3.3 (Johannessen et al., 2024).

Variations in the flexibility between saltmarsh restoration and saltmarsh creation pertain to differences in the capacity and skill, technical and organisational feasibility, and experimentation and learning. This might be in part explained by the extensive history of restoring saltmarshes, studied quite intensively by the responsible authorities as well as in LIFE projects including LIFE BARENE, and LIFE VIMINE, and the more limited experience related to the creation of saltmarshes as well as the fact that this second type of measure is more pervasive. Lower flexibility scores in terms of mudflat protection can be attributed to the limited application of this measure in the past, and the subsequent limited skill, technical feasibility and learning. On the other hand, extensive research has been done to the transplantation of seagrasses by both the Venice Water Authority as well as in research projects such as LIFE SeResto leading to ample knowledge, skill and capacity for these kinds of measures. Similarly, both saltmarsh restoration and seagrass transplantation display higher scores in terms of flexibility relating to the likelihood of their implementation, while mudflats have not been scored due to limited knowledge.

Remarkably, the Mo.S.E. as a measure generates a rather low score, and adversely affects the scoring within the pathways. This could be explained due to the singular focus of the measure on flood risk reduction. Another point that needs careful consideration is that the Mo.S.E. system is regarded as one of the measures contributing to the adaptation pathways. However, it is neither a nature-based solution nor an example of ecological restoration or an instrumental device for allowing those measures. Instead, it is an engineering system that operates when exceptionally high tides threaten Venice. While it can effectively reduce the risks related to climate change and sea level rise in the short term, its ecological role is uncertain, especially in the mid- and long-term. There are several reasons for these uncertainties. First, the Mo.S.E. system has only recently become operational, and its closures have not exceeded four days, preventing a comprehensive assessment of its effects on ecological processes. Second, while it mitigates the impacts of extreme events, it also disrupts the lagoon-sea continuum during its operational phases when the barriers are closed. Even for the effectiveness in protecting the city from flooding and the cost-effectiveness balance, the time scale under which the assessment is proposed changes significantly the outcomes. Indeed, if on the short-term (5-10 years) the Mo.S.E. is considered very effective for preventing the flooding of the historical centre of Venice and sufficiently safe for the lagoon environment, in the long term (e.g., 50 years) the evaluation of its performance and effectiveness for protecting the city are highly uncertain - since they also depends on climate change effects and their unpredictable tipping points -, while it becomes more likely that prolonged closures are going to negatively affect the lagoon hydrodynamics, its water quality, the sediment balance, saltmarshes accretion rates, and various other ecosystem dynamics. Moreover, while there are some positive social and economic effects, recent documentation has highlighted potentially negative effects on the ecological dynamics that counterbalance these benefits even in the short-term. Consequently, the influence of the Mo.S.E. system is difficult to evaluate within this framework because it is neither linear nor easily predictable, and it came out that it is strictly related to the temporal scale considered for the evaluation. To provide a consistent framework, the Rest-coast Venice team scored the effects of the measures by referring to short- to mid-term spatial scales.

Table 9: Pathway scoring

Criteria	Pathway 1	Pathway 2	Pathway 3	Pathway 4
	avg. (A+B+C+D+E)	avg. (A+B+C+D)	avg. (A+B+D)	E
Effectiveness	+1.03	+1.38	+1.39	-0.33
Feasibility	+0.01	0	+0.07	+0.08
Cost	N/A	N/A	N/A	N/A
Flexibility	+0.75	+0.75	+1	0

Considering the scoring of these different measures and the preliminary pathways, it is possible to score the four different pathways (Table 9). The first three pathways show little differences in their scoring, which can be associated with the similar composition of each pathway, with the only difference between pathway 1 and pathway 2 being the inclusion of the Mo.S.E. for pathway 1. While pathways 2 and 3 only differ in the fact that pathway 3 does not consider the protection and creation of artificial mudflats. This observed difference, or rather similarity, could in part be related to the overlap in measures, the fact that many of the interventions focus on the provisioning of various ecosystem services, as well as the fact that the governance in the Venice Lagoon is mostly top down, resulting in a shared score for many of the governance indicators. Pathway 4 is just about the Mo.S.E as the main objective is about storm surge and flood reduction and as such is solely influenced by the scoring of this single measure. It might be noted that feasibility is low for all four pathways, this in part can be attributed to governance barriers and political rigidity. This should be considered in relation to the legislative complexity surrounding restoration, as well as the ambiguous policy objectives and limited long-term adaptation plannings; which might be aided through the development of adaptation pathways highlighting various transformation options to reach the desired future.

3.3 Ebro Delta

3.3.1 Understanding the current situation

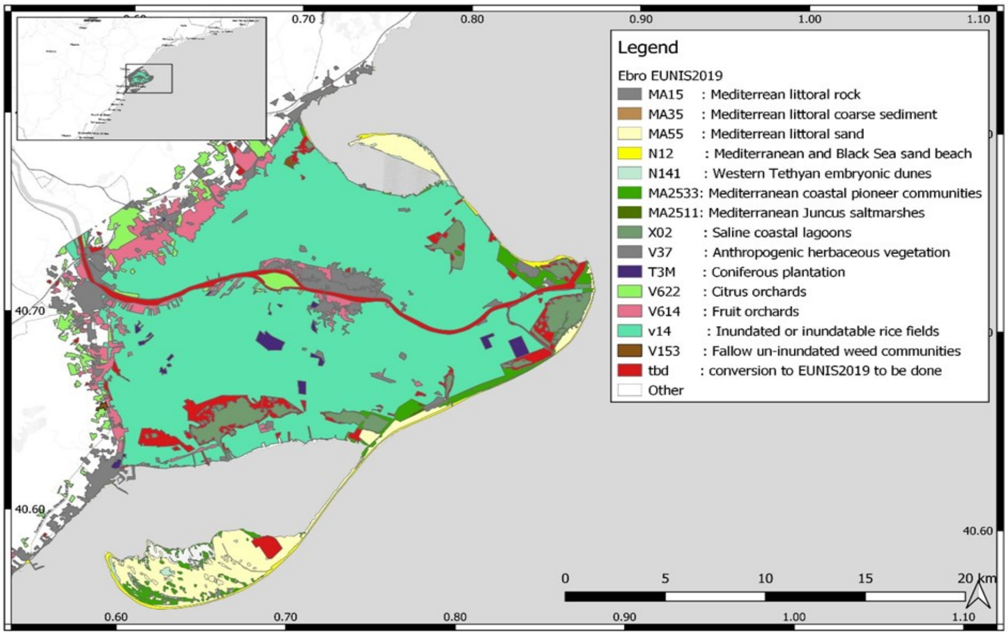

Figure 18: Map of Ebro Delta habitats (EUNIS 2019)

The Ebro Delta has an area of 320 km^2 and represents one of the main wetland areas of the Western Mediterranean, due to its extension and ecological importance. It is characterised by being a low-lying area, heavily anthropized, without significant (large) coastal engineering structures and with land-use dominated by agriculture: 70% of the surface area is agricultural land, mainly for rice production (95%). This area encompasses a wide array of natural environments: river, sea, bays, beaches, dunes, wetlands, riverine woodlands, salt marshes, coastal lagoons, etc. and, along with the rice fields, are home to many organisms that have adapted to the different habitats. This region comprises a unique and fragile combination of coastal protected areas and it hosts several priority habitats (*Cymodocea*, *Zostera* and *Ruppia* seagrass beds, coastal lagoons, salt marshes, etc.) and species (*Pinna nobilis*, *Aphanius iberus*, *Syngnanthus abaster*, *Phoenicopterus ruber*, etc.) referring to the EU Habitats and Birds Directives (Figure 18).

The Ebro Delta is included in different national and international frameworks for environmental conservation: category A (urgent priority) International Interest of Euro-African Wetlands (UNESCO, 1962); Wetland of International Importance (Ramsar Convention, 1971); Special Protection Area for birds, ZEPA (European Union, 1979); Natural Park (Spain, 1983); and Natura 2000 Network (European Union, 1992). However, this natural area faces major threats, both environmental and socio-economic, that require urgent intervention and sustainable adaptation strategies. The Ebro Delta's natural systems are under stress. Decades of human intervention, including dam construction and unsustainable agricultural practices, have disrupted the delicate balance of the natural ecosystems. Without a concerted effort to restore the Ebro Delta, the region faces a complex future.

The evolution of the Ebro Delta is conditioned by the balance between the sediment contribution from the Ebro River and wave (storm)-induced erosion. However, the construction of dams upstream and other human activities have significantly reduced the amount of sediment reaching the delta. In the Ebro River, total sediment transfer to the Mediterranean Sea dropped by over 99 % last century, from 30 to 0.1×10^6

t/year in 2010 (Rovira & Ibañez, 2007). This not only contributes to coastal erosion, but also affects the fertility of agricultural soil in the region.

Until 1960, deposition of suspended sediments via irrigation water in the rice fields resulted in a vertical accretion rate of about 0,5 cm per year. Since 1960, large dams on the lower Ebro River have trapped almost all river sediments, and there is now a net sediment loss from the delta plain (Day et al., 2006). The lack of vertical accretion of the delta plain intensifies the effects of the subsidence processes that take place due to the compacting of the sediments that make up the Ebro Delta.

In addition, the Ebro Delta is extremely vulnerable to sea level rise (SLR) due to climate change. The combination of coastal erosion, subsidence and the reduction of fluvial sediment inputs to the deltaic wetlands and rice fields exacerbates the impacts associated with SLR and the natural subsidence of the delta, causing an accelerated loss of land. In the Ebro Delta wetlands, the relative sea level rise (RSLR) ranges from 5 to 8 mm/year (Ibáñez et al., 2010). Rising sea levels will tend to gradually flood coastal lagoons and marshes unless there is enough sediment supplied to compensate for the increasing deficit (Ibañez & Caiola, 2021). It is estimated that if no measures are taken, a significant part of the delta could be under water in a few decades (Figure 19).

Saltwater intrusion in the deltaic plain is another serious problem, exacerbated by rising sea levels and reduced flow of the Ebro River, especially during periods of drought. Salinization severely affects agriculture production, especially rice farming, which is one of the pillars of the local economy.

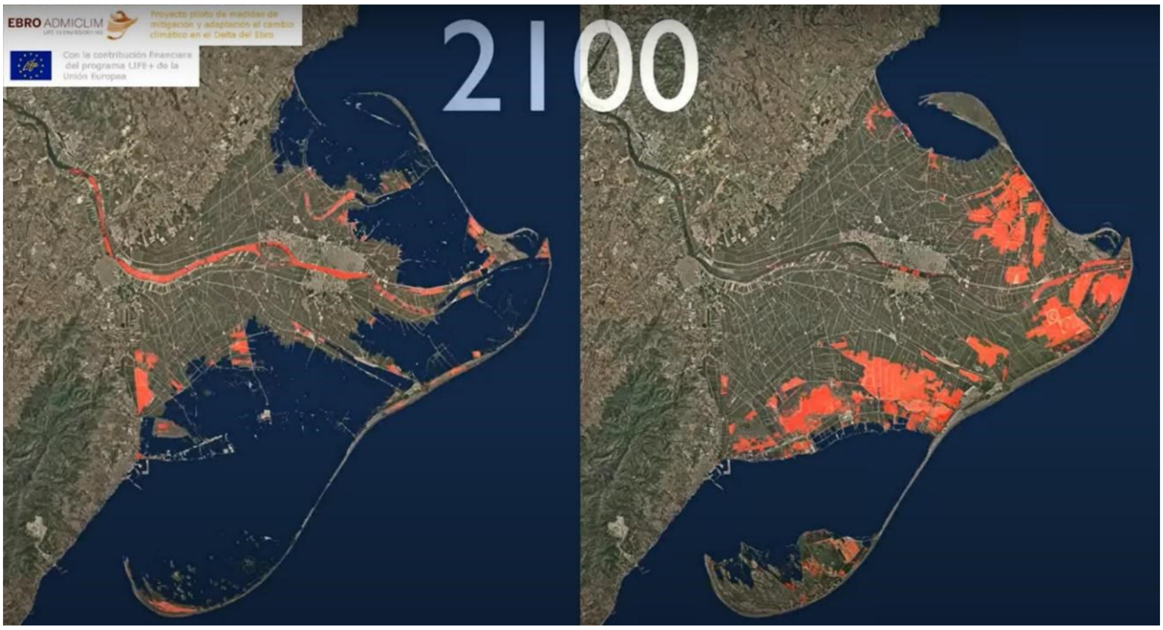

Figure 19: Flooding scenario predictions for the Ebro Delta without sediment contributions. On the left, the evolution with the current contribution of sediments. On the right, the evolution with the contribution of sediments required to compensate for relative sea level rise. The land areas shown in red in the simulation correspond to areas already below sea level due to subsidence, but not yet flooded (except coastal lagoons) because they are not directly connected to the sea (Source: Institut Cartogràgic i Geològic de Catalunya, https://www.youtube.com/watch?v=zi8k-2aN1aw)

Continued business as usual trends will exacerbate these problems. The Ebro's reduced sediment load will accelerate coastal erosion and subsidence, leaving the delta increasingly vulnerable to sea-level rise and storms, which are expected to be more frequent and intense in the future due to climate change. Wetlands and lagoons will shrink unless active restoration is carried out, compromising their ability to act as natural buffers and providing key ecosystem functions. Saltwater intrusion will render agricultural lands unproductive, particularly for rice cultivation. Without intervention, the Ebro Delta region will suffer severe ecological and economic consequences.

Therefore, it is essential to restore wetlands, lagoons, beaches and the river ecosystems in a holistic manner, by recovering the natural dynamics of water and sediment flows and habitats, while enhancing biodiversity and essential ecosystem services. At the same time, it is key to ensure the livelihoods and preventing rural abandonment of the region, through promoting sustainable rice farming, fishing, aquaculture and ecotourism, among other activities.

3.3.2 Defining policy objectives

The near- and long-term policy objectives for the future of the Ebro Delta focus on the conservation and restoration of the unique hydrogeomorphological and ecological functioning of this region, as well as promoting the transformation towards a regenerative bioeconomy and more sustainable agricultural, fisheries, aquaculture and tourism sectors.

On the one hand, the **recovery of the natural habitats** of the Ebro Delta (wetlands, coastal lagoons, beaches, etc.) is essential for the provision of ecosystem services (such as fish nursery, water purification, climate regulation, etc.) and the conservation of habitats and species. Furthermore, another policy objective is the **restoration of the natural dynamics** of the lower river through a better environmental flow regime, recovery of the river sediment transport to the delta and restoration of fluvial habitats. In addition, **improving coastal adaptation to climate change** (sea level rise) is key to ensure the Ebro Delta's future through NBS-like adaptation measures such as beach restoration and recovering river-to-coast connectivity through reservoir sediment by-pass systems, among other solutions. On the other hand, **maintaining the productivity of rice fields** in a climate change scenario (sea level rise and salt intrusion) is pivotal in the region because rice farming is the most important economic activity.

The Ebro Delta is governed by a complex interplay of different administrative levels, each with its own priorities and planning frameworks, which do not necessarily share the same priorities and vision of the potential use of NBS in coastal restoration activities. This multi-layered governance structure, encompassing national, regional, and local authorities, can lead to inconsistencies and challenges in coordinating restoration efforts. While various plans exist to address the delta's critical issues, their effective implementation requires a holistic approach that transcends administrative boundaries and ensures alignment of objectives. The most relevant policy instruments are the Ebro River Basin Management Plan, the Delta Plan, and the Delta Strategy.

The **Ebro River Basin Management Plan** (2022-2027) is a state-level planning instrument that seeks to ensure sustainable and balanced management of water resources in the Ebro River basin. This plan is pivotal in restoring the delta's natural dynamics. By ensuring adequate water and sediment flows to the lower river and delta, this plan should contribute to revitalising fluvial habitats, replenishing coastal areas, and supporting the overall health of the ecosystem. This plan is updated periodically, in line with the European Union's Water Framework Directive. The plan includes a pilot trial of sediment by-pass in the Riba-roja reservoir not yet executed.

The Delta Plan and Delta Strategy focus on the coastal fringe protection and restoration, aiming to restore wetlands, lagoons, and beaches. These plans are essential for enhancing biodiversity, protecting against coastal erosion and flooding, and creating suitable habitats for fish and other species. The **Delta Plan** is promoted by the Government of Spain (pending final approval) and focuses on mitigating the consequences of climate change and sea level rise (up to year 2100) through beach nourishment and restoration of coastal habitats. It is a long-term roadmap that seeks to ensure the survival of the delta in a climate change scenario. The **Delta Strategy** (2023-2032) is a plan promoted by the Government of Catalonia for the protection of the Ebro Delta. This planning focuses on coastal fringe restoration through the implementation of different projects for beach nourishment and sand dune restoration. It will be divided into three phases where different projects will be implemented: from now until 2024, from 2025 to 2028, and from 2029 to 2032.

Furthermore, stakeholder engagement and co-creation approaches will be desirable in a long-term vision policy for the Ebro Delta, by defining a **governance framework** capable of overcoming the barriers observed in previous planning and management efforts, and also to integrate local expectations in a participative way (similar to the discussion and co-creation efforts carried out in the CORE-PLATs of the REST-COAST project).

3.3.3 Identifying possible adaptation strategies and measures

Several initiatives and projects have been implemented to address the Ebro Delta's challenges that align with the near- and long- term visions of the planning instruments for Ebro Delta described in the previous section (see Section 3.3.2) (see Annex 3).

Understanding the effects of sea-level rise and marine storms on Mediterranean coastal wetlands is crucial to developing adequate climate change measures, strategies and adaptation pathways. Beach nourishment, marsh restoration, and river sediment by-passes can help to protect the delta plain and the coastline from erosion, sea level rise and storms. Hard engineering solutions, such as the construction of dykes, as a protection measure against marine storms are not sustainable under scenarios of climate change and energy scarcity. Constructing nature-based soft dikes within the coastal-line in combination with forced drainage systems can manage water levels effectively at least for some decades. Restoring and creating dunes further strengthens coastal defenses in a more climate-resilient manner is another challenge to be developed.

The EU-funded **project RISES-AM (2013-2016)** addressed the wide impacts of coastal systems to various types of high-end climatic scenarios (including marine and riverine variables). It focused on enhancing coastal systems sustainability by adopting a flexible adaptive pathway that identifies tipping points and makes use of green intervention options, more sustainable than the traditional coastal engineering solutions. The protection through soft dikes, the increase in forced drainage (pumping) or the segmentation of the drainage system in the Ebro Delta are examples of technical interventions addressed in this project.

The water and sediment flux of the Ebro River has declined due to human activities in the watershed and is vulnerable to the effects of climate change, which has accelerated the relative rise in sea level and coastal erosion processes. Specific management and restoration measures are therefore necessary to mitigate these negative effects. Restoring the lagoons and marshes of the Ebro Delta, as well as improving the state of habitats and priority species, is another key goal to mitigate the effects of coastal regression and climate change. The main goal of the **LIFE+ DELTA-LAGOON (2010-2017) project** was to improve the environmental status of two coastal lagoons, the Alfacada and Tancada lagoons, through habitat restoration and management measures, such as improvement of hydrological function, elimination of infrastructure that interferes with hydrological connectivity (river-lagoon-sea), and creation of new lagoon habitats in existing rice fields and abandoned aquaculture facilities.

The measures for climate change mitigation and adaptation in the Ebro Delta require integrated management through the development of comprehensive technical solutions and interventions. The **LIFE EBRO-ADMICLIM project (2014-2018)** proposed an integrated management approach for water, sediment and habitats (rice fields and wetlands), with the multiple objectives of optimising soil elevation (through contributions of inorganic sediment and organic matter), reducing coastal erosion, increasing the accumulation (sequestration) of carbon in the soil, reducing greenhouse gas (GHG) emissions and improving water quality. The reinjection of sediments to the Ebro Delta irrigation channels, or the injection of sediments to the river to calibrate and validate sediment transport models were some of the restoration techniques implemented in this project to reduce coastal erosion and subsidence. In addition, different water management schemes were tested by the optimization of two existing constructed wetlands. Novel agronomic practiques (alternate wetting and drying) were assessed to reduce GHG emissions and improve carbon sequestration in the rice fields.

To address some key challenges of coastal ecosystems, the **project REST-COAST (2021-2026)** focuses on improving large-scale restoration of coastal ecosystems through new technical, financial, management and upscaling methods and tools, aligned with the needs of vulnerable regions and society. In the Ebro Delta Pilot, hands-on restoration actions have been deployed to promote river-delta-coast connectivity and the recovery of natural coastal dynamics. On one hand, the creation of artificial embryonic dunes along the most vulnerable coastal spots (Marquesa beach and Trabucador barrier) have been carried out with the aim of reducing the risk of erosion by taking advantage of the natural processes of sediment distribution. On the other hand, the removal of a coastal dike, that has historically separated the beach from the Alfacada coastal lagoon area and wetlands, have been conducted with the aim of reconnecting these habitats, recovering their natural dynamics, increasing the buffering capacity of the coast against marine storms and enhancing biodiversity by reestablishing the natural salinity gradient (Figure 20). Moreover, the restoration of the coastal fringe in the Bombita Nature Reserve (Figure 21), formerly a rice field area, will increase the resilience of the coast to sea level rise and marine storms. Both interventions and good examples of coastal restoration that can be scaled up in the near future.

Regarding the recovery of river sediment transport to the delta and restoration of fluvial habitats, **a sediment by-pass** pilot trial at the Riba-roja reservoir (2022-2027) was proposed (but not yet implemented) to restore the flow of sediment from the Ebro River to the sea and help to reverse the coastal erosion and sustain delta habitats. At the same time, **beach nourishments**, **sand dune restoration** and **salt marsh restoration** are technical measures being implemented to enhance coastal adaptation to climate change (sea level rise) and the recovery of river-to-coast connectivity.

Figure 20: Alfacada Lagoon before (left) and after (right) the removal of the dike. (Source: EURECAT)

Figure 21: Coastal fringe area to be restored in the Bombita Reserve. (Source: MITECO)

Furthermore, one of the key strategies for the future of the Ebro Delta region is the **adaptation of the primary sector** to climate change (i.e. agriculture, aquaculture, fisheries, salt production). By rising rice field grounds with sediments, implementing regenerative agriculture practices, and developing sustainable aquaculture, among other measures, the region can improve socio-economic resilience.

Finally, to enhance the delta's overall ecological health and climate resilience, **green infrastructure initiatives** are essential. Restoring lagoons and marshes, revitalising river margins with forestation, and increasing urban green spaces contribute to improved water quality, flood prevention, and biodiversity conservation. By integrating these adaptation options, the Ebro Delta can build resilience, protect valuable ecosystems, and ensure the well-being of its communities. The **Delta Green Infrastructure Plan**, promoted by Eurecat and co-designed with the key stakeholders, proposes actions to implement that are collected in two blocks, a first block aimed at improving biodiversity and increasing ecosystem services to increase the resilience of the territory and the well-being of citizens, and a second block addressed to the ecotourism sector and related to equipment, mobility and heritage interpretation. Some measures included in this plan are the restoration of degraded coastal ecosystems, lagoons and wetlands as well as the improvement of the contributions of sediments and freshwater of quality to the deltaic and fluvial systems. In addition, this plan promotes the improvement of the green infrastructure of urban areas and the sustainable mobility network promoting the creation and adaptation of spaces for ecotourism.

3.3.4 Determining early warning signals and tipping points of adaptation measures

Different **adaptation measures** have been identified to address the management aims as a function of the impacts. Each adaptation measure has been assessed considering its effectiveness to reduce the most relevant Ebro Delta coastal system impacts such as subsidence, storms, sediment scarcity, erosion, salinization, etc. Threshold conditions that make a specific measure viable and threshold conditions for which the measure fails, making additional or other actions necessary (i.e., adaptation tipping point) have been defined whenever possible.

Considering the main strategies and projects described in the previous section (see Section 3.3.3) to address the adaptation challenges of the Ebro Delta region, different adaptation measures have been defined and/or implemented, for which early warnings and tipping points have been identified (see Table 10).

Table 10: Proposed measures, early warning signals and tipping points in the Ebro Delta, based on existing literature (see Ebro Delta references) and expert judgement

Measures	Early warning signals (biophysical)	Tipping points (biophysical)
A1. Rising grounds (rice fields): increasing rice field ground elevation through sediment supply.	Increased salt stress and waterlogging, reduced crop yields, sediment availability.	Crop yield reduction due to salinization and crop abandonment due to loss of available land (rising sea levels and erosion).
A2. Regenerative rice farming: agroecological practices to increase soil fertility and reduce inputs	Decrease in soil organic matter, increase in inputs to maintain production and to control crop pests and diseases.	Significant loss of soil fertility and crop production, crop failure.
A3. Sustainable aquaculture: climate-resilient aquaculture practices	Rising water temperatures, increasing algae blooms, water quality deterioration.	Significant decline in production, collapse of aquaculture sector.
B1. Beach nourishment: sand supply through nearshore or offshore sources	Rapid erosion of nourished beaches, increased inundations, the decrease in the stock of quality sediments to nourish the beaches, the growing social concern/opposition on beach nourishment as a coastal protection measure.	Loss of beach width to a critical point that cannot avoid flooding during average marine storm events.
B2. Marsh restoration (coastal fringe): increase of marsh surface in the backshore	Reduction of marsh vegetation cover, increased flooding and/or salinity, loss of biodiversity.	Significant loss of marsh habitat (flooding by sea level rise and/or coastal squeeze by erosion)
B3. River dam sediment by-pass: recovery of sediment flow to the delta	Reduction of sediment supply to the delta, accelerated coastal erosion.	Significant loss of coastal land in the river mouth area due to erosion.
B4. Soft dikes (bays) + forced drainage: construction of protection dikes along the inner shore of the bays and forced drainage of rice field water due to sea level rise	Increased frequency and intensity of storm flooding, increased pumping through the drainage infrastructure.	Uselessness of soft dikes due to sea level rise and storms. Uselessness of the widespread drainage infrastructure.
B5. Dune creation/restoration: recovery of dune systems to reduce flooding and erosion	Dune erosion, reduction of vegetation cover on dunes, limited sand sources for dune restoration.	Significant loss of dune systems due to increased coastal erosion, reduction of geomorphological complexity of the coastal fringe.
C1. Lagoon restoration: recovery of former lagoons and expansion of existing ones	Decrease in lagoon area due to coastal erosion.	Lack of space to restore due to rising sea levels.
C2. Marsh restoration (delta plain): recovery of former marshes and expansion of existing ones	Reduced vegetation cover in marshes, reduced marsh surface	Lack of space to restore due to rising sea levels.
C3. River margin restoration (including forests): restoration of riparian habitats	Increased riverside erosion, increased risk of inundation, water quality problems.	Significant loss of the ecological functions of riparian habitats.
C4. Urban & peri-urban greening: nature-based solutions in urban areas	Decline in air quality, increased heat island effect, reduced water infiltration.	Decreasing quality of local livelihoods.

3.3.5 Generating the adaptation pathway map

Three adaptation pathways have been formulated in the Ebro Delta region to visualise the upscaling of adaptation measures and restoration to reach the desired future (Table 11). They include different measures that can be implemented sequentially as time progresses and socio-ecological conditions change. The adaptation pathways defined for the Ebro Delta system are the following:

- Pathway 1: Adaptation of the primary sector (agriculture, aquaculture, fisheries, salt production)
- Pathway 2: Coastal adaptation to SLR and marine storminess
- Pathway 3: Green infrastructures (nature-based solutions for the delta plain)

In addition, the adaptation process is structured into three phases depending on measures implementation: 1) implemented and ongoing measures; 2) upscaling measures; and 3) new measures (when existing or planned measures are not sufficient for adaptation).

One of the key adaptation pathways of the Ebro Delta region is **the adaptation of the primary sector** (see Pathway 1; Figure 21). Rising rice field grounds, implementing regenerative agriculture practices, and developing a sustainable aquaculture are measures to improve socio-economic resilience of the Ebro Delta region. On the one hand, with the sea level rise, **rising grounds** (i.e., the filling of the rice fields with fluvial sediments for vertical accretion) is an adaptation measure to raise the land in response to rising sea levels. Low population density and concentration of towns in higher elevation areas, along with low-lying areas used mainly as rice fields and wetlands make this adaptation strategy feasible for moderate rates of sea level rise (Ibañez et al., 2014). This measure alone will not ensure the long-term economic viability of the rice farming sector, especially under high rates of sea level rise, which is why the transition to **regenerative rice farming** is necessary for maintaining soil fertility over time and avoiding crop failure.

On the other hand, rising water temperatures and the water quality problems in the Ebro Delta bays are causing increasing mussel mortality and a decrease in the aquaculture production (mussels and oysters). Aquaculture is therefore a sector that is very vulnerable to the impacts of climate change, and it is necessary to develop specific adaptation measures to face the changes in the sea and bays, which are already occurring (i.e., water temperature approaching 30 ºC in summer), and which will become more pronounced in the future. Promoting **sustainable aquaculture** and developing innovative solutions for adapting this economic activity to climate change is key for this sector.

Table 11: Summary of adaptation pathway measures

Pathway 1: Adaptation of the primary food production sector	Pathway 2: Coastal adaptation to SLR and marine storminess	Pathway 3: Green infrastructures (delta plain)
A1: Rising rice field grounds A2: Regenerative rice farming A3: Sustainable aquaculture	B1: Beach nourishment B2: Marsh restoration(coastal fringe) B3: River dam sediment by-pass B4: Soft dikes (bays) + forced drainage B5: Dune creation/restoration	C1: Lagoon restoration (delta plain) C2: Marsh restoration (delta plain) C3: River margin restoration (including forests) C4: Urban & peri-urban greening

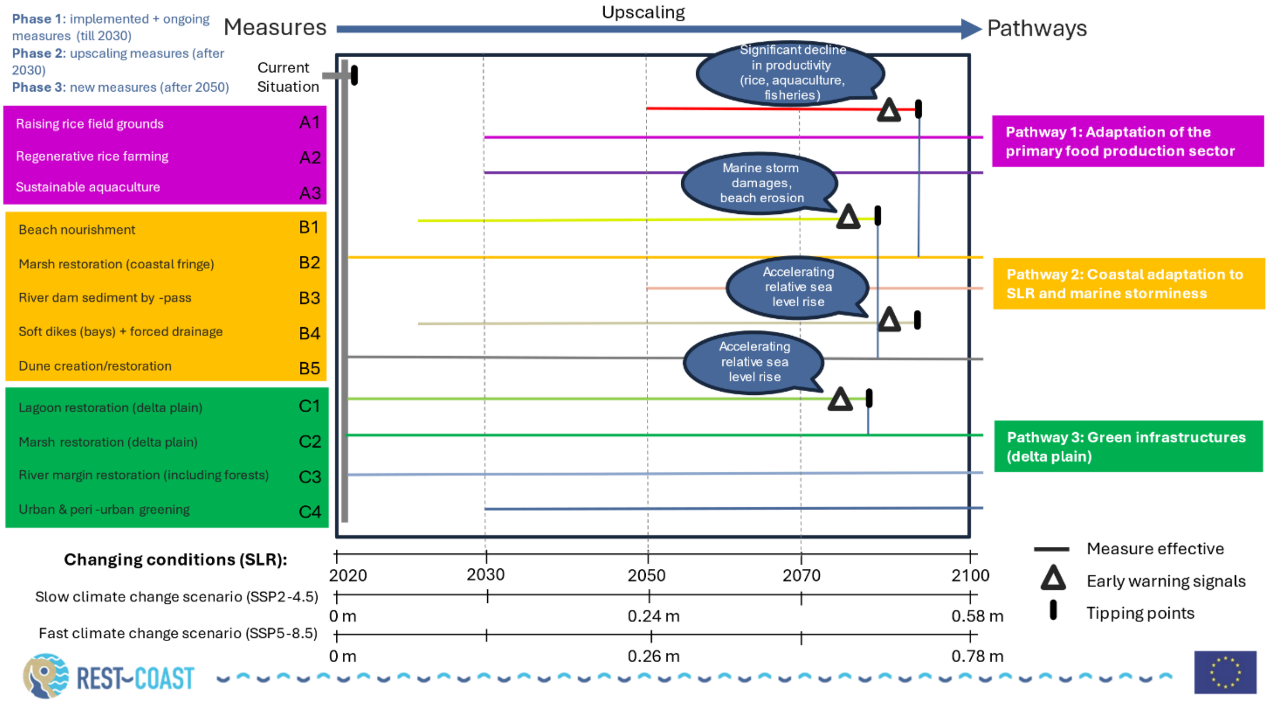

Figure 22: The adaptation pathway map of the Ebro Delta, with IPCC condition-based scenarios of SLR

The pathway 'coastal adaptation to sea level rise and marine storms' in the Ebro Delta (see Pathway 2; Figure 22) includes measures such as **beach nourishment** for the coastal system adaptation to increasing erosion and flooding risks. However, the decrease in the stock of sediments to nourish the beaches, the rapid erosion of nourished beaches and the growing social concern on beach nourishment as a coastal protection measure, will lead to this adaptation measure being temporary, reaching a tipping point, and not being effective in the future with the rising sea levels. At this point, **river dam sediment by-pass** is an adaptation technique to restore the river sediment flux through the reservoirs, providing sediment inputs to the delta to combat erosion of certain stretches of the coastline (especially the mouth area that shows the highest erosion rates), as well as promoting the accretion and fertility of agricultural soils for rice cultivation. Furthermore, the **restoration of marshes in the coastal fringe** behind the beach are necessary for coastal adaptation. Implementing wetland and marshes restoration projects and creating artificial marshes can act as natural buffers against rising sea levels and erosion. These areas could retain sediments, serving as sedimentation areas helping to maintain the balance of the delta, and could improve the water quality by creating green filters.

The protection of the Ebro Delta plain through **soft dikes** along the inner bay's shore, in combination with **forced drainage** and pumping are other measures of this coastal adaptation pathway. This measure is unavoidable since the delta plain is progressively becoming a polder area that needs to be protected and permanently drained to avoid sea flooding. However, with rising sea levels, soft dikes for coastal protection (in combination with beach restoration) will reach a tipping point in the long-term, where these measures will no longer be effective. Then, an upgrade of the dikes and/or a realignment of the shore will be needed. Complementary, **the creation and restoration of dunes** in the Ebro Delta provides coastal protection against wave surges, sea level rise, storms and subsidence. Therefore, implementing restoration and protection projects for coastal dunes, which act as natural barriers against erosion and rising sea levels, is crucial for climate-resilient management of the Ebro Delta.

A third adaptation pathway has been formulated in the Ebro Delta region which consists of the implementation of **green infrastructures in the delta plain** (see Pathway 3; Figure 22). The **restoration of**

coastal lagoons and marshes is a key adaptation measure in this pathway, as they act as carbon sinks, improve water quality and reduce the impact of sea level rise and subsidence while enhancing biodiversity. This is especially important in agricultural-dominated areas such as the Ebro Delta. The coastal lagoons are affected by the inundation of the deltaic plain that can occur when storms meet the meteorological tide. This process will be aggravated by sea level rise due to climate change, reaching a tipping point. If sea level rise permanently floods the lagoons and surrounding marshes in the future, they will lose their ability to act as natural barriers and buffers against storms and erosion.

Therefore, the **restoration of marshes in the delta plain** as well as the **river margin restoration (including forests)** are key adaptation measures that can be very effective in the long term. Both restoration measures, which are implemented across the delta plain and along the river, can be very effective against subsidence and rising sea levels. On the one hand, salt marshes act as a natural barrier to coastal erosion, trapping sediments and reducing flooding risks. They can dynamically adapt to sea level rise by sediment accumulation and landward migration, allowing them to maintain their long-term protective function. On the other hand, river margin restoration (including riparian systems) contributes to its stabilisation by reducing erosion caused by water flow as well as mitigating the impact of river flooding. The vegetation of the river margin also has an important ecological role, acting as a natural filter for the river by trapping sediment, nutrients and pollutants, thus improving water quality, while providing habitat for multiple species.

Finally, **urban and peri-urban greening** is a long-term adaptation measure proposed in this pathway. This measure contributes to reducing the heat island effect, common in towns, where temperatures can be significantly higher than in the countryside due to the accumulation of heat on artificial surfaces. Green areas, such as parks, gardens and trees, provide shade and moisture, contributing to the regulation of the urban microclimate, while improving air quality. In addition, urban and peri-urban vegetation improves the infiltration of rainwater into the soil, which reduces surface runoff and decreases the risk of flooding, especially during intense rainfall events that are increasingly common with climate change. In addition, green areas can act as buffer zones that retain water, reducing pressure on drainage systems. Urban and peri-urban greening increases biodiversity in urban environments, while providing recreational spaces for the population and promoting their well-being.

3.3.6 Evaluating pathways with multi-criteria analysis

As shown in Table 12, each adaptation measure is assessed semi-quantitatively with a five-point scoring methodology between -2 and +2 for all the sub-criteria: -2: major negative impact; -1: minor negative impact; 0: neutral or no obvious impact; +1: minor positive impact; +2: major positive impact.

Table 12: Measure scoring

Criteria	Sub-criteria	Measure (scoring -2 to +2)											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	C2	C3	C4
Effectiveness	Reduction coastal erosion (RCE)	+1	0	0	+1	0	+1	0	+1	0	0	+1	0
	Reduction flood risk (RFR)	+1	0	0	+2	+2	+1	+2	+1	+1	+1	+1	+1
	Water purification (WQP)	0	+1	+1	0	+1	0	0	0	+1	+1	+1	0
	Climate change regulation (CCR)	+1	+1	0	-1	+2	+1	-1	0	+2	+2	+1	+1
	Food provisioning (FP)	0	+1	+1	0	+1	0	0	0	+2	+1	+1	0

	Biodiversity	0	+2	+1	0	+2	+1	0	+1	+2	+2	+2	+1
	AVERAGE	+0.50	+0.83	+0.50	+0.33	+1.33	+0.67	+0.17	+0.50	+1.33	+1.17	+1.17	+0.50
Feasibility	Inclusive and effective decision-making	0	+1	+1	+1	0	0	0	+1	0	+1	+1	+1
	Recognition and respect for tenure rights	+1	+2	+2	+1	0	+1	+1	+1	0	+1	+1	+1
	Capacity and skills	+1	-1	+1	+1	+2	+1	+1	+1	+2	+2	+2	+1
	Technical and organisational feasibility	+1	0	+1	+2	+1	+1	+1	+2	+1	+1	+2	+1
	Leadership	-1	+1	+1	+2	+1	-1	+2	+2	+1	+1	+1	0
	Experimentation and learning	+1	+1	+2	+2	+2	+1	+1	+1	+2	+2	+2	0
	Governance structure and legal alignment	-1	+2	+1	+1	+1	-1	+1	+2	+1	+1	+1	0
	Diversity of knowledge, cultures and institutions	+1	+2	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
	Strategic vision, learning and direction	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	0
	Coordination and coherence	-1	+1	0	+1	+1	-1	0	+1	+1	+1	+1	0
	Grievance and conflict resolution (trust)	-1	+1	0	0	0	-1	0	0	0	0	+1	0
	Drivers of change	0	+2	+1	0	+2	0	0	+1	+2	+2	+1	+2
	Devolution	-1	+1	+1	+1	+2	-1	+1	+1	+1	+1	+1	+2
	Accountability	+2	+2	+2	+2	+2	+2	+2	+2	+2	+2	+2	+2
	AVERAGE	+0.21	+1.14	+1.07	+1.14	+1.14	+0.21	+0.86	+1.21	+1.07	+1.21	+1.29	+0.79
Cost	Total cost (per ha)	+1	-1	0	-2	-1	+1	-1	0	+1	+1	+1	+1
	Public funding ratio	-2	-1	-1	-2	-1	-2	-2	-2	-1	-1	-2	-2
	Funding gap	+2	+2	+1	+1	+1	+2	+2	+2	+1	+1	+1	+1
	Cost-effectiveness	+1	+2	+1	+1	+2	+1	+2	+1	+1	+2	+2	+2
	AVERAGE	+0.50	+0.50	+0.25	-0.50	+0.25	+0.50	+0.25	+0.25	+0.50	+0.75	+0.50	+0.50
Flexibility	Flexibility	+1	+1	+1	+1	+1	+1	0	+1	+1	+1	+1	+1

In general terms the highest scores (around 1) are obtained for the criteria of feasibility and flexibility, while the lowest one corresponds to cost (between 0.15 and 0.56), and effectiveness yields values between 0.6 and 1.04. Regarding the pathways, the highest score is reached by the green infrastructure in the delta plain, followed by the adaptation of the primary food sector and lastly by the coastal adaptation to climate change. In this last one the criterion that most contributes to the low score is the cost, as it is for the other two pathways too (but with less intensity). In summary it can be said that the three adaptation pathways are potentially quite feasible and flexible, relatively effective and with high costs.

Table 13: Pathway scoring

Criteria	Pathway 1	Pathway 2	Pathway 3
	avg. (A1+A2+A3)	avg. (B1+B2+B3+B4+B5)	avg. (C1+C2+C3+C4)
Effectiveness	+0.61	+0.60	+1.04
Feasibility	+0.81	+0.91	+1.09
Cost	+0.42	+0.15	+0.56
Flexibility	+1.00	+0.80	+1.00

4 Findings and conclusions on the way forward

Adaptation pathways are increasingly used to manage climate change impacts by providing a structured approach to long-term planning. The adaptation pathway approach does not offer a single, optimal sequence of measures in time. Instead, it supports policymakers by presenting a broad spectrum of potential measures, helping them to identify opportunities and prioritise measures over time. Pathway design needs to be flexible and adaptive, allowing decision-makers to switch strategies based on changing circumstances and emerging information.

The development of adaptation pathways in the REST-COAST pilots consist of several important steps which combine quantitative inputs based on models and scenarios and qualitative inputs through participatory approaches with stakeholders. The visualisation and storyline behind the pathway development offers a great opportunity for awareness raising about the 'solution space' (under deep uncertainty) and for bridging the (implementation) gaps between science, practice and decision making by translating and applying scientific data into practical actions. Application of the adaptation pathway approach (e.g. defining tipping points and assessing effectiveness) is relatively easier when management objectives are clear and quantified. However, this is often not the case due to complex governance processes and structures, different interests of stakeholders and lack of resources. For example, in the Wadden Sea pilot, we use modelling to identify the early warning signals and tipping points and evaluate effectiveness for three measures. But for other measures we need to rely on literature study and expert adjustment. For Venice and Ebro pilots, the measures are identified and evaluated based on qualitative assessments. Although this creates more uncertainty and potential bias, depending on which experts are involved and their fields and knowledge scopes, still this exercise is considered very helpful.

The interdependencies and trade-offs between different adaptation measures are crucial considerations, as they impact the effectiveness, feasibility, and long-term sustainability of these strategies. Jones et al. (2012) argue that successful adaptation requires recognizing the synergies and conflicts between measures, especially when dealing with complex systems like water management, ecosystems, and agriculture. In the Wadden Sea pilot, some measures such as farmland raising (with local material) and biodiverse dike reinforcement are dependent on sediment extraction and clay ripening. Therefore, a proper sequential order of these measures in a phased plan with transfer stations linking different measures are crucial. Trade-offs occur when the implementation of one measure compromises another, affecting their overall effectiveness or creating unintended consequences. Sediment extraction for example, can lead to coastal erosion due to its impact on the natural balance of sediment supply and coastal processes (Syvitski et al., 2005). It is recommended to prioritise flexible, adaptive measures that can be modified as conditions evolve, rather than fixed, singular solutions that might exacerbate trade-offs.

It was observed that the effectiveness of measures depends on the choice of objectives. For example, the choice of engineered flood defence systems would score high in the effectiveness of 'Reduction of coastal flooding risk (RFR)', but low in other ESS and BDV. But if the policy objective is focused on enhancing flood protection rather than balancing all ESS, this measure is still considered highly effective. It also became clear that some objectives could not be thoroughly assessed due to insufficient information, such as some financial data, highlighting the importance of prioritising MCA indicators that align with available data.

When it comes to upscaling, we acknowledge the great challenges of going from local restoration to large-scale implementation, as required by increasing climatic and anthropic pressures. For the Wadden Sea pilot, there have been on-going discussions and plans for the upscaling of current measures within the overarching long-term vision. In the Venice and Ebro pilots the long term vision still needs to be further developed with a joint effort of stakeholders. However, in all cases the development of adaptation pathways is instrumental to broaden the scope, exchange and discuss possible solutions and to decide which adaptation path(way) is most appropriate to follow. Upscaling can be hampered by a range of barriers, including technical barriers due to limited knowledge and data available; financial barriers due to limited funding and a lack of capacity to develop restoration business plans that are attractive to investors; as well as governance barriers that are caused by fragmented structures, social inertia and stakeholder conflicting interests (Sánchez-Arcilla et al., 2022). Overcoming these barriers and facilitating these factors are crucial to the success of upscaling plans. A historical analysis of morphological changes, combined with the monitoring of natural dynamics, can provide valuable insights into when and where to implement similar restoration measures to achieve optimal outcomes on a broader, regional scale. This understanding supports the effective scaling up of strategies by identifying key locations and timings for intervention. This will be further elaborated in the upcoming deliverable - D4.4 'Scalable plan for adaptation-through restoration to close the implementation gap'.

Understanding and addressing uncertainties is crucial for effective decision-making and implementation. In the development of adaptation pathways for REST-COAST, we have identified four main types of uncertainties regarding the effectiveness of measures, the determination of early warning signals and tipping points as well as multi-criteria evaluation: climate uncertainty, environmental uncertainty, socio-economic uncertainty, and policy and governance uncertainty (Haasnoot et al., 2019; Zandvoort et al., 2017). Climate uncertainty arises mainly from the lack of knowledge (e.g. the processes governing the rate of melting of the Antarctic ice sheet), and simplifications and assumptions in the climate models. Environmental uncertainty is related to ecosystem responses, namely the unpredictable response of natural systems to climate change and human interventions. Changes in ESS and BDV can significantly impact the effectiveness of adaptation strategies. Socio-economic uncertainty is caused by the uncertain social acceptance and (financial) support towards adaptation measures, affecting the feasibility and prioritisation of adaptation measures. Fluctuations in economic growth, investment capabilities, and technological advancements can influence the resources available for adaptation efforts. Policy and governance uncertainty is regarding the shifts in policies, regulations, and governance structures at local, national, and international levels that can affect the implementation and continuity of (nature-based) adaptation measures. Stakeholder engagement is key for developing adaptation pathways. Differing priorities and values among stakeholders can lead to conflicts and delays in decision-making but through a participatory approach consensus may be reached in time.

Last but not least, as defined in Section 2.4, we focus on identifying the biophysical scopes of early warning signals and tipping points for the pathway map, while in many cases the political shifts and socio-economic transitions play a major role in the changes of measures. That is why we suggest evaluating the pathways across a wide range of financial and governance indicators, and re-evaluate and adjust the scores when situations change over time. Keeping this in mind, it is important to design adaptation pathways that are inherently flexible, allowing for adjustments in response to new data, changing conditions, and emerging risks. It is crucial to recognize that the time scale and spatial scale on which the assessment is conducted substantially affects the outcomes. As the time horizon and spatial scale extends, the associated uncertainty increases correspondingly. Periodic reassessment and adjustment based on new information and changing conditions can promote flexibility and continuous learning.

Besides climate scenarios and relevant biophysical responses, socio-economic scenarios can play a significant role for exploring the long-term consequences of anthropogenic climate and environmental change and available response options (Kriegler et al., 2012; van Vuuren & Carter, 2014). In addition to policy support, the adaptation pathway approach can promote awareness, learning, collaboration, and capacity building within society, facilitating consensus building among stakeholders. Correspondingly, It is important to foster collaboration, for example by building strong partnerships with stakeholders across sectors and scales to leverage diverse perspectives, share knowledge, and align adaptation efforts. Given these uncertainties and challenges, the adaptation pathway approach offers great opportunities for exploring possible futures both in the near and long term. In each pilot detailed recommendations and measures that can facilitate adaptation strategies will be further developed in the 'Scalable plan for adaptation-through restoration to close the implementation gap (D4.4)' in collaboration with all the other work packages.

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Appendix 1 Governance indicators

Pilot / region level	
Governance structure and legal alignment	The legal alignment of policy frameworks and institutional arrangements at various (vertical) levels, such as local, regional, national, and international. *(Source: adapted from IUCN - 'Governance Structure' and Adaptation Pathways)*
Diversity of knowledge, cultures and institutions	Natural resource governance is grounded in sound and diverse forms of knowledge and respect for diverse cultures, values and practices. *(Source: IUCN)*
Strategic vision, learning and direction	Natural resource governance is guided by an overall vision of desired environmental and social outcomes, and allows for adaptation in response to learning and changing conditions. *(Source: IUCN)*
Coordination and coherence	Actors involved in or affecting natural resource governance coordinate around a coherent set of strategies and management practices. *(Source: IUCN, Adaptation Pathways)*
Grievance and conflict resolution (trust)	People are able to seek and obtain remedies for grievances and resolve conflicts regarding land and natural resources. *(Source: IUCN, Wadden Sea pilot)*
Drivers of change: urgency + liveability/wellbeing	The collective understanding that there is a problem or crisis (flood threat etc.) is considered an important driver for collaboration. This creates an awareness and a shared problem space, a common goal and a culture of societal responsibility. Likewise, if people perceive the action is aligned with their own goals of liveability (love, work, leisure), stakeholders can get engaged more easily as this resonates with their own realities. *(Source: Wadden Sea pilot)*
Devolution	Decisions are taken at the lowest possible level appropriate to the social and ecological systems being governed, with particular attention to empowering the roles and authority of Indigenous peoples and local communities in natural resource governance. *(Source: IUCN)*
Accountability	Actors responsible for or affecting natural resource governance are accountable for their actions and the environmental and social impacts they produce. *(Source: IUCN)*
Project / measure level	
Inclusive and effective decision-making	Decision-making regarding natural resource policies and practices is based on the full and effective participation of all relevant stakeholders, with particular attention to the voice and inclusion of rights-holders and groups at risk of marginalization. *(Source: IUCN, Pilot Paradox)*
Recognition and respect for tenure rights	Rights to lands, resources and waters are recognised and respected, with particular attention to the customary, collective rights of Indigenous peoples and local communities, and to women's tenure rights. *(Source: IUCN)*
Capacity and skills (working processes, collaboration for implementation)	Important at both individual and institutional level. Individual capacity can enable actors to plan, implement, and maintain measures and systems. When innovations are introduced, new capacity and training is needed. For example, new capacities for implementing adaptation include capacity to integrate risk considerations in spatial planning processes. *(Source: Adaptation Pathways)*

Technical and organisational feasibility	The adoption of innovative measures such as Nature based Solutions is an opportunity but can also encounter resistance as they do not align with existing technical and organizational procedures. Changing these procedures is necessary to make implementation feasible. Several actors in the implementation chain need coordination to help change things like Standard Operational Procedures. *(Source: Adaptation Pathways)*
Leadership	Leadership skills are increasingly understood as the ability to form collaborative partnerships, joint agreements, etc. to support collaborative governance, collective leadership and collective impact approaches. Effective adaptation to climate change will require the coordinated effort of all actors at all scales. Collaboration and genuine partnership between actors are therefore essential. *(Source: Pilot Paradox)*
Experimentation and learning	Experimentation, learning, and reflection that helps adapt strategies and plans is of crucial importance. De-learning and re-evaluation of assumptions and working objectives is necessary for changing course when one pathway or strategy turns out to be untenable in the long run. In enabling learning processes between people with different backgrounds and perspectives, it is known by for example mediators and negotiators that some environments are better than others for bringing about learning, such as open communication, facilitation, constructive conflict, multiple sources of knowledge, unrestrained thinking, and diverse participation etc. *(Source: Pilot Paradox, P2R)*

Appendix 2 Overview of key indicators for EWS and TPS (Wadden Sea)

Measures	Early warning signals (biophysical)	Tipping points (biophysical)
A1 Sediment removal (from harbor) *Based on Modelling*	Sediment extraction is causing ecological degradation and ESS loss: Erosion-caused by e.g. altered sediment supply (clay extraction elsewhere); habitat destruction or biodiversity loss	Sediment extraction is causing ecological degradation and ESS loss: Erosion-caused by e.g. altered sediment supply (clay extraction elsewhere); habitat destruction or biodiversity loss
A2 Farmland raising with local material *Based on Literature Review*	Lack of local sediment as land raising material (same EW as A1); risk salt intrusion damage (chloride concentration of seepage ~1 g/L Higher probability of seawater intrusion in pastures with sand layers; avoiding seawater intrusion requires precipitation lens of min 100 mm freshwater[1] and thickness of min. 1.25 m[1]; saltwater intrusion can negatively impact crop growth and can decrease water quality (saltwater may promote nutrients that can increase algae growth)	Lack of local sediment as land raising material (same TP as A1); risk salt intrusion damage (chloride concentration of seepage >1 g/L Higher probability of seawater intrusion in pastures with sand layers. Precipitation lens of <100 mm freshwater[1] and thickness <1.25m[1]; saltwater intrusion can cause a decrease in types of crops that produce a decent yield; land abandonment
A3 Farmland raising with other sources *Based on Literature Review*	Seawater intrusion	Seawater intrusion
A4 Aquaculture and saline agriculture *Based on Literature Review*	No EWS	No TP
B1 Facilitating natural deposition (PAGW) *Based on Modelling*	No EWS	No TP
B2 Clay ripening *Based on Literature Review*	Decreasing capacity for clay ripening due to changes in freshwater availability (e.g. in periods with precipitation deficit[2] that mostly occurs in summer period Apr-Sept) and salinity level (<4g/L/NaCl[2])	Lack of capacity for clay ripening due to changes in freshwater availability (e.g. in periods with precipitation deficit[2] that mostly occurs in summer period Apr-Sept) and salinity level (>4g/L/NaCl[2])
B3 Biodiverse dike reinforcement *Based on Literature Review*	Lack of sediment as construction material (based on A1 and B2); local criteria for dike construction must comply with erosion class II or I, have a consistency index of at least 0.6 , material has to be naturally deposited, max. sand content of (<63 µm), <5% organic matter after hydrogen peroxide treatment, <25% lime content, <4g/L/NaCl salinity level, no significant admixture of rubble, gravel	Lack of sediment as construction material (based on A1 and B2); local criteria for dike construction must comply with erosion class II or I, have a consistency index of at least 0.6 , material has to be naturally deposited, max. sand content of (<63 µm), <5% organic matter after hydrogen peroxide treatment, <25% lime content, <4g/L/NaCl salinity level, no significant admixture of rubble, gravel (<40% sand

	(<40% sand content), slight to no discoloration of clay material[3]	content), slight to no discoloration of clay material[3]
B4 Coastal protection with other measures *Based on Literature Review*	No EWS	No TP
C1 Tidal area restoration (with culvert in the sea dike and saltmarsh within the dike) *Based on Modelling*	Intertidal area clogging; 1 point decrease in ESS scores, due to increasing flood risk and coastal erosion	Changing from intertidal to subtidal area (SLR); 2 point decrease in ESS scores, due to increasing flood risk and coastal erosion
C2 Saltmarsh outside the dikes *Based on Literature Review*	Insufficient fine sediment (<63 µm) for saltmarsh development (min. suspended sediment concentration ~200 mg/L[4]); decreasing water quality (oxygen, pollutants, algal blooms, nutrient levels); tidal range <2 m[5]; SLR – threshold between 10-50 mm/y[4]	Insufficient fine sediment (<63 µm) for saltmarsh development (min. suspended sediment concentration ~200 mg/L[4]); tidal range < 2 m[5]; SLR – saltmarshes drowned at > 50 mm/y[4]
C3 Nesting islands *Based on Literature Review*	SLR – nesting islands submerged at storm tides (mean high water > 1.5m) (inundation frequency of 13 times yearly[6]) resulting in nest loss, shifting of nest locations and decline in adult fitness (e.g. disease outbreaks); loss of foraging possibilities for migratory birds Increased sightings of invasive species, predators; Storm events (~9.9 times annually with peak residual water levels of ~1 m)[8]	SLR – nesting islands completely submerged (~2.7m) [7] Habitat degradation e.g. invasive species or poor water quality; Storm events (>9.9 times annually with peak residual water levels of ~1 m)[8]

Sources: [1] Sweco (2022), [2] Ecoshape (2022), [3] Technische Adviescommissie voor de Waterkeringen (1996), [4] Marijnissen *et al.,* 2020), [5] Kirwan *et al.,* (2016), [6] Elschot *et al.,* (2023), [7] Boorman (2003), [8] Schuerch *et al.,* (2013),