The multi-functional potential of nature-based solutions in deltas - a systems approach

Exploring the application of system dynamics modelling to assess the social, ecological, and economic trade-offs of Nature-based Solutions under climate change

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Enabling Delta Life

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by

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Acknowledgements

Dear reader,

Completing a MSc thesis is challenging and demanding, especially if personal circumstances do not align with the research process. Nonetheless, before you lies a thesis of which I am proud. Naturally, such a feat is impossible without the support of others, both in practice and in life, which I was fortunate enough to receive. Perhaps, as a good friend argued, the primary outcome of your research is personal growth, and only secondly come the scientific and societal insights. This perspective has allowed me to appreciate the journey on a deeper level, despite the difficulties, and recognize the invaluable support I received along the way from those around me. I want to take this opportunity to thank them for the insights they have provided, whether I asked for it, didn't ask, or even when they didn't realize they were teaching me valuable lessons.

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Enjoy reading,

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Executive Summary

This research addresses the need for comprehensive assessment and understanding of multi-functional trade-offs of Nature-Based Solutions (NbS) for climate change adaptation (CCA), and aims to explore the applicability of a system dynamic modelling (SDM) approach in this context. Multi-functionality is defined as the three main impact dimensions of NbS: the social, ecological and economic. A guiding meta-model and quantitative SDM are created to capture these multi-functional trade-offs in the Catalan Ebro Delta, an area facing existential (climate) threats.

This executive summary is written as a concise yet comprehensive document to ensure decision-makers have all relevant information at their disposal. To that end, more detailed descriptions of the research are provided than usual for a MSc thesis. The chapters discussing the research findings (3, 4, 5, and 6) have been structured to function as (fairly) standalone units. If detailed insights are desired after consulting this summary, they can be read individually in the main sections.

Introduction, knowledge gaps, and research question

Nature-based Solutions (NbS) have emerged as a globally recognized response to address the challenge of balancing continued societal development while adapting to climate change and maintaining biosphere integrity. NbS can be defined as strategies meeting societal challenges through the utilisation of natural features or processes which simultaneously provide biodiversity and human well-being benefits. However, widespread implementation and realisation of NbS potential remain elusive. A significant factor contributing to this is the poor understanding of associated multi-functional trade-offs, leading to compromised social-ecological integrity, green-washing concerns and shift away from overarching goals, distraction from the urgency for ecosystem protection and restoration, and impeded widespread up-scaling of the concept. This poor understanding of NbS multi-functionality is largely the product of (the failure to account for) the intrinsic and systemic complexity of NbS. NbS are intrinsically complex due to their wide multi-functional solution space which spans multipledisciplines and sectors, which complicates successful integrative assessment. NbS are inherently embedded in complex social-ecological systems (SES), characterized by non-linearity, uncertainty, and multi-stakeholder environments. As such, literature urges for a systems approach to enhance understanding of multi-functionality (Castro, 2022; Nelson et al., 2020; Seddon et al., 2021).

The scope of this research is threefold. Firstly, we consider the complexity of NbS multi-functionality and associated trade-offs. Secondly, we employ a system dynamics modelling (SDM) methodology as we believe that SDM is a highly suited application of the systems approach in this context. Thirdly, the research is geographically bound to deltaic regions as deltas are high-impact, high risk regions in the face of climate change. Consequently, the objective of this research is to explore the application of a system dynamics modelling approach for assessing the social, economic, and ecological trade-offs associated with Nature-based Solutions for climate change adaptation in deltaic regions.

As a case study, the heavily humanized social-ecological system of the Ebro Delta in Spain is highlighted, where NbS are being considered for climate change adaptation. It is part of the REST-Coast umbrella project, which aims to find scalable solutions to climate change adaptation by restoration of coastal ecosystems, specifically river to coast connectivity.

Research approach

To arrive at the main research objective a mixed method approach grounded in the SDM methodology was adopted, which was applied on a deltaic case-study. The research approach is a core-aspect of this study, and therefore requires a more elaborate explanation.

Case study research

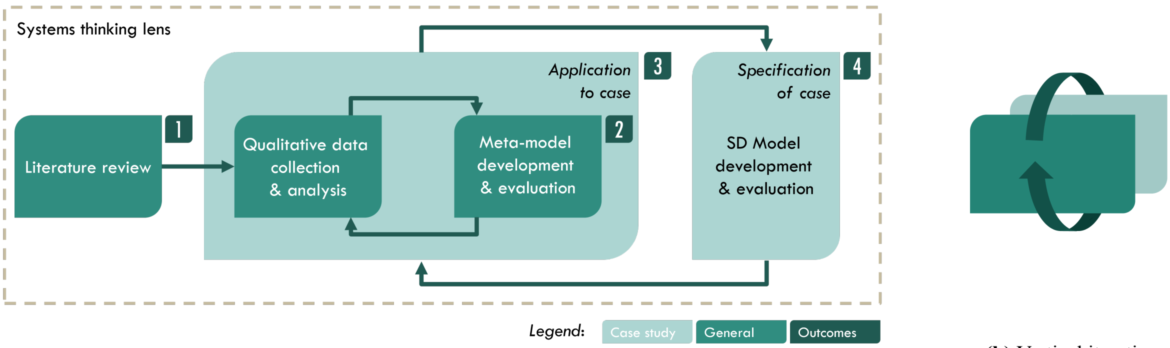
The case study is a key focus in NbS research and literature, as NbS are context heavy and case studies investigate complex phenomena in their contexts, representing a bounded system (by space, time and activity) to manage complexity. For the Ebro delta, local NbS data is already available and the integration with stakeholders is facilitated by the research network, which supported the research.

Mixed method research design

We intended to explore a quantitative SDM methodology, and as such, a mixed method approach employing both quantitative and qualitative methods was adopted given that a quantitative SDM also requires an elaborate understanding of qualitative complexity. Our design deviates slightly from a standard design, and is heavily iterative, drawing mostly from sequential and concurrent explorative strategies (see (Creswell & Clark, 2017; Creswell & Creswell, 2017)).

The research aimed to deliver four outcomes. 1) Initially, we sought to deepen the understanding of the knowledge gaps related to the objective. This understanding set the stage for the heavily iterative exploration that followed, where we 2) developed a guiding meta-model able to capture social, economic, and ecological dynamics associated with NbS for CCA in deltaic regions, 3) detailed this meta-model to the case-study, and 4) applied the detailed meta-model to guide the quantitative SD modeling effort.

While all model building is inherently iterative, our approach distinguishes itself in the employment of a holistic iteration, where the progression on the outcomes informed and enhanced the others. As the object of inquiry, the case-study served to refine and illustrate our exploration, while yielding contextual insights benefiting local policy. As such, the design distinguished between horizontal and vertical iteration, where vertical iteration is found in the case application. Horizontal iteration is found between the collection of qualitative data and the meta-model building, and also between the detailed meta-model (case-specific) and the SDM specification. The mixed method research design is visualized in figure 1.



(a) Process and Outcomes. The arrows visualize the process flow, whereas the boxes visualize the content. An overarching systems thinking lens shapes the research.

(b) Vertical iteration between the general and case analysis

Figure 1: The mixed method process design

Questions and outcomes

To attain the main research objective, four questions are constructed which correlate to the four outcomes. The first two questions address general aspects, whereas the second two concern the case-study application. Table 1 presents the overview of the outcomes of these questions.

1. What is known on the social, economic, and ecological trade-offs and SDM applications associated with NbS for CCA in deltaic regions?
2. Which factors and interactions yield the social, economic, and ecological dynamics associated with NbS for CCA in deltaic regions?
3. Where do the social, economic, and ecological trade-offs associated with Nbs for CCA lie in the Ebro Delta?
4. Which specification is able to capture the social, economic, and ecological dynamics associated with NbS for CCA in the Ebro delta?

Obj.	To explore the application of a SDM approach for assessing the social, economic, and ecological trade-offs associated with NbS for CCA in deltaic regions		
RQ 1	**Outcome: Literature review** • Deepened understanding of **knowledge gaps** on **multi-functionality of NbS for CCA and associated trade-offs** • **Knowledge gaps** geographically scoped to **deltaic regions** • **Applicability** of the **systems approach and SDM** to bridge these knowledge gaps • **Previous applications of SDM** to multi-functionality of NbS for CCA and associated trade-offs	General	Linear
RQ 2	**Outcome: ICE - model** • **Theoretical knowledge base** of deltaic social-ecological systems and (climate) threats with role of NbS • Formulation of **guiding concepts and indicators** to describe social, economic, and ecological dynamics associated with multi-functional NbS trade-offs under CCA in deltaic regions • **ICE-model:** Synthesis into system diagram	General	Iterative
RQ 3	**Outcome: ICE - Ebro** • Integrated **Ebro delta** social-ecological **system and problem description** • Non-exhaustive **categorization of** potential **NbS strategies** • Synthesis into **ICE-model detailed for the Ebro delta** in this context	Case application	Iterative
RQ 4	**Outcome: SDM application ICE – Ebro** • Formulation of **system boundary** • **SDM formalisation** that is able to capture and integrate the social, economic, and ecological dynamics in the Ebro delta.	Case application	Iterative

Table 1: Outcomes of the research questions (1 to 4) with corresponding products and methods, leading up to the overarching objective. The distinction between linear & iterative research and general & case-applied is highlighted on the right and with respective colours. Question 1 is answered with a literature review. Question 2 is answered with a literature study, and validated with semi-structured interviews. Question 3 and 4 are answered with a literature study, semi-structured interviews, a field trip, and naturally the SDM methodology

Methods adopted included a literature review, literature study, semi-structured interviews, field trip, as well SD as our dominant method, which is discussed in more detail below. For the case application, integration and validation were facilitated by a two-level triangulation structure depicted in figure 2.

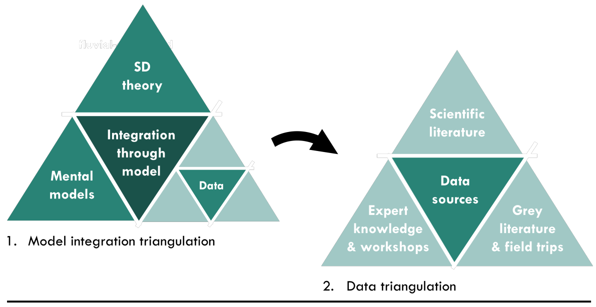


Figure 2: The adopted two-level triangulation structure adopted for the case application.

System dynamics modelling

SDM is a computer simulation technique based on differential equations employed to gain understanding of the complex nonlinear dynamic structure and behaviour of systems over time (Forrester, 1993; Sterman, 2002). SDM primarily models system structure and behaviour through feedback, accumulation and delays originating from (endogenous) causal mechanisms.

Research findings

Below the outcomes of the four research questions are discussed.

Outcome: Literature review

The literature review underscored the need for greater integrative understanding of the multi-functional trade-offs of multiple NbS strategies - over scale (temporal, spatial), under climate uncertainty and for various stakeholders. Despite the close alignment of the systems approach with NbS principles and SES, it is sparingly applied. SDM was identified as a suitable application of the system approach, primarily given its capability to capture and aggregate complex system structure and behaviour, effectively incorporating the numerous feedback loops characteristic of coupled systems. As integrative and quantitative applications are scarce, especially in non-urban contexts, there's a call for further exploration of SDM's applicability in this domain.

Outcome: The ICE-model

Deltas are regions of high heterogeneity and connectivity that boost economic and ecological productivity, which have historically resulted in concentrated human development integrated with vital ecosystems. Deltaic evolution is highly dynamic, and is primarily governed by the balance between fluvial and coastal processes — especially river discharge and sediment are important for shaping its morphology. However, deltas globally are experiencing severe environmental degradation due to direct human activities (e.g., poor sediment management, intensive agriculture, groundwater extraction), with climate change exacerbating these threats.

NbS have emerged as a promising approach to help deltaic SES adapt to climate change impacts. Recognizing the complexity of deltaic SES, we proposed that a comprehensive understanding of system structure and behaviour is essential for evaluating trade-offs thoroughly. To this end, we developed a general meta-model (named ICE-model) which has a 'scaffold'-like character serving to 1) support problem exploration as it is adaptive for different contexts and use cases, and 2) guide the SDM modelling effort. The meta-model is based on a system diagram, and focuses on the flow of ESS to structure multi-functional dynamics. The modular and flexible framework is able to place NbS within their intended context, facilitating engagement, learning and policy making.

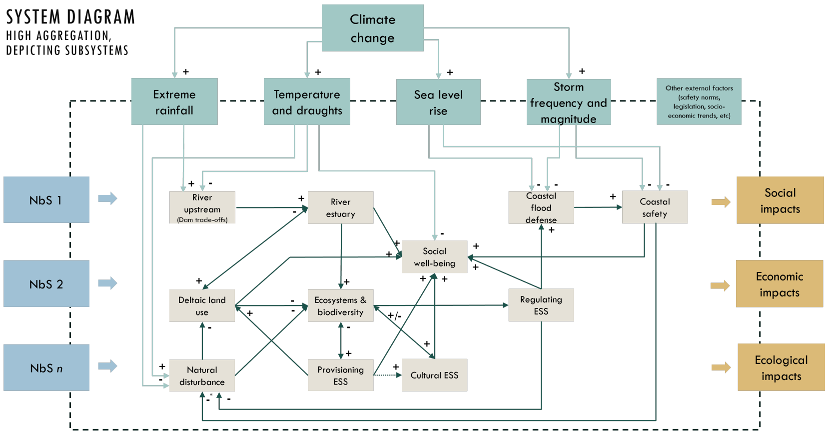


Figure 3: ICE-model, a general system diagram of NbS for CCA in deltas. The polarity of the arrows indicates the direction of change. No causality is defined for both the means (NbS) and the criteria as they are context-dependent.

Outcome: ICE-Ebro

The Ebro Delta is heavily humanized and must be understood and managed as a single social-ecological unit. Almost 80% of the area has been reclaimed, with rice cultivation dominating land-use. Ecologically, the Ebro delta stands out for its high diversity of both habitats and species on a relatively small surface, many of whom are scarce or endangered. This ecological wealth is crucially supportive for the socio-economic structure. Related functions and values are tightly interwoven with the landscape, and have always depended on natural resource exploitation, and ultimately on the varying influxes of water, nutrients, and sediments transported by the Ebro. Consequently, dependency on (climate-sensitive) ESS is high.

Due to river dams depleting sediment transport by over 99% and eliminating flooding events, coupled with intensified agricultural activity the Ebro delta faces three primary challenges: the lack of fluvial sediment and discharge, environmental degradation, and the impacts of climate change, as the former two collectively increased vulnerability to natural hazards. Proposed NbS to alleviate these threats can be categorized in environmental flows, sediment by-passes, building up of the coastline, and habitat restoration. These mainly aim to restore natural conditions and processes to establish a stronger social-ecological resilience. Sediment is a crucial variable for each of these interventions.

The ICE-model was detailed to the Ebro delta by synthesizing the analysis above, resulting in the ICE-Ebro, see figure 4. The ease of adaptation suggests that coupled with the contextual SES understanding, the ’scaffold’-like character of the ICE-model is attainable.

Outcome: SDM application ICE-Ebro

Coupling the contextual understanding and ICE-Ebro yielded the quantitative SDM describing the multi-functional trade-offs of NbS for CCA. Typically, formalizing a model (developing equations and parameterizing variables) starts with a conceptualisation which is followed by specification. In this research these were executed concurrently to increase the alignment with available data. The model is partially specified, as parameterization was out of scope for this thesis.

The model was developed along the axis of the Ebro delta (which is a co-flow of fluvial discharge and sediment), where the system boundary include not only the delta plain but also the upstream river extending up to the first three dams as they are the most influential for the Ebro delta. The flow of ESS connects ecosystems with social and economic assets and values. The flows are primarily affected by human activities and natural hazards, the latter of which is exacerbated by climate change. Naturally,

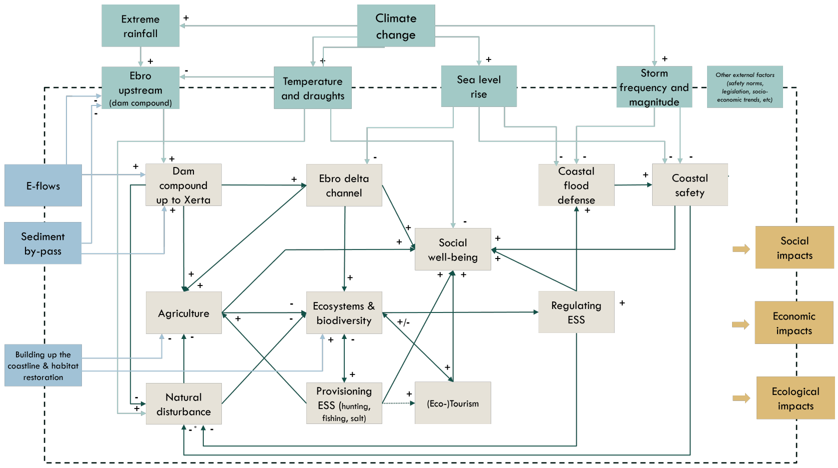


Figure 4: ICE-Ebro.

NbS interventions leverage these flows as well. Main aspects modelled include the fluvial discharge, the sediment (in the channel & on delta plain and concerning shoreline dynamics), coastal processes & climate effects, agriculture, and ecosystems & tourism. The change in ESS flows and their resultant impacts on the social, economic, and ecological dimensions can be assessed to understand the varying multi-functional trade-offs of NbS. Herein, heuristics were adopted to assess behavior relative to a baseline.

The model was able to successfully capture the social, economic, and ecological dynamics of NbS for CCA in the Ebro delta. It is flexible and modular by accommodating for various NbS and perspectives, and is likely to be relatively easily expanded or detailed as needed (e.g. also including non-NbS measures, adding a sector). Effective communication is ensured through the coupling with the Ebro-ICE model. Still, quantitative modelling of NbS multi-functionality results in a broad and complex model, even at a high level of abstraction, underscoring the inherent and systemic complexity of NbS. Subsequently, the aggregation and integration of heterogeneity, especially spatially, was challenging and required heavy assumptions. The model's successful capture of multi-functional dynamics suggests heuristics can support the quantitative assessment of social, economic, and ecological impacts, especially given the challenges in valuing non-monetizable impacts of NbS. Assessing behavior relative to a baseline can be more insightful than striving for precision and risking inaccuracy. Furthermore, we noted social impacts can be difficult to capture comprehensively, while ecological impacts are difficult to capture accurately, requiring extensive aggregation. Finally, the formalized model substantiates, even without outputs, that sediment is the fuel for the functioning of the Ebro delta SES.

The SDM formulation helped illustrate that the ICE-model is 1) able to effectively guide the modelling effort, 2) helpful in its communication, and 3) able to illustrate the high level of intrinsic and systemic complexity of NbS.

Deriving policy insights for the Ebro delta

It has been determined with high confidence that action is necessary in the Ebro delta to maintain (and restore) social, economic, and ecological processes. Based on our understanding of the system, although implementing Nature-based Solutions (NbS) may cause short-term social and economic challenges, we hypothesize that they will enhance long-term resilience and alignment with multi-functional values, as well as providing relatively prompt ecological benefits. The significance of these benefits is amplified when considering the impacts of climate change. Improved consideration of ingrained values is required in the design of NbS strategies, as has been shown especially well with the concept of sediment equity.

Concluding on the objective

The conclusions are formulated on the exploration of the SDM methodology for assessing trade-offs associated with NbS for CCA in deltaic regions, on NbS multi-functionality and associated trade-offs from a content-focus, and on contextual insights benefiting Ebro delta policy.

Methodological insights

The results suggest that the SDM methodology is suited to assess the social, economic, and ecological trade-offs associated with NbS for CCA in deltaic regions. Three aspects of the methodology have been clarified in this research:

1. The need for the application of the SDM methodology to this context has been strongly underscored.
2. The SDM methodology is able to *comprehensively* quantify multi-functional trade-offs, while maintaining *versatility* for different applications (i.e. contextual and/or case-specific) and facilitating *communication* and learning.
3. The ICE-model is suitable to facilitate a) problem exploration and b) guide a quantitative SD modelling effort.

We expect that the suitability to assess multi-functionality at the regional scale is not limited to deltas. Although the research has not finished a full modelling cycle, has been limited to one case, and has only moderately included participatory elements, the process itself represents a step forward in the understanding of multi-functionality of NbS and SDM applications on this topic.

One of the dis-advantages of the methodology is the time intensiveness; especially for complex SES the right integration demands a thorough and iterative analysis. However, we argue that the time costs are justified: once the model has been built it greatly enhances understanding of the system interactions and responses, facilitates multiple applications, and can be rapidly expanded as needed. Additionally, it facilitates engagement and learning, and could serve as a strong argument for the multiple values of NbS (especially non-monetizable). Furthermore, it may lead to greater alignment, long-term benefits, and reduced overlooked impacts or rebound effects of NbS strategies.

Towards comprehensive assessment of NbS impacts

It was demonstrated that the trade-offs associated with NbS under climate change depend for a large extend on the existing social, economic, and ecological structure and associated values of the system where the interventions are intended to function. The trade-offs of NbS arise both between and within the impact dimensions, between short- and long-term temporal scales, and seem highly dependent on stakeholder perspectives. An important identified insight is that the understanding of the (historic) context is imperative to uncover hidden relations and ingrained values that are missed at first glance. For these reasons, we argue that an extensive understanding of this structure and its behaviour (under changing conditions) is imperative if an accurate and comprehensive assessment of NbS impacts is desired. Moreover, in the context of regional-scale NbS, policy should be cautious of simplicity. Instead, it should embrace the inherent and systemic complexity of NbS, recognizing and leveraging the wide and multi-functional solution space that spans multiple disciplines and stakeholders.

Limitations

The research is limited by several aspects, of which the most important are listed here. First and foremost, the full modelling cycle has not been completed. The need for an explorative analysis that acknowledges uncertainty and multiple perspectives was identified, and a full modelling cycle would address this need while also facilitating reflection on the model's behaviour. Secondly, the research approach focused on one case application only, and as this case was used to refine and illustrate our exploration, this limits the strength of generalized conclusions. Thirdly, although one of the main found knowledge gaps is the lack of local stakeholder participation in the design and implementation of NbS, this research only minimally included participatory processes. Finally, because the SDM model captures such a broad system, aggregation will have produced "average" behaviour insensitive to spatial, sectoral, or characteristic heterogeneity which could be of importance. This is exacerbated by the complexity of ecosystems and the interdependencies between different services, which can introduce significant uncertainty in assessing and managing ESS.

Recommendations

To enable successful multi-functional NbS implementations for all stakeholders, it is advised to establish a holistic understanding of the local social-ecological system (SES) and associated values and acknowledge the complexity of NbS ex ante by analysing their impacts in the context where they are intended to function. System dynamics is an effective tool to do both as it provides extensive quantitative system structural and behavioural insights for long-term time horizons while facilitating adaptability to different use-cases, engagement, and learning. It is comprehensive, versatile, and easy to communicate. Our research suggests that heuristics can support the quantitative assessment of multi-functionality, including non-monetizable impacts, by assessing behavior relative to a baseline. To aid in the modelling effort and scalability of NbS strategies in the deltaic context, the ICE-model may be utilized.

For the Ebro delta, we believe NbS are essential components in growing the SES resilience and magnitude which is crucially important in the face of climate change. However, implementation of NbS strategies in the Ebro necessitates improved consideration of ingrained values, communication and transparency, and participation between local and regional/national stakeholders. Policy that has not recognized the inherent systemic values stands at risk of inefficiency, creating push-back, or missing the essence, as has been shown especially well with the concept of sediment equity.

Proposed future research

A full modelling cycle needs to be executed to increase the confidence of conclusions and insights, and align the model with reality. This includes data specification, validation and verification, the design of experiments, and using the model in a practical/policy setting. Subsequently, the methodology needs to be applied to multiple cases, preferably different in characteristics, to evaluate the robustness and allow for refinement. Furthermore, inclusion of participatory elements along the lines of Giordano and Pagano (2023) or Pagano et al. (2019) would greatly enhance the validity and multi-functional alignment. To acknowledge and account for the high uncertainty present within a SES, a exploratory modelling approach as advocated for by Kwakkel and Pruyt (2015) could be adopted.

Nomenclature

Abbreviations

Abbreviation	Definition
CCA	Climate Change Adaptation
CLD	Causal Loop Diagram
ESS	Ecosystem Services
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
KPIs	Key Performance Indicators
IPCC	International Panel on Climate Change
NbS	Nature-based Solutions
RSLR	Relative Sea Level Rise
SES	Social-ecological System
SD	System Dynamics
SDM	System Dynamics Modelling
SLR	Sea Level Rise
TEEB	The Economics of Ecosystems and Biodiversity
UN	United Nations

Contents

1
Introduction

In September 2023 the third major update on the planetary boundaries framework established that six out of nine boundaries have now been transgressed due to human activity, risking incomprehensible loss of human societal welfare levels (K. Richardson et al., 2023). This scientifically established framework is rooted in the principles of system science, identifying critical thresholds of (human) disturbance to the Earth's major processes beyond which stability and resilience of our planet's system as a whole is lost (Rockström et al., 2009). Steffen et al.(2015) identified that from the nine boundaries, climate change and biosphere integrity (earlier 'biodiversity loss') are the most important to the functioning of the planet's system. Both of these are currently at high risk, and are mutually influential, meaning that there is high confidence of system destabilisation (K. Richardson et al., 2023). This gives rise to the existential challenge of balancing continued societal development while adapting to climate change and maintaining biosphere integrity (O'Neill et al., 2018).

A globally recognized key response to this challenge is the concept of ''nature-based-solutions'' (NbS) (IPBES, 2019). By consolidating the most commonly used definitions by the European Commission and International Union for Conservation of Nature (IUCN), NbS can be defined as strategies meeting societal challenges through the utilisation of natural features or processes which simultaneously provide biodiversity and human well-being benefits (Cohen-Shacham et al., 2016; European Commission, 2015). NbS examples include vegetated foreshores or mangroves for coastal surge reduction, wetlands for water retention and/or quality improvement, and tree planting for urban heat mitigation. As such, NbS offer the potential for climate change adaptation (CCA) (and mitigation) while strengthening biosphere integrity and societal well-being (Cohen-Shacham et al., 2016; Seddon, Chausson, et al., 2020).

However, although the concept use and support has exponentially grown over the last decade, widespread implementation and realisation of this potential remain elusive (Seddon, 2022). A significant factor contributing to these issues is the poor understanding of associated trade-offs on and across the three main dimensions where impacts of NbS are found: the social, ecological and economic. These impact dimensions are collectively referred to as the co-benefits or multi-functionality of NbS (Nelson et al., 2020; Seddon, Chausson, et al., 2020). This poor understanding of NbS multi-functionality is largely the product of (the failure to account for) the intrinsic and systemic complexity of NbS. NbS are intrinsically complex due to their wide multi-functional solution space which spans multiple disciplines and sectors. The wide solution space of NbS is an advantage over alternative (related) approaches, but successfully integrating various disciplines and sectors is challenging, especially given the multitude of stakeholders and the high potential for ambiguity (Chausson et al., 2020; Seddon et al., 2021). Moreover, as NbS aim to address societal challenges sustainably for both people and planet, they are naturally embedded in social-ecological systems (SES). These systems are notoriously complex (Ostrom, 2009), exhibiting characteristics such as non-linearity or system uncertainty and encompassing multi-stakeholder environments. Jointly, the characteristics of the intrinsic and systemic (contextual) complexity of NbS have inhibited a comprehensive understanding of multi-functionality and associated trade-offs, leading to compromised social-ecological integrity, green-washing concerns and shift away from overarching goals, distraction from the urgency for ecosystem protection and restoration, and impeded widespread up-scaling of the concept (Chausson et al., 2020; Nelson et al., 2020; Seddon, Chausson, et al., 2020; Seddon et al., 2021). As such, literature urges for a holistic systems approach to enhance understanding of multi-functionality (Castro, 2022; Nelson et al., 2020; Seddon et al., 2021). By generating knowledge on complex system structure and behaviour, this approach may facilitate a comprehensive understanding of NbS for CCA, and is therefore essential for success. Yet, it has rarely been applied.

The scope of this research is threefold: we consider the complexity of NbS multi-functionality and associated trade-offs, with a system dynamics modelling (SDM) methodology, which is geographically bound to deltaic regions. The content focus (1) stems from the need for a thorough comprehension of the poorly understood complexity of NbS multi-functionality. Methodologically (2), we believe that SDM is a highly suited application of the systems approach to assess multi-functional trade-offs associated with NbS. As a simulation modelling method, it is able to represent interconnectedness, complexity and variability quantitatively. The geographical scope (3) fits the significance of NbS for CCA in deltas. Globally, deltas serve as important social, economic, and ecological hubs, supporting high levels of biodiversity and a significant share of the population (Elliott et al., 2019). However, their land-sea interface and inherent characteristics render them highly vulnerable to climate change impacts, a susceptibility that is projected to intensify in the coming years.

Consequently, the objective of this research is to explore the application of a system dynamics modelling approach for assessing the social, economic, and ecological trade-offs associated with Nature-based Solutions for climate change adaptation in deltaic regions. A mixed method approach grounded in the SDM methodology will be adopted, which is applied on a deltaic case-study. Initially, we seek to deepen the understanding of the knowledge gaps related to the objective. A heavily iterative exploration follows, where we 1) develop a guiding meta-model able to capture social, economic, and ecological dynamics associated with NbS for CCA in deltaic regions, 2) detail this model to the case-study, and 3) apply the detailed model to guide the SD modelling effort. As the object of inquiry, the case-study serves to refine and illustrate our exploration, and yields contextual insights benefiting local policy.

One region looking to apply NbS for CCA while protecting and restoring biodiversity is the Ebro Delta on the Catalan coast in Spain. It is part of the REST-Coast umbrella project, which aims to find scalable solutions to CCA by restoration of coastal ecosystems, specifically river to coast connectivity. The Ebro Delta is facing existential threats which are exacerbated by climate change introducing sea-level rise and increased storminess among others (Rodríguez-Santalla & Navarro, 2021). It is a heavily humanized socio-ecological system: high biodiversity levels are present, which are densely integrated with human development and activities (Ibáñez & Caiola, 2016a). Thus, associated risks are social, ecological and economic. A system approach could help secure that NbS helps to solve the climate and biodiversity crisis the delta faces, and additionally grow socio-economic activities sustainably. Systematic case-specific knowledge can then be extrapolated to grow understanding of the multi-functionality and scalability of NbS.

This research is structured as follows. In chapter 2 the research approach, subquestions, and adopted methods are outlined. In chapter 3 the literature review is delineated, which sets the stage for addressing our objective. Then follows the outline of the remaining results; the inherently iterative and continuous approach that was adopted to attain these is presented in a discrete manner for clarification. Chapter 4 formalises the ICE-model, which is a meta-model based on a system diagram aiming to establish a general foundation for modelling and understanding of trade-offs associated with the multi-functionality of NbS for CCA in deltaic regions. Chapter 5 synthesises the ICE-model for the Ebro delta case, and chapter 6 applies this synthesis to guide the modelling effort, resulting in a quantified SDM specification. Finally, chapter 7 concludes. The chapters discussing the research findings (3, 4, 5, and 6) have been structured to function as (fairly) standalone units. They can be read individually if the executive summary is consulted for context.

2
Methodology

This chapter discusses the methodology of this research. The research approach is given in section 2.1, where the case study and mixed methods approach are discussed primarily. The formulation of (sub)questions follows in section 2.2. Subsequently, the methods and data collection to answer these questions are discussed: Section 2.3 delineates the literature search strategy, and section 2.4 describes the remaining iterative research in more detail. The latter concerns the formulation of the ICE-model, the detailing of this model to the Ebro delta case, and the SDM application. Finally, the research flow diagram is presented in section 2.5, summarizing the research structure.

2.1. Research approach

To arrive at the main research objective, a mixed method approach grounded in the SDM methodology will be adopted, which is applied on a deltaic case-study. First, section 2.1.1 briefly restates the main concepts, after which the case study (the object of inquiry) is discussed in section 2.1.2, and subsequently the mixed methods approach is delineated in section 2.1.3. SDM is discussed later in section 2.4.5.

2.1.1. Defining main concepts

Besides NbS, the fundamental concepts used in this literature review are NbS multi-functionality and the systems approach. Multi-functionality is seen as a framework of the three NbS impact dimensions: the social, ecological and economic. Literature also calls these the co-benefits, multiple benefits or added values. Note that these dimensions are inherently intertwined and mutually influential. As a practical application of systems thinking, the systems approach is a holistic method of understanding complex phenomena by examining the interactions and relationships between the components of a system (Arnold & Wade, 2015). It recognizes that complex system behaviour cannot be understood by studying components in isolation (Bertalanffy, 1968); a system is more than the sum of its parts (Weinberg, 1975). The systems approach serves as an overarching theoretical lens guiding the research.

2.1.2. Case study

NbS are embedded in complex contexts, encompassing political, economic, social, cultural, historical, and organizational variables. As such, an in-depth context understanding is imperative, meaning the case study is a key focus in NbS research and literature (Debele et al., 2023). Namely, case studies investigate complex phenomena in their contexts, representing a bounded system (by space, time and activity) to manage complexity (Harrison et al., 2017), especially when boundaries between the context and the phenomena are not clear (Yin, 2011). The case study can go beyond the study of isolated components and allows for inclusion of multiple sources of evidence.

The case study means that other employed methods should facilitate a high quality context understanding taking a transdisciplinary approach (see also Jahn et al., 2012), and therefore additionally guides the choice for a mixed method strategy. Secondly, the research should be structured and systematic, to combat biases and generalisation difficulties that can arise if case study research is conducted poorly (Yin, 2011). To that end, we keep in mind that the process is inherently shaped by the participants cultural backgrounds, local surroundings, and social connections among others. Findings can be analytically (not statistically!) generalized for other situations.

Case alignment

The alignment of the research and the case is high. Engaged stakeholders in the Ebro Delta seek strategies to adapt to climate change while enhancing natural capital and protecting cultural values (such as rice farming, gastronomy, and nature). To that end, local partners have already chosen NbS as viable strategies, though no consensus on the (set of) interventions has been achieved (Sánchez-Arcilla et al., 2022). Furthermore, NbS and the impacts of natural restoration practices have been extensively studied in the Ebro Delta (E.g. F.-Pedrera Balsells et al., 2020; Ibáñez and Caiola, 2021a; Sánchez-Arcilla et al., 2022). Summarizing, local NbS data is already available and the integration with stakeholders is facilitated by the research network. Next to advancing the decision-making process in the Ebro Delta, the in-depth understanding of the multi-functionality of NbS in context is crucial for scaling NbS in deltaic systems. This is a key goal of the broader REST-Coast project in which the case is embedded. Finally, the case study fits in the time-constraints of a Master thesis.

2.1.3. Mixed Method Approach

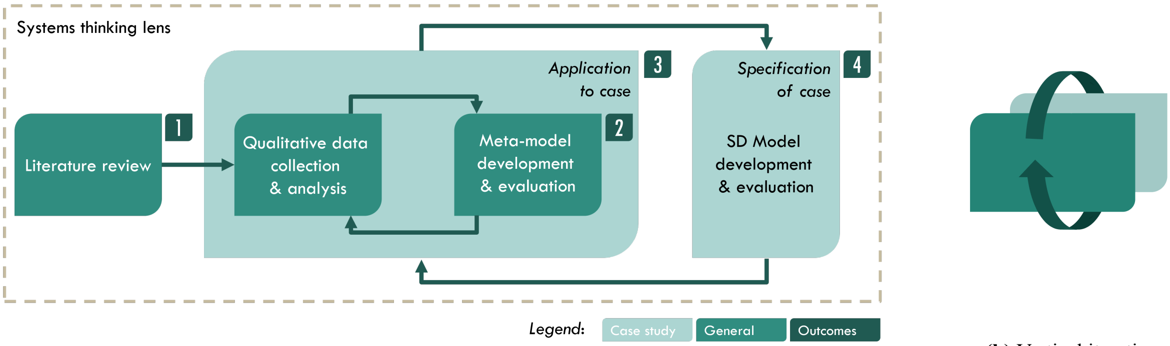
A mixed method approach is adopted, as SDM requires elaborate understanding of qualitative complexity: the background, the systems' causality, and stakeholders' objectives and perceptions among others. The fundamental idea this approach conveys is that employing both quantitative and qualitative methods offers a more comprehensive understanding of research issues (Creswell & Clark, 2017; Creswell & Creswell, 2017). This is especially true when researching complex problems, where either approach by itself is inadequate to address the complexity.

Within mixed method approaches, different designs can be adopted. We deviate slightly from a standard design, and instead incorporate different elements of these standards. Our design is heavily iterative, drawing mostly from sequential and concurrent explorative strategies (see (Creswell & Clark, 2017)). The grounded methodology (SDM) guides the project and is quantitative, but builds on qualitative analysis. Model stocks and flows are quantified with quantitative data, but qualitative literature studies and interviews have an important role in the development of the structure and behaviour of the model. Essentially, the model takes on an integrative role, synthesizing both qualitative and quantitative analysis.

The research aims to deliver four products. 1) Initially, we seek to deepen the understanding of the knowledge gaps related to the objective. This understanding sets the stage for the heavily iterative exploration that follows, where we 2) develop a guiding meta-model able to capture social, economic, and ecological dynamics associated with NbS for CCA in deltaic regions, 3) detail this meta-model to the case-study, and 4) apply the detailed meta-model to guide a quantitative SD modelling effort.

The iterative progression of the meta-model, detailed meta-model, and SD model structure demands additional explanation. While all model building is inherently iterative, our approach distinguishes itself in the employment of a holistic iteration, where each model's progression informs and enhances the others. Thus, as the object of inquiry, the case-study serves to refine and illustrate our exploration, while yielding contextual insights benefiting local policy. As such, the design distinguishes between horizontal and vertical iteration, where vertical iteration is found in the case application. Horizontal iteration is found between the collection of qualitative data and the meta-model building, and also between the detailed meta-model (case-specific) and the SDM specification. The design is visualized in figure 2.1a.

A considered limitation with this design is the potential discrepancy between qualitative and quantitative data (Creswell & Clark, 2017). Furthermore, the abstraction level of the model(s) is key for success. I.e. including all relevant relations without getting lost in details. Both of these pitfalls can be mitigated substantially by careful evaluation with stakeholders, ensuring that the model(s) capture the system correctly and deliver relevant results. Finally, the heavy iteration is prone to transparency and reproducibility loss. To prevent the black box effect, we aimed to carefully list and substantiate sources of information, as well as describe the synthesis. Also, we made sure to reflect with experts on our model after each iteration, to reduce the number of biases as much as possible.



(a) Process and outcomes. The arrows visualize the process flow, whereas the boxes visualize the content. An overarching systems thinking lens shapes the research.

(b) Vertical iteration between the general and case analysis

Figure 2.1: The mixed method research design

The system dynamics modelling cycle

It is not directly evident from the approach, but this research does acknowledge and follow the modelling cycle. This cycle consists of the following steps: problem identification and definition, system conceptualisation, model specification, model validation and verification, and finally model use for the designed learning/policy goals (Bala et al., 2017; J. Slinger et al., 2008). In that sense, the cycle denotes finer-grained steps beneath our design, although this research is executed up to the model specification (with some validation) due to time constraints, see section 2.4.6 for what this entails. Iteration and feedback are inherent to the cycle; each step grows understanding of the system and thereby changes the perspective. In essence, the philosophy of SDM for policy analysis says that the question (or problem formulation) is more important than the answer.

2.2. Research questions

To attain the main research objective repeated below, four subquestions are constructed which correlate to the four outcomes formulated in paragraph 2.1.3.

To explore the application of a system dynamics modelling approach for assessing the social, economic, and ecological trade-offs associated with Nature-based Solutions for climate change adaptation in deltaic regions.

The first two questions address general aspects, whereas the second two concern the case-study application:

1. What is known on the social, economic, and ecological trade-offs and SDM applications associated with NbS for CCA in deltaic regions?
2. Which factors and interactions yield the social, economic, and ecological dynamics associated with NbS for CCA in deltaic regions?

3. Where do the social, economic, and ecological trade-offs associated with Nbs for CCA lie in the Ebro Delta?
4. Which specification is able to capture the social, economic, and ecological dynamics associated with NbS for CCA in the Ebro delta?

As our approach to questions 2-4 is inherently iterative, the presentation of results requires careful delineation and explanation. We have chosen to present our results in the structure of the research questions, but note that the results were partially obtained outside their corresponding research question demarcation as subsequent questions led to new insights which demanded adaptations to previous questions (the iterative aspect). An example is the insights of key SES structure of the Ebro delta (Q3 & 4) leading to changes in the structure of general deltas (Q2).

The answers to these questions together reach the overall objective, and consist of several sub-products. To that end, table 2.1 presents the overview of these answers and products. The methodology adopted to answer these questions is delineated in the paragraphs below (section 2.3 to 2.4.2).

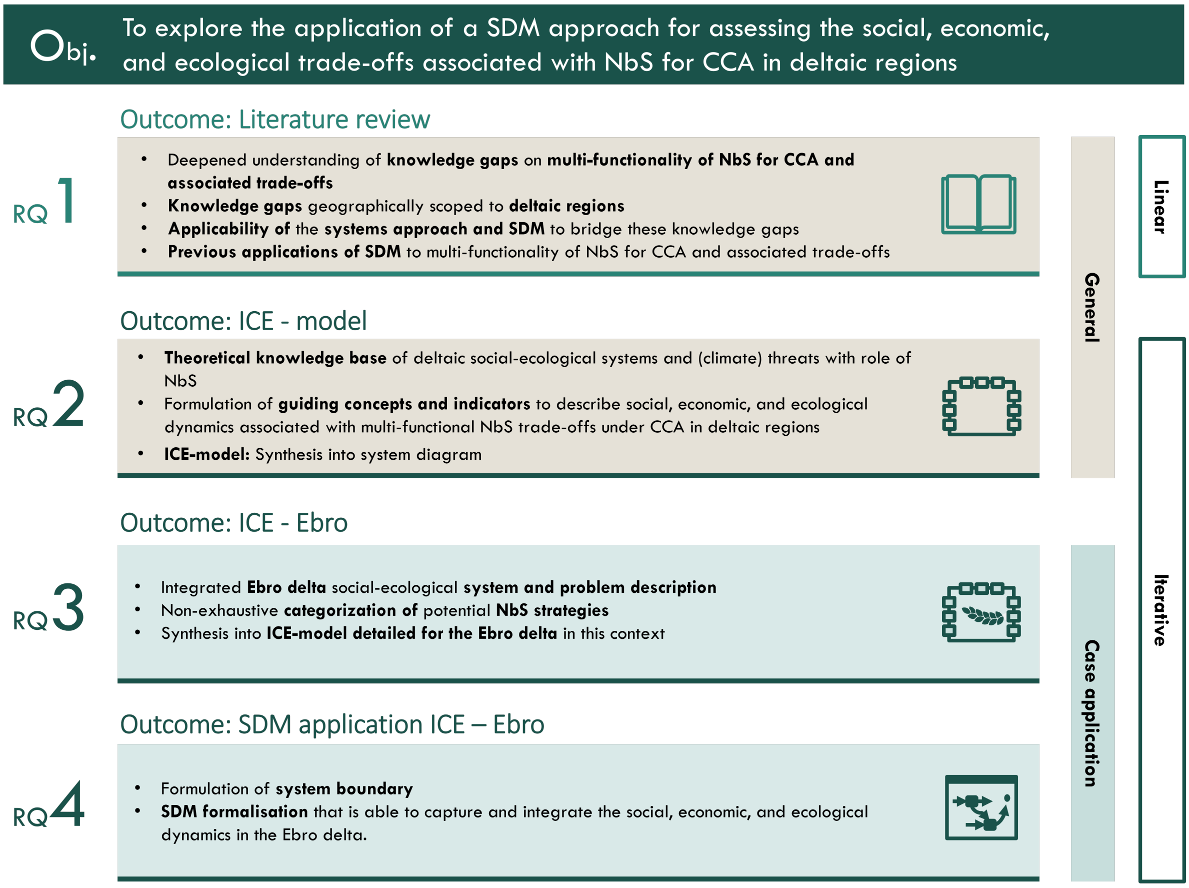


Table 2.1: Results of the research questions (1 to 4) with corresponding products, leading up to the overarching objective (Obj.). The distinction between linear & iterative, and general and case-applied outcomes is shown on the right and with respective colours.

2.3. Question 1: Literature review

The review sought to deepen the knowledge gaps related to the multi-functionality of NbS for climate change adaptation (CCA) in deltaic regions and examined if employing a system dynamics modelling approach may help overcome these gaps. To guide the reviewing process, four sub-questions were formulated.

1. What is known on multi-functionality of NbS for CCA and associated trade-offs?
2. Within this context, what is known on deltaic regions specifically?
3. What are the potential benefits of adopting a systems approach with a System Dynamics Modelling application to address these gaps?
4. How has system dynamics modelling previously been applied on multi-functionality of NbS for CCA and associated trade-offs?

SRQ1 - *What is limiting the multi-functional impact potential of Nature-based Solutions for climate change adaptation?* - was answered with a literature search. Using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyse) approach as described by Page et al. (2021) articles were selected. The search was conducted using the database of SCOPUS in September 2023, limited to English articles and reviews. Results were screened on title, abstract and content in that order, and selected articles were subjected to a forward/backward snowballing search strategy. The implemented search protocol is given in table 2.2 and is summarized in figure 2.2.

Keyword category	Search field	Keywords
Nature-based solutions	Title	"Nature-based solutions" OR "NbS"
Climate change adaptation	Title-abstract-keywords	AND "Climate change adaptation" OR "Climate resilience" OR "Climate-resilience"
Multi-functionality	Title-abstract-keywords	AND "Multi-dimensional" OR multidimensional" OR "Ecosystem-services" OR "Benefits" OR "Co-benefits" OR "Multiple benefits" OR "Added values" OR "Trade-offs" OR "Connectivity" OR "Connection" OR "Feedback" OR "Social-ecological"
Non-urban focus	Title-keywords	AND NOT "urban" OR "city" OR "cities"

Table 2.2: Search terms

We recognise that NbS is an 'umbrella concept' encompassing other approaches aiming to benefit humans by harnessing the power of nature (e.g. green infrastructure, ecosystem-based adaptation, building with nature, see Cohen-Shacham et al., 2016). Narrowing the search strategy to explicit use of NbS limits the quantity of relevant results, especially from older literature. Snowballing helped us to limit this constraint. The urban focus area was excluded from the relevant articles as we are interested in large scale systems (NbS at the landscape scale, like rural areas or river basins). Notably, this resulted in the exclusion of almost half of results. Further exclusion criteria were drawn up based on our interest in broader/standardisable NbS literature. Articles were dropped if they focused on 1) a singular type of NbS, 2) a geographic-specific issue without a primary objective to retrieve general lessons 3) small scale NbS 4) or one dimension. Finally, articles only discussing governance barriers were omitted as they provide limited insight into multi-functionality.

The literature search and screening process summarized in figure 2.2 resulted in the selection of 23 papers, of which 6 have been found through snowballing. The final list of selected literature is found in Appendix A.

SRQ2 - *What is limiting the multi-functional impact potential of Nature-based Solutions for climate change adaptation in deltaic regions?* - involved narrowing down the general findings geographically to focus specifically on deltas. By delving into the specifics of delta contexts, we can determine whether there exists a discrepancy between the contextual gaps and the broader knowledge gaps. Papers were selected from the original literature search based on their coverage of deltaic regions, supplemented

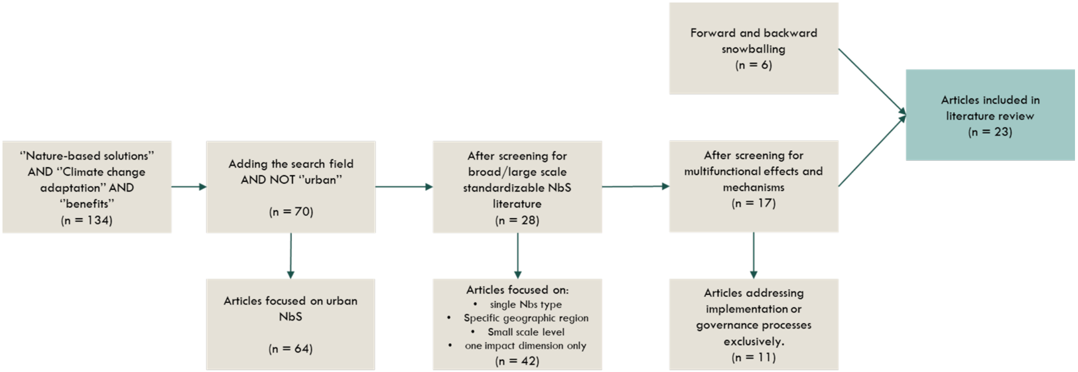


Figure 2.2: Search structure

with an additional paper detailing case-studies recommended by an expert.

SRQ3 - *What are the potential benefits of adopting a systems approach with a System Dynamics Modelling application to address these limitations?* - was answered by synthesizing the findings from the literature review with the expertise in systems thinking and SDM present within the research team (authors of this article). A deductive approach was adopted, where we assessed individual components of the question in order. Firstly, the potential benefits of utilizing a systems approach to overcome the found limitations were delineated. Secondly, we scoped down to SDM as an application of the systems approach, where we assessed the suitability of this modelling approach within the given research context. This top-down process allowed us to map out the applicability and benefits of an SDM approach comprehensively.

SRQ4 - *How has system dynamics modelling previously been applied to grow the knowledge base on these limitations?* - was answered with a heuristic literature review focusing on previous SDM approaches with a related scope. This helped us to 1) find specific SD-related gaps, and 2) construct our own model without reinventing the wheel. The selection was built with a small selection of four papers from the initial literature search that applied a systems approach explicitly to increase the understanding of NbS co-benefits and their trade-offs, and was expanded with two articles found through snowballing and consultation with experts, and two found through a search on the keywords "System Dynamics Modelling" AND "Nature-based Solutions" (or similar) on SCOPUS. See Appendix A for the list of selected papers.

2.4. Iterative exploration of an SDM application

Following, we describe the second to the fourth research question. These involve the heavily iterative exploration. As question three and four concern the case-application and therefore apply the same SDM methodology, they are discussed concurrently. Question four explicitly applies the SDM method.

2.4.1. Q2: formalizing the ICE-model

Subquestion two was answered using a literature study, drawing from scientific literature found on Scopus and Google Scholar primarily, and through iterative insights from later questions. The description of this literature study is integrated in the paragraph below for clarity. Semi-structured interviews were also used to validate findings, see section 2.4.4. We set out to construct a theoretical understanding, a frame of inquiry adequate to describe multi-functional trade-offs of NbS, and synthesize these into a systems thinking framework that is able to thoroughly and effectively visualize and structure an overview of the key factors and interactions.

The theoretical understanding consisted of deltaic properties in the relation to other coastal depositional environments, the (climate related) societal problems deltas face, and what role NbS can play in overcoming these. As our primary object of inquiry we chose ecosystem services (ESS). As NbS deliver benefits through the flow of ESS, consequently, trade-offs arise through a change in the distribution of ESS as well. Furthermore, we delineated a set of social, economic, and ecological indicators able to heuristically capture trends derived from the model behaviour. Together, the ESS lens and heuristic social, economic, and ecological KPIs formed the frame of inquiry adopted. The design of the systems thinking framework was aligned with the main objective: to be able to capture trade-offs associated with the multi-functionality of NbS for CCA. Insights from the theoretical base and main guiding concepts (primarily ESS) were leveraged through a systems thinking lens to construct a general model foundation based on the system diagram which is rooted in the science of deltas, NbS & SES, and systems thinking.

The model is named ICE after the three main aspects considered:*Integration* of multi-functionality, in *coastal* depositional environments, described through a lens of *ecosystem services*. The model primarily describes deltas, but as the contextual properties of deltas were delineated and the structure remains high-level and general, it also lays the groundwork for potential future adaptations for other coastal depositional environments.

2.4.2. Q3 & 4: Applying the ICE-model to the Ebro

Subquestion 3 and 4 were answered with a fourfold method package: A field trip, literature study, semi-structured interviews, and the overarching system dynamics method. They align with the modelling cycle, where question three leads to the system synthesis (system and problem description), after which question four delivers the formalised model. The system synthesis of the Ebro Delta case is facilitated by an extensive high quality database and research network (including local stakeholders), resulting in easier fulfilment of data requirements and favourable data gathering, see section 2.1.2. The modelling effort and data exploration, collection and analysing was carried out according to a two-level triangulation structure, see section 2.4.3 below.

The ICE-model for the Ebro delta was detailed with an integrated synthesis on the local SES, associated (climate) threats, and proposed NbS strategies. It subsequently guided the modelling effort, while the modelling effort, in turn, informed the ICE-model in the iterative manner that is characteristic of this research. This case-applicative process involved vertical integration.

2.4.3. Triangulation

Although there are a few experts with a holistic understanding of the Ebro delta, the wealth of literature and knowledge that has been created is still mainly dispersed and single-focused (relating to one or two disciplines). This means an integrated system perspective is still elusive for most. Thus, for our purpose, the model needed to integrate the (scientific) data and expert mental models to arrive at an abstraction of the Ebro SES that is able to describe multi-functional trade-offs of different NbS strategies over time. The author's systems thinking and SD (modelling) knowledge facilitated this integration (employing systems concepts and methods, see (J. H. Slinger et al., 2022)). Essentially, these form a triangulation structure, which is the process of combining multiple methods or data sources to comprehensively understand phenomena and validate findings through the convergence of information (Triangulation, 2014). Dis-aggregating the data component reveals a second triangulation structure; Data triangulation is achieved through the use of published data, data from experts or workshops, and grey and field data. If a distinction between the two levels needs to be made, then the data triangulation primarily answers research question three, while the model integration triangulation primarily answers research question four. See Figure 2.3 for this two-level triangulation structure.

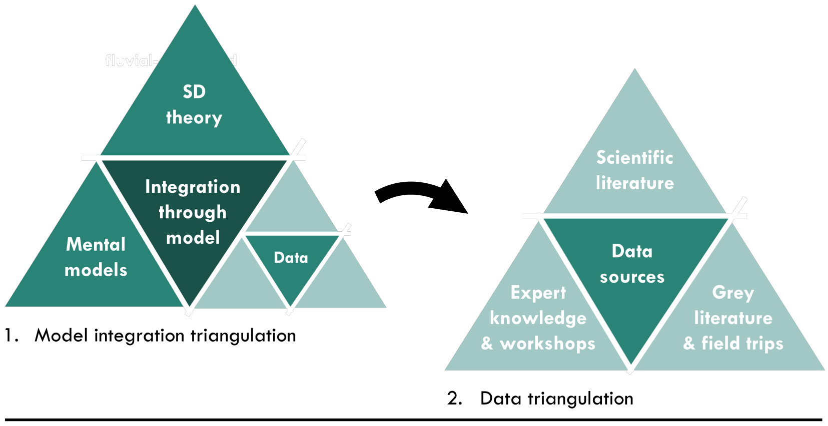


Figure 2.3: The adopted two-level triangulation structure. Mental models and triangulated data are integrated through SD theory to build the model, meaning the integrative process is triangular itself.

2.4.4. Methods for data collection

In the following sections, the data collection methods adopted are described. The literature study adopted to answer question two was already described in section 2.4.1 for clarity.

Semi-structured interviews

The context-specific nature of NbS and the case requires the exploration and comprehension of the meaning that different stakeholders assign to the issues under investigation (Creswell & Creswell, 2017). Furthermore, SD models may be mathematical abstractions of systems, but often the best and most available information is the qualitative knowledge in the stakeholders' heads or the "mental database" as argued for by Forrester (1993). To that end, semi-structured interviews were conducted.
The semi-structured interview has a conversation style, and although questions are prepared in advance, the flow is allowed to be flexible and deviate resulting in an explorative character (J. A. Smith, 1995). A drawback of interviewing is the time intensiveness. Still, it is an essential step in the validation of our conceptualisation, especially because of the ad hoc approach taken where the author's systems thinking and SD (modelling) knowledge facilitated integration of knowledge (which will have inherently introduced errors and biases). Furthermore, it helps to explore different perceptions, objectives, and criteria which provide guiding narratives and a qualitative basis for the building of the system's causality and uncertainty. As interviewers, we take on a neutral broker role, limiting the chance of political friction hindering the process.

As such, the semi-structured interviews were mainly held to validate conceptualisation iterations (i.e. the ICE-model, the ICE-Ebro, and the SD model), but they additionally served to deepen contextual understanding. The experts to be interviewed were selected based on their knowledge and experience along two axes. The first axis focused on obtaining both high-level and specific expertise, while the second axis aimed at contextual (Ebro Delta) and general (e.g., deltas, estuaries, SDM) expertise. By selecting experts from either end of these axes, we tried to optimise alignment of the aggregation, integration, and content, both contextually and generically.

The interviews were guided by a presentation of the respective conceptualisation, and the questions guiding the (semi-)structure of the interviews had the following essence (they may have deviated from this exact formulation, but conveyed the same message):

1. Do you agree with the conceptualisation shown (structure, causal relations, aggregation level, boundary, assumptions, etc)?
2. What would you change and how?

3. Is something missing or redundant?
4. Can the conceptualisation be used to grow understanding of the system in a multi-actor environment, and/or as a basis for NbS strategy discussion?

Upon learning the answers to these questions, the researcher's interpretation was reflected and only if confirmed to be correct incorporated in the conceptualisation. No recordings (audio or textual) were made. If needed, this new iteration of the conceptualisation was also reflected back to the same experts.

Throughout the entire research process, close consultation was maintained with a team of experts specialized in the fields of systems thinking and SDM, NbS (both general and water-based), and deltas and estuaries. After the initial iterations, additional guidance was sought from a delta and estuary expert and NbS specialists. As the research progressed to its final stages, we targeted experts in sediment, in ecology, and on the Ebro delta to specifically validate the results. Validating consultations with experts on the Ebro Delta provided insight in the general socio-ecological system and its balance trajectory, ecology, hydraulic and coastal engineering, and the proposed NbS for the region.

Field trip

A field trip right at the start of the research helped to set the stage for a thorough contextual understanding of the Ebro delta. The field trip mainly consisted of unstructured (conversation-style) interviews with local experts, a multi-day workshop, and a stakeholder meeting. The interviews with local experts were primarily explorative. In essence, the local experts delineated a high-level problem description through a conversation-style explanatory tour around the Ebro delta which identified primary causal relations, where any unknowns or important details were clarified. The attended work-shop focused on story-lining: local experts were encouraged to map out the historic, business-as-usual, and ”ideal” future balance trajectory of the Ebro delta SES (Husken, 2023). ”Ideal” in this context aligns with the goals of the Rest-Coast program, and envisions a sustainable growth of the Ebro SES. The workshop additionally included reflections on the state, progress, and stakeholder perspectives of activities aligned with the Rest-Coast program. Lastly, the field trip included a meeting with the key stakeholders, where opinions and concerns were voiced. The synthesis of this information helped shape and direct the subsequent research, and informed the system and problem description.

Literature study

The applied literature study examined the background of the Ebro system and the problem context in more detail, which included the historical developments, socio-economic activities, associated (climate) risks, and morphological evolution among others. This painted the picture of the current and predicted future trajectory of the SES. The literature was primarily found through local experts and the contextual knowledge base constructed from the field trip. Namely, the latter highlighted the important areas of interest, which allowed the researchers to effectively deepen their contextual understanding as relevant articles were easily identified and/or explicitly targeted. An example is the identification of the relevance of the salt wedge in the Ebro delta; with that understanding, a targeted search on ”salt wedge” and ”Ebro delta” yielded the exact papers needed. Note that although this process allowed the researchers to effectively deepen their understanding and weed out irrelevant details, it could have introduced bias. The adopted data triangulation hopefully reduced this bias, see figure 2.3.

2.4.5. System dynamics modelling

The choice for SDM was substantiated in section 3.3.1. Below expands on SDM as a method, and the modelling process adopted.

System dynamics modelling fundamentals

SDM is a computer simulation technique based on differential equations employed to gain understanding of the complex nonlinear dynamic structure and behaviour of systems over time (Forrester, 1993; Sterman, 2002). SDM primarily models system structure and behaviour through feedback, accumulation and delays originating from (endogenous) causal mechanisms. Summarized, a system dynamics model (SDM) is characterized by: (1) a bounded system with a basic structure composed of feedback loops, (2) stock variables that capture accumulative processes within these feedback loops, (3) flow variables that indicate changes in the stock variables, and (4) a depiction of the discrepancy between the system's observed state and its desired state, and related actions (Papachristos, 2019).

It seeks to create an environment for learning and to evaluate policies that enhance system performance through leveraging this feedback structure, as structure drives behaviour. In this way, it helps stakeholders gain insights into the behaviour of systems and make informed decisions, meaning that although it can be time-consuming, it is able to manage complexity and handle multi-actor problems exceptionally well. It is a flexible method, and can be applied to almost any complex system (societal, natural, technical, economic, organizational, and combinations). Within integrated environmental assessment and management it is a respected tool, where it has been shown to excel in improving systems understanding and facilitate learning (Kelly et al., 2013). See section 2.4.6 and 3.3.1 for the limitations of SDM.

Modelling process

The knowledge attained previously guided the modelling effort, where we primarily utilized the structure of the ICE-model as a scaffold-like framework to base the formalized model on. In essence, the modelling cycle is followed: a problem identification and definition, a system conceptualisation (ICE-model), and model specification, which is then to be validated and verified. Note that in our case the conceptualisation is high-level as the ICE-model describes (relations between) subsystems. Any modeller knows these steps are iterative (Bala et al., 2017; Forrester, 1993), but we have opted to enhance the integration of the model formalisation further by concurrently executing the conceptualisation and specification. This is explained in the paragraph below.

As our overarching objective concerns the comprehensive integration of the social, economic, and ecological dynamics, the formalisation should reflect this integration. Furthermore, this integration should align with the roles and values of different sectors and disciplines that make up the Ebro-delta. To that end, we proposed to increase the case alignment and integrative capacity of the model by merging the steps that make up the model formulation, resulting in a bottom-up or intertwined formalisation. Essentially, the conceptualization and specification step were executed as one (concurrently), instead of specifying the model from a CLD in a sequential manner. The difference lies in how one conceptualizes when considering the applicable specification. Namely, a broad and complex system model can be formulated in countless ways, neither inherently good nor bad. The applicability mainly depends on the availability of data and what you plan to use the model for; in our case for growing the integrative, comprehensive understanding of multi-functional trade-offs.

Finally, the model setup must facilitate continuous learning, adaptation, and collaboration between researchers and participants. This way, the process remains dynamic and responsive to emerging insights and changes to most accurately capture the studied system in a heuristic abstraction.

2.4.6. Model limitations

It is imperative to expand on SDM limitations in our context upfront to be aware of what the model/method can and cannot do. Furthermore, our scope brings with it some methodological limitations which need to be addressed.

Contextual SDM limitations

As a starter, the combination of qualitative and quantitative concepts, but also the uncertainties regarding complex structure and behaviour or parameter values, indicate SDM is not a precise forecasting tool (Wright & Meadows, 2008). Although no exact future predictions should be made, valuable insights are derived from understanding behaviour or magnitude of effects. Furthermore, the structure of SDM facilitates learning among stakeholders (Kelly et al., 2013). As a second limitation, we should be aware of the trade-off between aggregation and comprehension (Rahmandad & Sterman, 2008). A model is always an abstraction of reality, but the top-down, highly aggregated and intersectoral perspective we take in the Ebro delta accentuates this trade-off. We are in search of a broad analysis and lose depth as a consequence. In that sense, validation and verification processes are crucial to ensure alignment with real world behaviour, especially because our method will lead us to formulate many assumptions (which additionally increase bias). Uncertainty can be seen as a third limitation, as SDM does not explicitly incorporate this aspect while the system structure and its behaviour under analysis are highly uncertain (Kelly et al., 2013). Uncertainty can and should be included through sensitivity or scenario analysis, but this requires time-consuming activities. A concluding remark regarding the limitations described above is that we are essentially in search of relatively *accurate* results (exploring behaviour patterns) rather than *precise* (computing behaviour forecasts).

Model development constraints

The time constraints of this research lead us to formulate the aim to deliver a formalized model without parameterization, as this would require significant additional effort. To that end, question four delivers a specified *non-running* model; step four (verification and validation) and five (policy evaluation) of the modelling cycle are not carried out. This means quantitative verification and validation tests like sensitivity analysis or behavioural reflection with experts are not possible. We acknowledge these limitations upfront, and highlight that to attain a well-functioning model they *should* be executed, but argue that the approach in its current form is still able to deliver valuable insights as a route is taken that directly confronts the limitations in understanding of NbS multi-functionality and associated trade-offs. A full specification - by the modelling of stocks and flows - surpasses the simplicity of a qualitative model, providing more accurate structural but especially behavioural insights (G. P. Richardson, 1986). Of course, for comprehensiveness, future research should aim to finish the modelling cycle. Reasons for our development constraints are elaborated upon in the paragraph below.

Firstly, NbS are by themselves broad and ambiguous, and to find out how they influence trade-offs in our context requires extensive theoretical and empirical research. Next, The Assessment of trade-offs is carried out on a wide spectrum: understanding of the social, economic, and ecological impacts requires a thorough understanding of the socio-ecological system; both general and case-specific. The third reason builds on the second; by choosing to create a quantitative model, we have to not only understand the system in more detail, we also have to integrate quantitative and qualitative relations from literature with qualitative mental models from experts across and within these three dimensions. The *adequate yet comprised* quantitative description of multidisciplinary and multi-sectoral demands a thorough understanding of the system, as the complexity of a model increases rapidly the more stocks (and variables) one adds (Forrester, 2009). Subsequently, the complexity of a specified model describing social, economic, and ecological impacts is exponentially larger than a causal loop diagram or qualitative SDM of the Ebro delta would be.

2.5. Research flow diagram

The research flow diagram depicted in figure 2.4 summarizes the structure around which the research is organized.

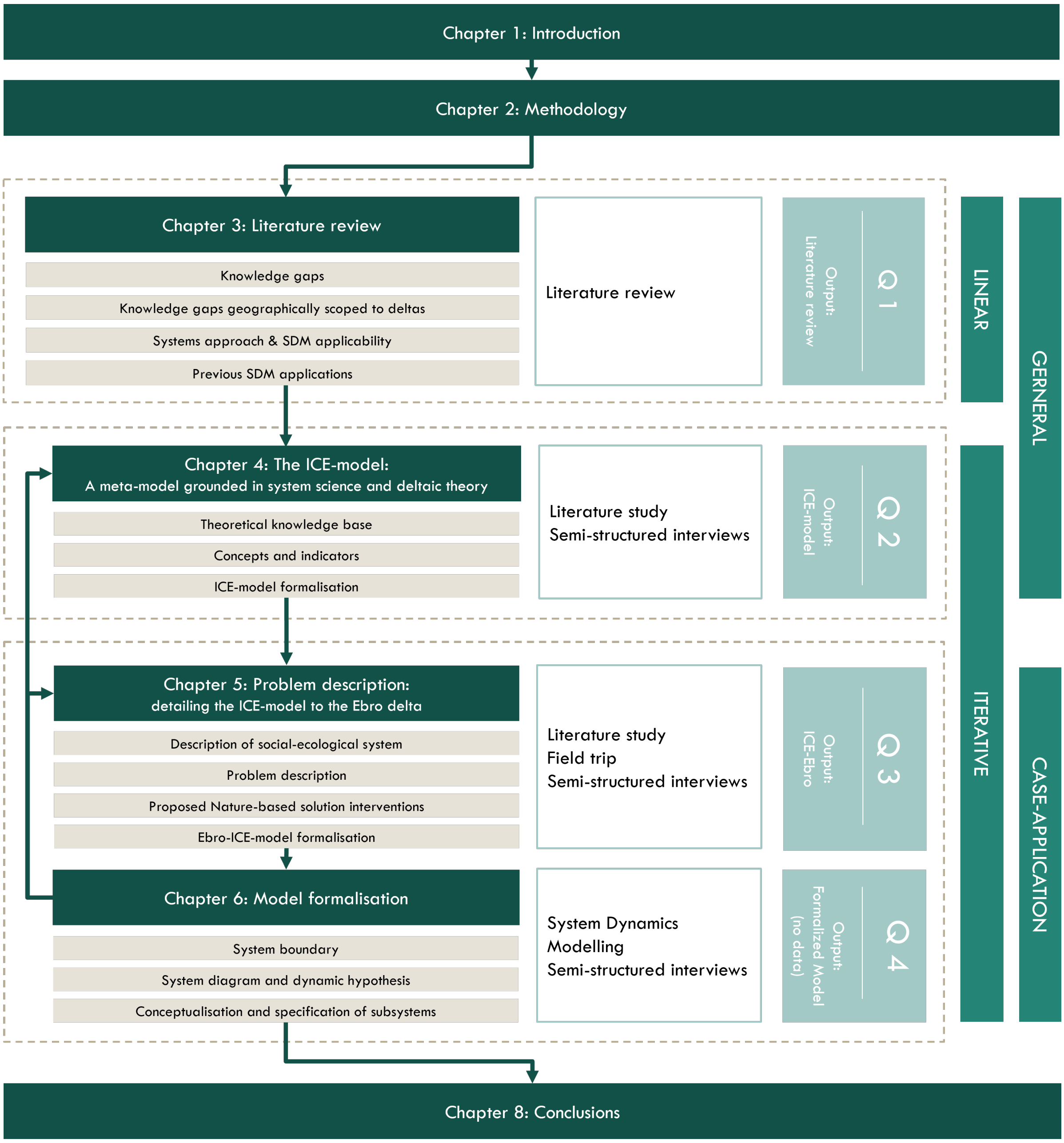


Figure 2.4: Research Flow Diagram. The blue bordered boxes represent the methods used, and the outcome of each question is presented in the solid blue boxes. Chapter three and four relate to question one and two respectively, and are not specified to the case. Chapter five and six relate to question three and four respectively, and concern the case application. The answers question two, three, and four were attained in an heavily iterative manner.

3

Literature review

This chapter discusses the literature review. An overview of the concepts and the knowledge gaps is given in section 3.1, after which section 3.2 delineates the main knowledge gaps, generally and for deltaic regions. Following, the potential contribution of the systems approach and the SDM application to this knowledge gap are discussed in section 3.3. Finally, section 3.4 discusses the review, after which section 3.5 concludes.

3.1. Concepts

A clear and expanded definition of related concepts is required as a build-up before mapping out the found limitations in understanding of NbS multi-functionality, which is given below. This sets the stage for understanding the context in which NbS for CCA are intended to function.

Ecosystem Services

Ecosystem Services (ESS) are the now widely recognized concept for the benefits that people obtain from ecosystems, or “Nature’s contributions to people” (IPBES, 2017). NbS channel positive benefits through a flow of ESS (Cohen-Shacham et al., 2016).

The Millennium Ecosystem Assessment (MA) has formulated the four categories of services provided: supporting (e.g. soil formation, nutrient cycling); provisioning (e.g. food, wood); regulating (e.g. carbon sequestration, flood mitigation); and cultural (e.g. cultural heritage, sense of place), see appendix C (MA, 2005).

Complex Social-ecological Systems

Social-ecological systems (SES) represent the integrated concept of humans as part of nature, emphasizing the complex interconnectedness and interdependence between social-economic and ecological dimensions (Folke, 2006; Redman et al., 2004). The dimensions cannot be seen as separate, and social and economic patterns like wellbeing, production, and consumption depend on capacity of both for sustenance. The multiple components of complex systems exhibit non-linear and dynamic behaviour as a whole through their interaction. They are characterized by feedback loops across various nested scales, the ability to self-organize and adapt to external changes, and display emergent phenomena.

The concept of resilience has been adopted to analyse SES, where it refers to the ability of the system to withstand shocks while preserving functionality, and additionally (and importantly) also describes this adaptive capacity for renewal, re-organization and development that complex systems inhibit. Resilience should therefore not be confused with stability or equilibrium-state. Holling (1973) defined stability as ”the ability of a system to return to an equilibrium state after a temporary disturbance”, whereas resilience is concerned with the ability of a system to persist under disturbances. Given that change is one of the few reliable phenomena in SES (Folke, 2006; Kotir, 2020), the often adopted equilibrium-centred view where policy aims to sustain a certain state of the system can carry heavy costs or overlook important behaviour.

NbS for Climate Change Adaptation

CCA is defined as adjusting to current and future climate impacts, and the role of NbS is best explained with the social-ecological vulnerability framework by the IPCC (Seddon, Daniels, et al., 2020). Vulnerability to climate change is generally given by three dimensions; the exposure to impacts, the sensitivity to these impacts, and the adaptive capacity to adjust to changing conditions. By leveraging the power of nature, NbS can act at the interface of ecosystems and socio-economic systems to holistically strengthen SESs, see figure 3.1.

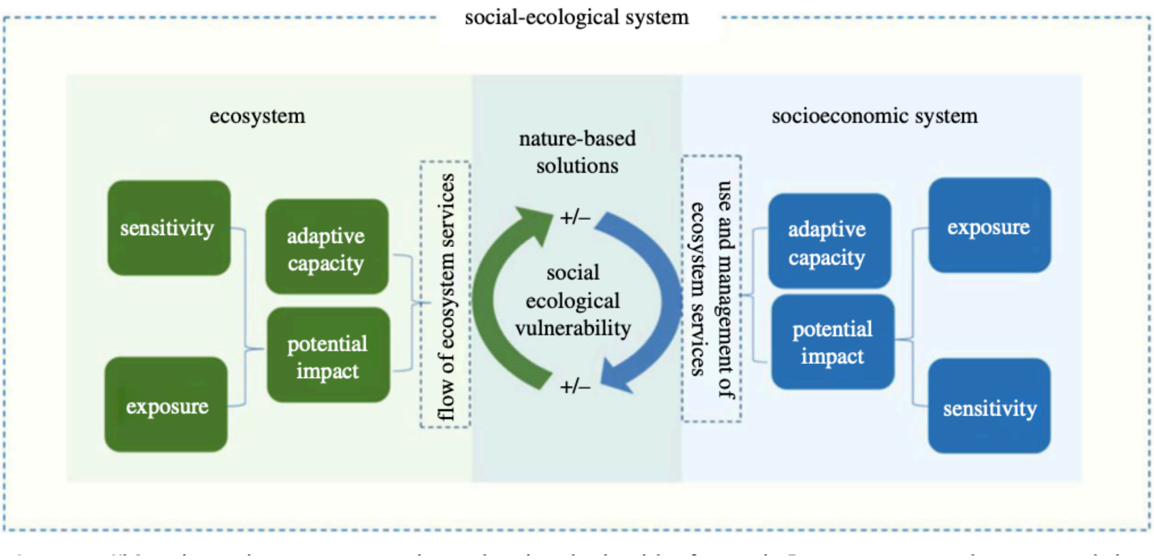


Figure 3.1: Nature-based Solutions within the social-ecological system (Seddon, Daniels, et al., 2020). In the figure, the ecological dimension is found within the "ecosystem" (green), and the social and economic dimension within the "socioeconomic system" (blue). They overlap in the middle, exactly where NbS are intended to function.

3.2. Knowledge gaps

Several challenges for realizing the multi-functional potential of NbS have been discussed in the reviewed literature. Table 3.1 summarizes the findings. There is a lack of insight into the social, ecological and economic trade-offs of different Nature-based solutions. This is because holistic assessment of multi-functionality is rarely carried out, leaving the variation in effectiveness poorly understood. Given the characteristics of complex systems this is concerning, as gaps are mainly found in a poor understanding of dynamic behaviour and the interactions between different dimensions including trade-offs in impacts, multi-actor environments, issues of scale (time, space), and uncertainty. This limits performance (across all dimensions), generates adverse effects, compromises equity and increases pushback.

Lack of integrative multi-functional assessments

The integrated assessment of multi-functional outcomes has been scarce and lacks structure. NbS often get portrayed simplistically, isolating specific impacts and disregarding potential trade-offs with other system elements which compromise effectiveness or increase adverse effects and vulnerability (E.g. Gunn et al., 2021; Martín et al., 2021; Seddon, 2022; Turner et al., 2022; Welden et al., 2021. An example is the current emphasis on forestry, leading to monocultures which capture carbon exclusively but compromise biodiversity and resilience (Seddon, Daniels, et al., 2020). Comprehensive reviews of

Knowledge gap	Elaboration
Lack of integrative multi-functional assessments	• Holistic assessment of multi-functionality rarely carried out • Impacts assessed in isolation • Trade-offs disregarded • Particularly social and (non-marketable) economic impacts underrepresented
Limited cross-scale assessments	• Underreporting (and assessment) of multi-functionality over the temporal and spatial scale, and under (climate) uncertainty • Limited understanding of interactions between subsystems • Few multi-NbS strategies assessed
Limited inclusion of local stakeholders	• Inclusion of local stakeholders limited • Compromising inclusion of their perceptions in identifying and valuing (multi-functional) benefits.

Table 3.1: Overview of knowledge gaps

literature and case studies confirm this oversight: the impact dimensions are frequently neglected and the integrated assessment of all three impact dimensions is rarely undertaken (Chausson et al., 2020; Hanson et al., 2020; Ruangpan et al., 2020). Herein, the social and economic dimension are particularly underrepresented (Debele et al., 2023; Hanson et al., 2020). Other literature finds non-tangible/non-market benefits like health or well-being are often neglected (Han & Kuhlicke, 2019; Viti et al., 2023; Woroniecki et al., 2023) and appraisals often underestimate economic benefits, especially long-term (Seddon, Chausson, et al., 2020).

Limited cross-scale assessments

The variation in the effectiveness of NbS multi-functionality over the temporal and spatial scale and under uncertainty is rarely reported on (Martín et al., 2021; Turner et al., 2022), especially considering climate scenarios (Seddon, 2022). Furthermore, as was highlighted before, much of the literature has focused on small-scale solutions (Urban and local scale)) (Hanson et al., 2020; Martín et al., 2021). This has resulted in limited comprehension of the interactions between different subsystems/ecosystems (Seddon, 2022) and few multi-NbS assessments (Ruangpan et al., 2020). Namely, large scales allow for the implementation of multiple NbS, potentially resulting in stronger and better-balanced solutions.

Limited inclusion of local stakeholders

The scientific evidence base is strongly and consistently aware that the limited inclusion of local stakeholders is pervasive and that therefore alignment of multi-functional benefit valuation is compromised (e.g. Anguelovski and Corbera, 2023; Cottrell, 2022; Hanson et al., 2020; Pino and Marquez, 2023; Seddon, 2022; Turner et al., 2022; Viti et al., 2023). Local stakeholders have differing perceptions, values, and power, and are embedded within the SES under study. Without a participatory and interdisciplinary approach several issues arise. (Dis)benefits or unintended outcomes can be overlooked, equity is compromised, and (long-term) support can be obstructed. Without fair multi-functional alignment, NbS therefore fail to deliver their promised social and ecological outcomes.

3.2.1. Knowledge gaps scoped to deltaic regions

Knowledge gaps in the coastal, deltaic, and estuarine areas overlap with the earlier broader NbS knowledge gaps defined, with especially the assessment of long-term effectiveness compared to traditional approaches as a major challenge (Jordan & Fröhle, 2022; Moraes et al., 2022; Paxton et al., 2023). Despite favourable policy conditions, these areas see a limited implementation of NbS compared to other environments globally (Chausson et al., 2020; Moraes et al., 2022; Ruangpan et al., 2020). On the other hand, the coastal management sector appears to be more aware of the benefits of hybrid designs than the broader NbS practice is, as can be deduced from case study research where hybrid designs dominate (Bridges et al., 2021; Moraes et al., 2022). This could be because hybrid designs are especially effective for high intensity hazards such as coastal flooding (i.e. wave energy reducing salt marshes in front of dikes) (Seddon, 2022), but generally hybrid designs could also enhance effectiveness through broadening of the solution space, their capacity to balance socio-ecological trade-offs, and enhancement of (existing) ”hard” structure’s life-cycle and maintenance (Anderson et al., 2022; Moraes et al., 2022; Ruangpan et al., 2020).

3.3. The systems approach to address the knowledge gaps

The important role that NbS can take in the facilitation of sustainable development within planetary boundaries is not guaranteed, as has been illustrated by the challenges and knowledge gaps discussed in the previous section. Scholars have identified systems-thinking as essential for success (Pino & Marquez, 2023; Seddon, Chausson, et al., 2020). Yet, it is rarely adopted for NbS strategies. This includes applications in coastal management as noted by J. H. Slinger et al. (2022), even though integrative ambitions have risen over the last decades. Additionally, Sebesvari et al. (2016) notes that both multi-hazard and regional assessments for deltaic SES are scarce, highlighting the need for evaluation of diverse threats and delta-wide scales to reduce information gaps and overlooked trade-offs/feedback.

The system approach, although often resource intensive, has several highly advantageous characteristics to address the knowledge gaps. Firstly, it transcends linear causal thinking which offers a restricted depiction of the numerous interactions, dependencies, and constraints within the systems where NbS are intended to function (Arnold & Wade, 2015; Richmond, 1994). Secondly, it is particularly fit to evaluate dynamic performance over scale (space, time) for different measures and (climate) scenarios with the help of scenario analysis; this is essential for adaptation planning in NbS (Chausson et al., 2020; Martín et al., 2021). Thirdly, it allows for an integrated assessment which incorporates multiple disciplines, contextual knowledge, and the different values and perceptions of multiple stakeholders (Enserink et al., 2022; J. H. Slinger & Vreugdenhil, 2020). Summarizing, the systems approach is able to investigate complex behaviour over time for different interventions while facilitating wider participation and understanding.

3.3.1. System Dynamics modelling as an application of the systems approach

As SES are highly complex and dynamic, it is difficult to construct mental models which are able to understand the system adequately. This difficulty is exacerbated by the many uncertainties present (e.g. the effect of interventions, the magnitude of climate impacts) and the multi-actor environment. To that end, problems affecting SES can be seen as ”wicked” (see Rittel and Webber, 1973). Herein lies the strength of simulation modelling. It creates a necessary abstraction of a studied system over time which is able to represent interconnectedness, complexity and variability explicitly, which is particularly helpful for policy evaluation under a deeply uncertain future (Gilbert et al., 2018; Robinson, 2014).

Modelling methods for complex adaptive systems

If one wants to quantitatively model complex system structure and behaviour and their adaption to changes, there are two main contenders: Agent-based and System Dynamics modelling (and their combination) (Rahmandad & Sterman, 2008; Scholl, 2001; Van Dam et al., 2012). Trade-offs between both methods in this context are summarized in table 3.2. Agent-based Modelling (ABM) is a modelling technique which is primarily used to capture micro-level system behaviour, such as the spreading of fire in a forest or human decision-making. Unlike ABM which models ground-up, SDM is a top-down approach which simulates aggregate behaviour (e.g. movement of resources or change of quantities in a system). SDM’s capacity to integrate technical (often quantitative) elements alongside social (often qualitative) factors at a high aggregation level aligns with the knowledge that describing SES requires a blend of quantitative and qualitative concepts. Although ABM would allow for the inclusion of spatial and heterogeneous aspects, the complexity of the SES means the computational requirements are impracticably high. Respecting the trade-off between model scope and detail, we conclude SDM is the

	SDM	ABM
Advantages	• Fit for high and broad aggregation of complex model structure and behaviour, incorporating a wide range of feedback effects • Computationally relatively efficient • Communication is straightforward and smooth	• Can capture spatial aspects • High granularity; can capture heterogeneous agents and behaviour
Disadvantages	• Aggregation is homogeneous, with heterogeneity only possible between compartments • Severely limited ability for modelling spatial aspects	• High computational and data requirements, limiting sensitivity analysis and scope of model • Complex models difficult to communicate effectively • Complex model behaviour can be difficult to understand and link to structure

Table 3.2: Trade-offs between SDM and ABM, based on (Scholl, 2001) and (Rahmandad & Sterman, 2008).

appropriate choice for our use.

Previous SDM approaches for NbS trade-off assessment

This section heuristically evaluates how SDM has previously been applied to the understanding of trade-offs in NbS multi-functionality, finding very little and limited applications. A more comprehensive search strategy might uncover additional papers, especially if the search is expanded on with related concepts to NbS. However, we argue that although our applied method is heuristic, it strongly suggests a lack of research in this area.

The initial literature search specified above yielded four articles that applied a systems approach explicitly to increase the understanding of NbS co-benefits and their trade-offs (Coletta et al., 2021; Giordano et al., 2020; Martín et al., 2021; Pagano et al., 2019). Leaning strongly on participatory processes, the studies capture trade-offs for the three impact dimensions, over scale (time, space) and under (climate) uncertainty, and for different NbS scenarios or stakeholders. However, none of these studies captures all together, with Coletta et al. and Giordano et al. not developing a SDM also. Thereby, the studies bridge the knowledge gaps identified in 3.2 and capture NbS complexity, but fail to do so in an integrative manner. Without this holistic integration, insight for decision-making is limited. Further literature that uses SDM to assess NbS (co-benefits) trade-offs - found through snowballing, expert consultation, and a heuristic literature search - is extremely scarce. There are a few near-topic Causal Loop Diagram (CLD) and/or Fuzzy Cognitive Mapping (FCM) applications (see figure 3.2) which either do not focus on NbS specifically (Castro, 2022; Kotir, 2020) or have an urban focus (Martín et al., 2020). Almenar et al. (2023) construct a SDM, but evaluates for the ecological and socio-economic dimension only and is urban focused also.

Causal Loop Diagrams
The Causal Loop Diagram (CLD) is a qualitative causal mapping tool often used within the field of system dynamics, displaying the polarized causal relations in a system to display its essential components and interactions. Because of its simplicity and ease of use it is mainly applied for communicative or conceptual purposes, but can sometimes be misleading because it loses the crucial role of accumulation processes (G. P. Richardson, 1986).

Fuzzy Cognitive Maps
Fuzzy Cognitive Mapping (FCM) is a related semi-quantitative causal mapping tool. By assigning weights to causal relations and applying fuzzy logic, FCMs offer additional capabilities for modelling uncertainty and complexity beyond what bare causal mapping provides (Kosko, 1986). It is similarly easy to use and carries low computation costs, but among its limitations are poor causal semantics and time relations, meaning that beyond lack of quantitative aspects it is not able to capture the dynamics of complex systems adequately (Nair et al., 2019).

Figure 3.2: CLD and FCM

3.4. Discussion

The literature search and screening process found several important limitations in the understanding of NbS multi-functionality. However, the peer-reviewed literature base on NbS is large, having exponentially grown over the last decade (Seddon, 2022). As stated, NbS is an umbrella concept with many related approaches, meaning the actual literature base is a few orders of magnitude bigger. Additionally, there is an extensive grey literature base on NbS which was not consulted, meaning potential insights may have been missed due to our scope. While we aimed to identify key knowledge gaps on NbS multi-functionality, in that process we have not reported on others. Gaps related to our scope include but are not limited to the lack of systemic data (especially on the social dimension), the link to perceived high costs, or poor understanding of the difference between NbS and technological approaches (Seddon, 2022; Viti et al., 2022). No direct governance barriers were included either, despite their relevance for the successful adoption of NbS. However, an enhanced understanding of NbS multi-functionality will likely contribute to overcoming related gaps as well.

We have looked through a systems thinking lens at the identified knowledge gaps, and have demonstrated that the system approach is theoretically comprehensive and beneficial when studying NbS and SES. It's important to note that alternative perspectives may offer different insights, and the systems approach is not the only holistic method available. Furthermore, it remains to be seen if the practical application delivers the promised benefits in the context of multi-functional NbS. Moreover, as the benefits were derived from combining knowledge gaps with the author's expertise in systems thinking, biases will have been introduced; both in the interpretation of literature and the author's perception of these benefits.

3.5. Conclusion

This review aimed to map out the knowledge gaps related to the multi-functional trade-offs (social, ecological, and economic) of Nature-based Solutions (NbS) for climate change adaptation (CCA) (generically and for deltaic regions), examined if employing system dynamics modelling (SDM) as an application of the systems approach may help overcome these gaps, and evaluated how SDM has previously been applied to NbS multi-functionality and associated trade-offs.

We found that there is a need for greater integrative understanding of the trade-offs of various NbS strategies - over scale (temporal, spatial), under climate uncertainty and for various stakeholders. The lack of integrative multi-functional analysis was especially strong. The systems approach is still sparingly applied to this research area, while it aligns closely with the NbS concept and is imperative when analysing complex social-ecological systems. Benefits such an approach can provide can be summarized in its capacity to investigate complex behaviour over time for different interventions while facilitating wider participation and understanding.

We consider System Dynamics Modelling (SDM) an appropriate modelling technique for applying a systems approach within our defined context. It is able to model nonlinear relationships between various sub-elements in a coupled system, include and aggregate both material and information flows, and fits the research area well due to the numerous feedback loops that complex SES inhibit. Yet, a practical application of SDM on NbS multi-functionality and associated trade-offs is extremely rare, especially for non-urban contexts. No system dynamics model has comprehensively addressed the identified limitations in NbS multi-functional trade-off understanding.

To that end, there is a clear need for further exploration of the applicability of SDM approaches in the context of NbS multi-functionality, in order to grow both the understanding of the benefits of the systems approach in comprehensively assessing multi-functional trade-offs and expand the knowledge base of SDM applications. NbS are context-heavy and integrated in unique social-ecological systems by definition, meaning that this research could not only advance scientific understanding but hopefully also demonstrate SDM to be a suitable method for enhancing local or case-specific NbS understanding and decision-making. Concluding, the knowledge gaps substantiate the need to comprehensively assess the multi-functional trade-offs of various NBS strategies using a system dynamics model- integrating aspects over time, space, under different climate scenarios and for various stakeholders. Essentially, this implies the need for an explorative analysis that acknowledges uncertainty and multiple perspectives. Although the time constraints of this research does not leave room for these, we do want to acknowledge its importance.

4

The ICE-model; a meta-model grounded in system science and deltaic theory

In this chapter, we develop the ICE-model. The ICE-model is a meta-model of social-ecological delta systems, and consists of three ingredients: a deltaic theoretical knowledge base, a conceptual framework describing multi-functionality of NbS, and systems science, particularly using the system diagram to comprehensively visualise the contextual storyline.

Section 4.1 gives a concrete description of deltas and deltaic challenges, and links these with NbS. Subsequently, section 4.2 identifies and develops guiding concepts and indicators to describe multi-functional dynamics of NbS in this context. Finally, section 4.3 synthesizes the above into the ICE-model, and reflects on its applicability. Section 4.4 concludes.

4.1. Delta systems: properties, challenges, and management

The sections below discuss the delta context, the problems deltas face globally, and why NbS emerged as a valuable strategy in helping adapt to these problems.

4.1.1. Properties of deltas

Deltas are dynamic and transitional coastal ecosystems, resulting from fluvial sediment deposition at the point where a river meets a stationary body of water. The interplay of fluvial sediment input and coastal processes is the main driving force of delta morphology, resulting in temporally and spatially variable sections of accretion (sedimentation), erosion and stability. As tidal currents and wave surge are the coastal processes that primarily dominate delta progradation, deltas are generally classified along three axes on a ternary diagram formulated by Galloway (1975), resulting in three corresponding classification types: 1) fluvial-dominated deltas, 2) wave-dominated deltas, and 3) tide-dominated deltas. One can distinguish deltas from other coastal depositional environments with a process-based classification prism, modified after Dalrymple et al. (1992) (Boyd et al., 1992). Merging the classification prisms of Galloway and Boyd et al. yields figure 4.1. The key-take-away for deltas is the relative importance of fluvial processes.

Due to their high connectivity and steep gradients, deltaic ecosystems rank among the most productive in the world (Elliott et al., 2019). Rare and valuable deltaic ecosystems such as freshwater swamps, mangroves, or saltwater marches provide important habitats and ESS such as fertile soils and freshwater resources, resulting in their leading global ecological and economic value. For these reasons, deltas

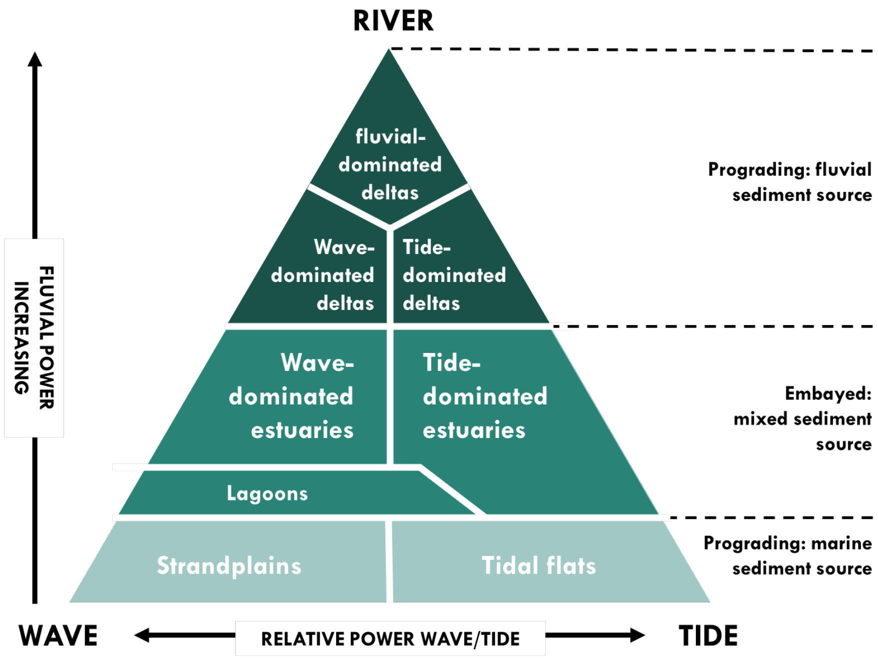


Figure 4.1: Merged coastal depositional environment classification prism after Galloway and Boyd et al. The uppermost triangle represents deltas, the middle trapezoid estuaries, and the bottom trapezoid are prograding coastlines. Lagoons are wedged in between estuaries and prograding coasts. Note that as the processes describing the classification are dynamic and subject to change, the position of an environment on this diagram is not static over time.

have always served as major centres of urbanisation, trade and agriculture (Ericson et al., 2006; R. M. Oliver et al., 2022). The concentrated human development along these ecologically important regions has transformed global deltas beyond recognition, resulting in highly complex SES and human-induced delta morphology.

4.1.2. Delta degradation

However, this extensive modification tends to degrade the system's resilience and its ESS capacity, which has high implications given the significance of deltas worldwide (Elliott et al., 2019; R. M. Oliver et al., 2022). In the developed world, sediment loads have plummeted: many major rivers see a 60% to 99% reduction in sediment load due to river damming[1] rapidly changing the morphology of deltas (Giosan et al., 2014; Nienhuis et al., 2020). Although deforestation has historically accelerated delta growth by increasing anthropogenic sediment run-off, the current net loss of sediment therefore drives the drowning of these ecosystems. Groundwater extraction and intensive agriculture and / or urbanisation have resulted in accelerated[2] subsidence and loss of habitats means self-adapting/protective ecosystems such as dunes are lost, increasing vulnerability to environmental/human hazards and accelerating the drowning process (Dunn et al., 2019; Elliott et al., 2014). Further impacts include saline intrusion, reduced water quality, and invasive species, among others.

These threats are exacerbated by the temporal and spatial impacts of climate change, which is

[1] Note that globally and especially in developing countries, sediment loads due to deforestation in the drainage basin exceed the loss due to dam construction. Still, global sediment losses are expected to accelerate, as will the relative rise of sea level (Nienhuis et al., 2020)

[2] Deltas naturally experience relative sea level rise due to compaction of sediment or tectonics for instance (Dunn et al., 2019)

expected to hit coastal/estuarine areas especially hard, including sea level rise, increased variability in precipitation and fluvial discharge, frequency and intensity of storms, and increased temperature (Day et al., 2008; Elliott et al., 2019; Moraes et al., 2022). Deltas and estuaries are low-lying, and their location at the land-sea interface means they are highly susceptible to flooding, especially considering the compound effects of simultaneous coastal and fluvial high waters (Scown et al., 2023; Ward et al., 2018). Still, coastal wetlands are surprisingly resilient and can often adjust to these impacts. For example, many natural deltas share the ability to accumulate sediment at a pace surpassing erosive marine processes or RSLR (Wells & Coleman, 1984). It is likely to be direct human effects that pose the greatest threat to deltas, with the impacts of climate change as the second contender (Day et al., 2008; Ericson et al., 2006; Scown et al., 2023).

Global pressures will only keep growing, mainly through population growth, ineffective governance, agricultural use, adaptation capacity and relative sea level rise (Scown et al., 2023). As global exploitation of ESS rich deltas grows and development intensifies in these areas, ecosystems are degraded further (Elliott et al., 2019). This raises both exposure and vulnerability to risk. This means that deltas face all three components of risk escalation through the combined impacts of anthropogenic pressures and climate change, as the latter exacerbates hazard frequency and size (hazard, exposure, vulnerability). A lock-in effect exacerbates the problem: The dense development forms a high-risk trap, where adaptation requires expensive and inflexible strategies such as the Dutch Delta Works (Scown et al., 2023). Unfortunately, deltas facing the most significant pressures see the weakest socio-economic conditions for successful adaptation.

4.1.3. The coastal management perspective shift

Traditionally, adaptation is delivered by (hard) hydraulic engineering (dikes, breakwaters, storm surge barriers, etc) which control or withstand variability (J. H. Slinger & Vreugdenhil, 2020). However, the negative impacts of this infrastructure on beneficial ecosystems are understood well nowadays. Understanding both natural systems and the disparity of societal needs has grown, and together they are shifting the field of hydraulic engineering to ecosystem-based design. Moreover, traditional coastal protection is expected to not be able to withstand climate-intensified hydrometeorological hazards and / or maintenance costs will be far too steep (Moraes et al., 2022). The social, economic, and ecological importance and complexity of deltas means that most issues are deeply nested within the SES context, implying that holistic strategies are needed that incorporate uncertainties and account for a multiplicity of stakeholders and objectives (Elliott et al., 2019; Hinkel et al., 2023). Together, these create a context for cost-effective, sustainable, integrative, and resilient solutions, in which NbS has emerged as a top contender (helped by its potential for diverse interpretations). In coastal management, NbS offers a way to effectively restore/maintain/create resilient and regulative ecosystems including sediment systems or salt marshes, aligning environmental, social and resilience goals.

4.2. Modelling multi-functionality of NbS in deltas: concepts and indicators

The model will need to be able to capture outcomes on the social, economic, and ecological dimensions. We also need to know *how* we describe and structure the feedback leading to these outcomes, or in other words, what perspective we adopt that describes the system. Namely, the adopted problem perspective will determine which aspects of the related system are essential for analysis (Enserink et al., 2022). To that end, the formulation of guiding concepts and key performance indicators (KPIs) are required. The sections below will delineate our choices.

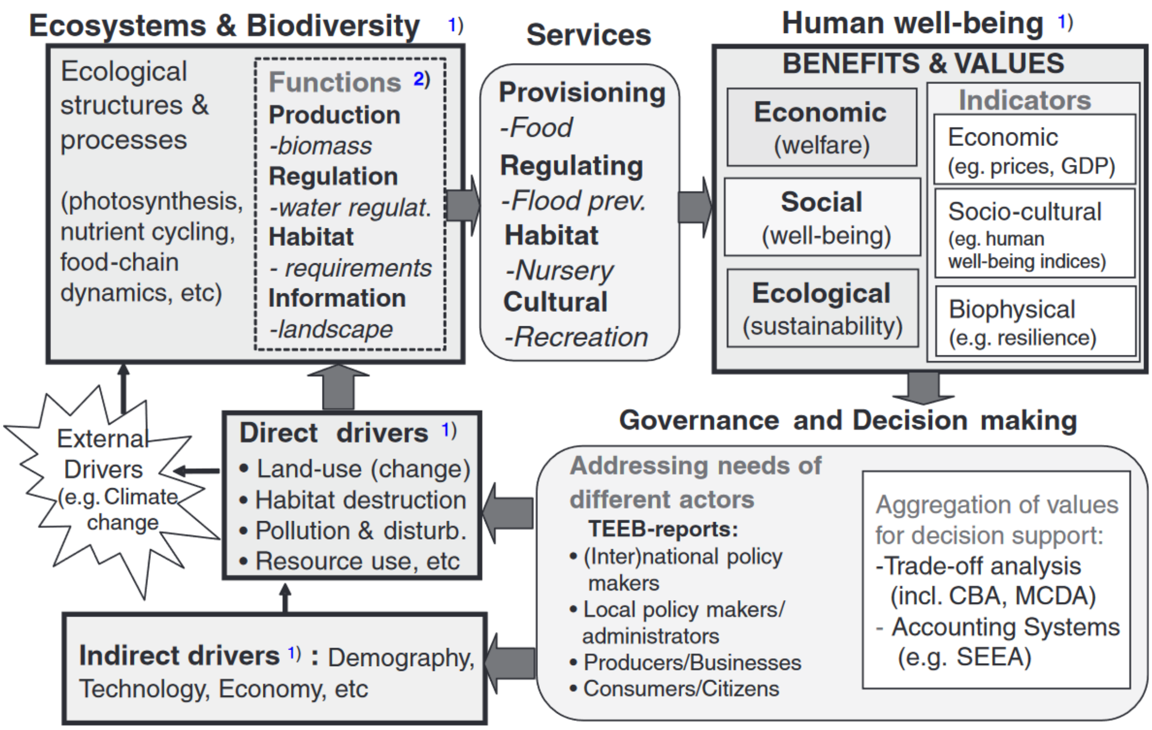


Figure 4.2: TEEB conceptual framework for linking ecosystems and human well-being, adapted from (Kumar, 2012). See appendix C for the MA-framework. Note that TEEB use habitat services instead of supporting services.

4.2.1. Generation of trade-offs through ecosystem services

ESS are chosen as a primary object of analysis in this research. Clear and consistent multi-functional trade-off assessment from the loss of ecosystems and biodiversity requires the linking of biophysical aspects of ecosystems with human benefits through ESS, as is underscored by the Economics of Ecosystems and Biodiversity project (TEEB) (Kumar, 2012), (see also 3.1). Trade-offs arise mainly when the exploitation of one ESS has a negative impact on other ESS (e.g. timber extraction negatively affects carbon sequestration among many other ESS; loss of structure implies loss of function). Indeed, in SES assessment ESS are widely adopted. Three channels of inquiry are used to study the link between society and ecosystems: how human benefits are derived from ecosystems (ESS), how human demand for ESS impacts the integrity of ecosystems, and finally how both the social and ecological dimension react to endogenous and exogenous drivers of change[3].

Although TEEB focuses on economic (monetary) consequences, their conceptual framework helps to understand and map out (propagation of) trade-offs due to both external and direct drivers of change that impact ecosystems and biodiversity, see figure 4.2. The causal chain structure of this framework can be adopted for our delta context, where NbS channel the distribution of ESS by leveraging functions derived from ecological structures and processes. The causal mechanisms driving climate change are considered out of scope.

4.2.2. Indicators

Essentially, we are in search of indicators able to capture trends derived from the model behaviour. These trends should reflect trade-offs on the social, economic, and ecological dimensions when applying NbS strategies. To that end, indicators need to be able to heuristically show varying impacts and

[3](often through vulnerability, see also section 3.1)(Berrouet et al., 2018). While vulnerability analysis is valuable in certain contexts, this research prioritizes a comprehensive understanding of SES dynamics beyond vulnerability alone.

problem patterns while remaining flexible. Heuristic, because the scope and method do not suit exact quantification or prediction, and flexible because the model will be highly context dependent, and we want it to retain transferability. Following that philosophy, and to tackle valuation and quantification difficulties of indicators, we adopt Forresters SDM ad hoc approach. Although Forrester's relatively simple abstractions of (social) systems have been criticized (i.e. Gray et al., 1972; Schwartz and Foin, 1972), in reality system dynamics is not simple (Forrester, 2007). In SDM we are in search of understanding of behaviour through basic principles that together describe the complex systems' architecture; the structure governs behaviour. If we understand the structure and the shock that cause behaviour, we can determine behaviour of the system (Featherston, Doolan, et al., 2012). And even behind humans' behaviour, too, is a system of rules and obligations; social systems are not as irregular as one might think. Thus, leaning on system structure and understanding allows us to assess behaviour even with heuristic indicators. Still, we remain aware of the limitations, and want to readdress that our goal is not to forecast, but to assess trade-off trends.

Ecological impact indicators

Ecosystems and biodiversity are notoriously complex to measure and assess (Kumar, 2012). Generally, three categories are adopted; diversity (species diversity, richness and endemism), quantity or extent (area, population sizes, biomass), and condition (Indicators are less intuitive; includes population integrity, invasive species, ecosystem connectivity/fragmentation, etc). We can capture Habitat extent heuristically by defining surface area of ecosystems, but diversity and habitat condition require a larger setup.

To structure changes in habitat condition in our model, we adopt the five direct drivers leading to decline in nature, formulated by IPBES (2019); land-/sea-use change; direct exploitation of organisms; climate change; pollution; and invasive alien species. These are in turn caused by indirect drivers related to human values and behaviour (e.g. socio-cultural, economic). While indirect drivers will be considered, we refrain from categorizing them within a specific framework, as they encompass a wide range of possible relations. Diversity will be heuristically defined by creating a species diversity, richness, and endemism variable, adopted from a review of existing biophysical measures Kumar (2012). Although the variable is easily understood by a wide audience, it is generally difficult to quantify. However, perhaps it shouldn't be; often the simplest answers are the closest to the truth. Hodgson et al. (2009) follows this philosophy, advocating for adopting the basics in biodiversity metrics. Namely, he notes that preservation and restoration of habitat area and quality robustly strengthen biodiversity in the face of climate change. Both are concrete metrics, and an increase in either also coincidentally and effectively increases connectivity (one of the main goals of Rest-Coast). To that end, to quantify the diversity variable, we adopt a function of both habitat extent and condition. Due to the well-supported 'insurance effect' and other aspects of biodiversity which correlate biodiversity with resilience, we consider it as a buffer against direct drivers of change (T. H. Oliver et al., 2015; Sebesvari et al., 2016).

Social and economic impact indicators

To derive impacts on the social and economic dimension, we need to quantify ESS, and a useful frame of inquiry is environmental or ecosystem accounting. The UN System of Environmental-Economic Accounting (SEEA) regards ecosystems as assets providing services to people, where accounts are used to describe change of stocks and flows over time (Resonating with SDM in that sense) (Comte et al., 2022). Ecosystems are naturally referred to as natural capital, which is a function of habitat condition and extent; enhancing either will likely boost the provision of ESS. So, by again adopting habitat extent and condition, we can roughly quantify trends in ESS production and use and thereby assess social and economic impacts.

For simplicity, economic impacts are captured in the monetization of ESS with the most straightforward link to welfare (i.e. income streams and expected costs). The valuation of the full range of (indirect) economic impacts is not the focus of this research, and at the time of writing many other researchers are working to progress this area. Regardless, a non-insignificant amount of economic impacts will be indirectly captured in our social and ecological indicators. Social impact assessments (SIA) are more complex due to both the broadness of impact possibilities, (conflicting) valuation of different stakeholders, and difficulty of quantification. We chose to adopt the framework proposed by Vanclay et al. (2015) as advocated for by J. Slinger (2021). The social impact framework defines eight categories of social change on which we can map out different ESS: way of life, culture, community, political systems, environment, health & well-being, personal and property rights, and fears and aspirations. Although different NbS interventions will not necessarily affect all categories, the framework helps us to structure and will likely reduce overlooked insights. That leaves the complexity of quantifying social impact. To solve this issue, we chose to 'quantify' social impacts as change relatively to a certain normal, and if quantification is compromised, multiplier effects can be adopted to roughly estimate change. To that end, many social impacts will be expressed in relative change, or in other words, a Δ.

Resulting overview of indicators

Table 4.1 summarizes the indicators that were argued for in the sections above, describing social impacts (on social wellbeing), economic impacts (on economic welfare), and ecological impacts (on ecological state).

Ecological impacts			Economic impacts	Social impacts
Habitat extent	**Habitat condition**	**Species diversity, richness, and endemism**	**Welfare**	**Social Impact Assessment framework**
Natural surface area	**Function of resilience and decline (direct drivers)** ***Resilience:*** • Species diversity, richness, and endemism ***Direct drivers of decline:*** • Habitat dagradation • Overexploitation • Climate change • Pollution • Invasive alien species	**Function of habitat extent and habitat condition**	**Monetized ESS** • Revenue of ESS • Costs of ESS • Costs of hazard impact	**(Relative change of) ESS mapped onto 8 social impact categories** 1. Way of life 2. Culture 3. Community 4. Political systems 5. Environment 6. Health \& well-being 7. Personal and property rights 8. Fears and aspirations

Table 4.1: Overview of ecological, economic, and social impact indicators

4.2.3. The system diagram

Within systems analysis the system diagram is a respected conceptual tool, which aims to delineate the boundary and aspects relevant to the problem (Enserink et al., 2022). The system diagram, by essentially creating a conceptual model of the problem situation, serves as the foundation for analysis and aids in communicating system demarcation, structure and behaviour, see figure 4.3. For these reasons, we opt to use the system diagram to consolidate the above.

4.3. Formalising the ICE-model

In this section we aim to consolidate the theoretical insights found by constructing a framework on which a contextual storyline can be plotted. Next to helping structure general understanding, the framework may serve as a versatile 'scaffolding' on which case-specific aspects can be built, facilitating scalability.

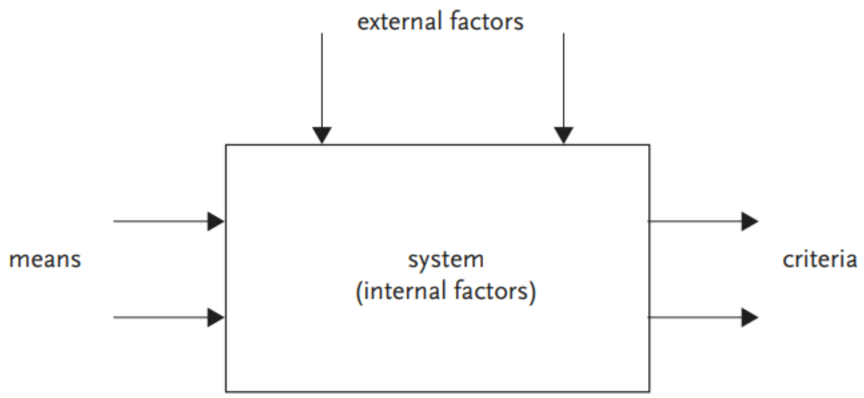


Figure 4.3: General system diagram, see (Enserink et al., 2022). The boundary delineates the system scope (level, spatial, and temporal). Four categories can be described: Criteria (indicators measuring extent of problem-solving), external factors (influential factors beyond control), means (possible influential actions), and internal factors (all other factors within the boundary contributing to causal chains affecting the criteria). The direction of the arrows indicates that the means, external factors and even criteria exert influence on the system, whereas internal factors help us to understand how behaviour propagates through said system.

4.3.1. The ICE-model: a conceptual model of the problem situation

Structuring the theoretical insights and research objective yields the ICE-model 4.4, which depicts the general system diagram for NbS in the deltaic context facing climate change, with as criteria the social, economic, and ecological impact dimensions. The model is named ICE after the three main aspects considered: *Integration* of multi-functionality, in *coastal* depositional environments (although we focus on deltas), described through a lens of *ecosystem services*. Note that the focus is laid on NbS that help *adapt* to climate change and related natural hazards, and their associated impacts. Subsequently, we've opted to not emphasize other positive benefits like carbon sequestration. However, as ICE-model is essentially a contextual system diagram, potential future adaptions can incorporate different means, ends, and external factors; this also entails inclusion of mitigative measures/criteria.
From the system diagram we derive the main feedback leading to the degradation of deltas. As discussed in section 3.1 and 4.2, the mechanism behind the capacity of NbS to affect the criteria (social, economic, and ecological dimensions) is through leveraging ESS. Trade-offs that NbS strategies carry will be the result of feedback propagating through the system: e.g. if a strategy consists of converting farmland to dunes or wetlands improving natural capital and subsequently coastal safety, a negative arrow is added from natural capital to deltaic land use (agriculture), which in turn impacts social well-being, economic impacts, and perhaps cultural ESS as people are attached to the agricultural land and way of life.

Causality that demands further explanation is described below. The complete stretch of the river basin excluding the delta is considered as upstream. This river carries mainly a discharge transporting sediment. As both are crucial for ecosystem condition, they improve natural capital, with sediment subsequently strengthening coastal flood defence through accretion (this is a regulative ESS). The causality between the river estuary and deltaic land use is two-directional, as deltaic land use benefits from a healthy river, but by leveraging these benefits it creates pressures depleting river health. The same logic is applied to the two-directional causality between natural capital and provisioning ESS. The dotted causality between provisioning ESS and cultural ESS depicts the local identity derived from to certain livelihood activities like fishing; cultural and provisioning services are often intertwined, and recent developments in ESS research have started to recognize and emphasize these relational values (Kaltenborn et al., 2020). Finally, the link between coastal safety and ecosystem resilience cannot be polarized easily; although intense coastal hazards can be too much for the resilience of an ecosystem,

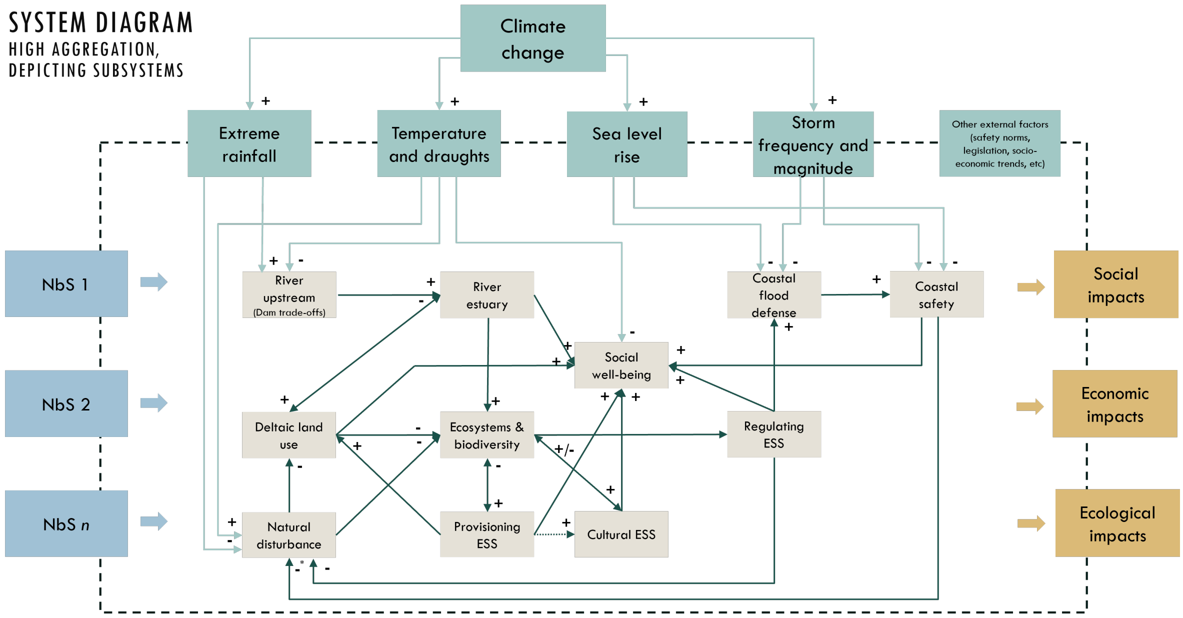


Figure 4.4: The ICE-model. The polarity of the arrows indicates the direction of change, and is assigned according to the average (i.e. anthropogenic land use is primarily unsustainable). No causality is defined for both the means (NbS) and the criteria as they are context-dependent. Two subsystems have been disaggregated: the river is natural capital itself, but by separating it the feedback becomes evident. Secondly, note that agriculture is a provisioning ESS, but for clarity it has been structured under land use. The arrow from the provisioning ESS to deltaic land use tries to limit the inconsistency. The * indicates that a coastal flood may not necessarily be bad for a coastal ecosystem, and in some cases may even improve the condition. Cultural ESS may exert a negative (e.g. unsustainable tourism) or positive (e.g. ecological stewardship) impact on ecosystems & biodiversity.

some natural disturbance can actually improve ecosystem conditions positively effecting resilience. This is also the reason why fluvial floods actually improve ecosystem resilience; they deliver a healthy set of nutrients to the system while simultaneously countering subsidence through aggrading sediment (Ibáñez & Caiola, 2016a).

4.3.2. Insights from the ICE-model

We can conclude that the high complexity of deltaic SES necessitates holistic strategies that consider multiple dimensions and stakeholders, where NbS may be adopted. The system diagram visually demonstrates the high SES embeddedness of NbS, even in this high aggregation. This helps us to realize that NbS interventions will inevitably see a high level of complex feedback, likely creating a broad array of trade-offs on and between the social, economic, and ecological dimension. Subsequently, it is evident that valuation of true NbS is never straightforward; a thorough system understanding is required for this purpose.

As the causality arrows have no weight assigned, an important insight not immediately clear from the diagram is that direct human pressures take precedence over climate pressures in their negative impact on deltas. It is mainly human activities, such as damming rivers and urbanization, that have led to the degradation of deltas, impacting their resilience and ecosystem service capacity. Climate change exacerbates these threats. Together, the direct and indirect anthropogenic (climate change) pressures could potentially shift the deltaic social-ecological and morphological balance.

4.4. Conclusion

This completes the formulation of the ICE-model. We set out to find which factors and interactions yield the social, economic, and ecological dynamics associated with NbS for CCA in deltaic regions. In this regard, we employed a literature study and semi-structured interviews, and iteratively improved the conceptualisation through insights from the case-application, see chapter 5 and 6.

To that end, 4.1.1 described the properties and classification of deltas, highlighting their social-ecological importance, dynamic nature and the importance of fluvial processes in shaping their morphology. 4.1.2 explored the degradation of deltas, focusing on human pressures such as sediment reduction and groundwater extraction, as well as the exacerbating effects of climate change, leading to increased vulnerability and risk. 4.1.3 discussed how NbS have emerged to help overcome these challenges. Finally, 4.2 derived heuristic indicators and concepts useful for capturing varying impacts across the social, economic, and ecological dimensions, focusing on the flow of ESS primarily. This theoretical knowledge base was consolidated within a system diagram framework and aligned with the overarching research objective to formulate the ICE-model (section 4.3).

The ICE-model has two main uses. Firstly, it is intended to facilitate problem exploration. To that end, its high level of aggregation and modular structure allow for adaptability to different contexts and use-cases. Secondly, it creates a solid foundation and guiding role for the SD modelling effort. Because of this adaptability and guiding role, the ICE-model could be described 'scaffold'-like on which to build on either horizontally (e.g. to different cases) or vertically (detailing to SDM). The ICE-model is able to comprehensively depict the social, economic, and ecological dynamics associated with NbS for CCA in the deltaic context. It highlights that NbS are deeply embedded within complex socio-ecological structures. The ICE-model provides limited *actionable* information for local stakeholders as delta-wide assessments do not capture spatial socio-ecological heterogeneity (Sebesvari et al., 2016), but a general perspective can be attained. Indeed, placing NbS in the general context where they are intended to function may already help to grow understanding of complexity and contextual dependence of NbS strategies, and may help to communicate the broad array of (non-monetary) values of NbS and/or ESS to stakeholders not familiar or reluctant with the concept. Even knowledge of the basic system structure can help to counter blind spots, and reduce the impact of rebound or unintended effects. In summary, exploration and learning, stakeholder engagement, and policymaking could be facilitated, although the ICE-model should be applied in practice for definite conclusions.

Despite being included implicitly, the current ICE-model does not address resilience to riverine flooding in as much detail as it does for coastal flooding, as the latter was identified to be the most threatening. Future adaptations of the ICE-model should focus on incorporating this important mechanism to provide more comprehensive assessment of flood resilience. Although the authors had a basic understanding of the related concepts, they are mainly system scientists, meaning biases will have been introduced and important aspects could have been overlooked. Experts on deltas and estuaries were consulted to limit these. It remains to be proven if the system diagram is adaptive enough to be used as a basis for case study analysis. This will be further explored in chapter 5.

5

Problem description: Detailing the ICE-model to the Ebro delta

In this chapter the Ebro delta system and problem description are synthesized and detailed to the ICE-model, resulting in the ICE-Ebro. Section 5.1 and 5.2 describe the SES, after which section 5.3 delineates the morphological evolution. Subsequently, section 5.4 summarizes the main threats faced, and shortly expands the momentum and governance backdrop. Section 5.5 provides an overview of the main NbS categories considered. Finally, these are synthesized in section 5.6 which details the ICE-Ebro. Section 5.7 ends with the conclusion.

5.1. Case study background

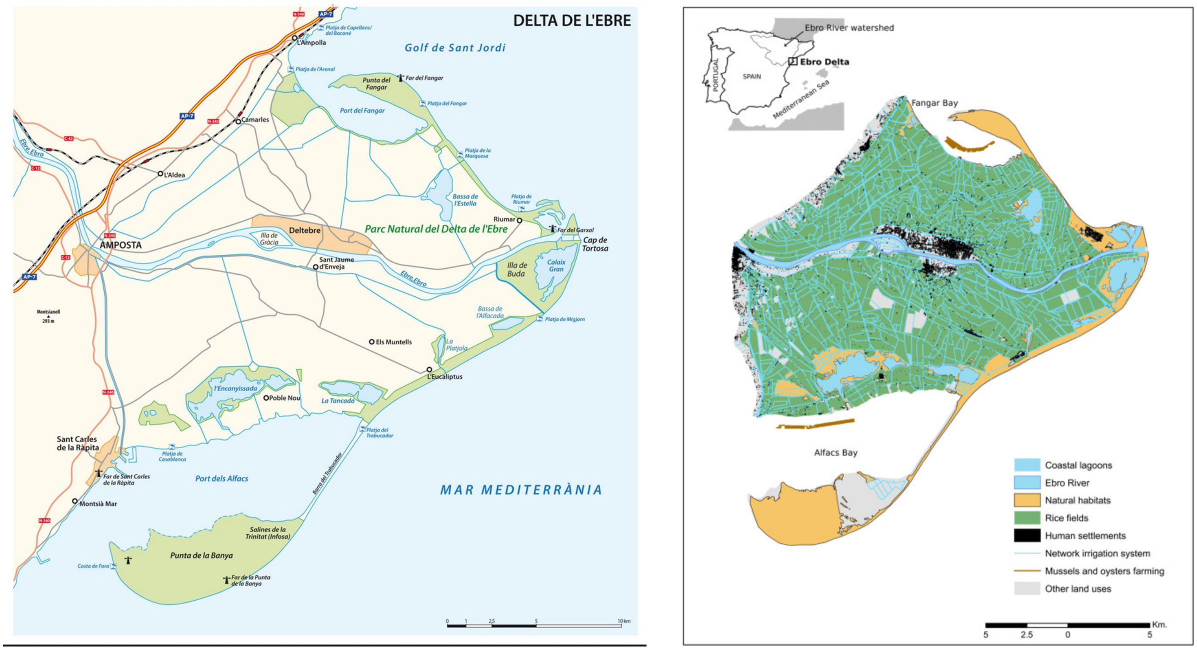
The Ebro River basin is Spain's largest, covering 88,835 km2. It receives contributions from the Cantabrian Mountains, Pyrenees, and Iberian mountain range (Ibáñez & Caiola, 2016a). The river's course has been altered to irrigate around 700.000 Ha, accounting for over 90% of water consumption. Downstream, The Ebro Delta covers 320 km2 and is heavily humanized socio-ecological system, see figure 5.1a. It has a population of nearly 60.000 inhabitants, of which around 20.000 reside within the delta, with the remainder living near its inner boundary. Almost 80% of the area has been reclaimed with rice farming dominating land use, leaving 56 km^2 of wetlands and 14 km^2 of lagoons. Rice farming amounts up to 65% of (210 km^2) of the total surface and plays an essential role in both the economy and ecology. Further utilization of its natural resources are attained through fishing, hunting, salt pans, and (eco-)tourism. Yet, the dense network of human activity is intertwined with highly valuable and rare natural assets, which serve as a crucial habitat for numerous plant and animal species. The environmentally productive wetlands and marshes amount to 10% of the territory, and the remaining 10% of land mostly consists of beaches and sandbanks.

5.2. The socio-ecological system

The Ebro Delta is a dynamic and interrelated system that must be understood and managed as a single social-ecological unit, and as is evident from literature and experts alike, is tightly integrated across the social, economic, and ecological dimensions. Nevertheless, the sections below describe the social, economic and ecological dimension for a better overview.

5.2.1. The social dimension

The social structure and culture of the Ebro delta is tightly interwoven with the landscape and its exploitation, and reflects its diverse and ancient origin. The historic cultural evolution has produced a society with a deeply ingrained relationship with rice cultivation, as well as an inherent fishing and



(a) General map (Adobe Stock, n.d.)

(b) Land use distribution (Prado et al., 2019)

Figure 5.1: The Ebro delta

hunting connection, and salt production tradition. As a result, gastronomy has become a major social aspect. Furthermore, sediment is interwoven with the delta and its people, having enabled delta life and rice production. Dependency on climate-sensitive income sources is very large, as the most important economic sectors are all climate-susceptible. Below, this origin and culture are expanded upon.

Cultural history

During the Roman era, the first documented permanent settlement emerged, with improvements made to existing fishing and cattle ranching practices (Barcelona Field Studies Centre, n.d.-a). The Moors brought place naming and agricultural influences including rice and irrigation techniques. Upon Christian reconquest, the delta became a favoured hunting ground for royalty and nobility (Barcelona Field Studies Centre, n.d.-a). In the thirteenth century the first public fishing rights were granted, and with religious administration fishing became an important sustenance activity, later accompanied by salt and game exports. In 1719 the first royal concessions were given to farm the land, marking the transition towards land privatization. A book from the 16th century, praising the delta as a ”paradise” for the natural resources and benefits wetlands it offers, serves as a compelling illustration of how ESS were valued historically (Ibáñez & Caiola, 2016a).

Before the irrigation canals, the Ebro Delta had a low population and there was minimal cultivation. The main activities were salt production, glasswort harvest burned for soap ash, fishing, hunting, livestock, and some farming along the river and inner borders (Dobby, 1936). The salt industry was the economic base until canal construction[1] introduced fatal freshwater influxes to the salt pans, transforming the salt marshes into rice paddies. Only rice was economically viable as it favoured the natural conditions and imposed irrigation system. This transition was rapid, with rice acreage multiplying by an eleven-fold factor from 1860 to 1960 (Barcelona Field Studies Centre, n.d.-b). See

[1]Originally built for navigational purposes, but with the increase in ship tonnage the use was modified and shifted to irrigation purposes.

figure 5.2 for current of the irrigation network

The rich testimony of the Ebro delta that Dobby (1936) describes helps to understand the cultural significance of rice. Rice has built the wealth of the region, highly correlated with deltaic population growth, and is a staple in the local diet, bringing dishes otherwise associated with Valencia only. This specialisation has formed the cultural landscape, and the population's success has correlated highly with the fluctuations in the yield and price of rice. Additionally, the short but intense three month duration of rice cultivation has historically maintained the population's strong interest in fishing and hunting.

Furthermore, he describes the high influence of sediment. On the one hand, sedimentation necessitated regular and costly cleaning to facilitate navigation of the canals and the river. Furthermore, Dobby observed how recurrent floods decreased effective door heights by 50 cm since 1900. However, rice paddies were enabled and shaped by the sediment-rich fresh river water delivered to previous salt marshes by irrigation, which not only flushed the salt but also deposited a fertile layer of fluvial sediment (Dobby, 1936). This created the 'rising grounds' culture, still rooted deeply in the local society to this day (Ibáñez & Caiola, 2016a). The recognition of fertilisation and subsidence-countering benefits of sediment-rich water are reflected in the historical practice of *colmateo*, a sediment distribution rights system across the irrigation canals before construction of dams (Gorostiza et al., 2023). The turbid water was commonly referred to as liquid 'gold'.

5.2.2. The economic dimension

The deltaic economy has always depended on natural resource exploitation, and ultimately on the varying influxes of water, nutrients, and sediments transported by the Ebro (Ibáñez & Caiola, 2016a). Nowadays, the major functions of the Ebro delta still rely on ESS provided by the productive wetland habitats, which further perform various essential functions including water storage, storm protection, coastal stabilization, and the recycling of nutrients and pollutants. In order of importance, the main productive activities are agriculture (rice), fishing and aquaculture, and salt production. Tourism - mainly based on the eco-tourism model - has also developed into a cornerstone of the economy. Below these are expanded upon.

- As the main economic activity, rice farming produces nearly 120,000 Mt/year (around 6 t/Ha) which represents 98% of Catalonia's production (Ibáñez & Caiola, 2016a; Rodríguez-Santalla, 2004). The relatively low productivity is linked to the highly saline soil. Some vegetable and fruit farming is done as well. The great weight of the rice crop has reduced livestock farming to a negligible scale. The historical, social, and economic importance has led to the significant influence of the rice farmers' cooperative.
- fishing and aquaculture represent the next sector, respectively capturing ca. 7.000 and producing 5.000 Mt/year (Ibáñez & Caiola, 2016a). The fishing yield has been reduced because of over-exploitation coupled with the lagoon degradation.
- The little industry that has developed is agricultural mainly, with the salt extraction pans at the Southern spit as the only exception worth mentioning (Rodríguez-Santalla, 2004).
- Eco-tourism has only developed since 1980 with the declaration of the Ebro Delta Natural Park which brought publicity on traditional, natural and landscape values (Rodríguez-Santalla, 2004). The sector is now approaching 800.000 visitors yearly (Roca & Villares, 2012), and it is the sector with the highest growth projections. Yet, the infrastructure is not suited to these types of numbers, and underexploitation of the economic potential of nature related tourism persists.

5.2.3. The ecological dimension

Ecologically, the Ebro delta stands out for its high diversity of both habitats and species on a relatively small surface, many of whom are scarce or endangered (Ibáñez & Caiola, 2016a). As is evident

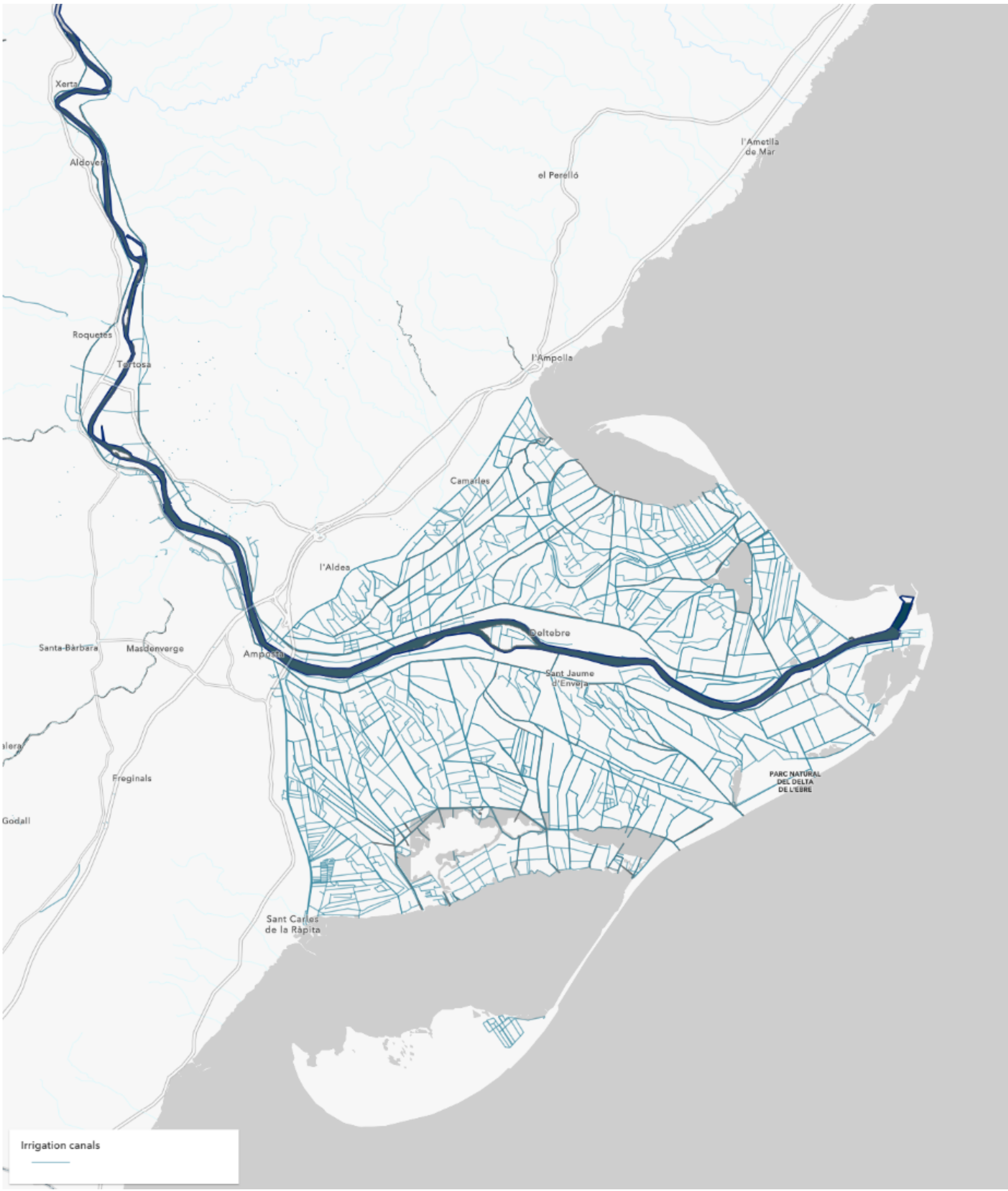


Figure 5.2: Irrigation network. The main canals diverting the irrigation water from the Ebro originate at Xerta.

from the social and economic dimensions, this ecological wealth is crucially supportive for many socio-economic functions and values. The Ebro Delta stands as one of the most important wetland regions in Europe, and over 8000 hectares are safeguarded by Spanish legislation (Ibáñez et al., 2020). Ecological significance is evident from the multitude of protective legislations: the Ebro delta is recognized globally as ecologically vital and boasts as a Natural Park, Special Protection Area (SPA) under the Birds Directive, Natura 2000 area (12.000 ha), Ramsar site (Convention on Wetlands of International Importance), World Biosphere Reserve, and others. Birds can be considered as a charismatic species category, with 330 species observed many of whom breed in the delta, attracting high numbers of tourists. Further important flora and fauna include halophyte (salt-tolerating) plants and some species of fish, see (Ibáñez & Caiola, 2016a).

Since the 1960s, the Ebro delta has experienced significant socio-ecological change, including challenges in water and sediment management (through construction of dams), shifts in agricultural practices towards mechanization and increased use of synthetic pesticides and fertilizers (Ibáñez & Caiola, 2016a). The latter degraded natural systems through direct pressure or eutrophication, peaking in the 70s with water colour turning greenish. Moreover, additional pressures were introduced through tourism, overexploitation of fish stocks, hunting intensification, and exotic (invasive) species. The delta still keeps a high variety of species and habitats, and more sustainable practices have been implemented in the last two decades, but there is still a cause for action from an ecological perspective. As it stands, human activities govern the ecological functioning of the Ebro Delta because of modification of the natural hydrological regime.

Still, the influences that the social and economic dimension have on the ecological dimension are sometimes bipolar and not black or white. For example, eco-tourism can be considered a sustainable activity to profit from natural capital if carried out sustainably. Yet historically, the delta has been subject to sun & sea tourism which has had a negative effect on the ecosystem, with the construction of residential areas in the 1960s leading to the destruction of vast and environmentally valuable expanses of dune and marsh (Roca & Villares, 2012). Another example lies in the rice fields: Despite the agricultural transformation reducing the delta's natural surface by 65% and thereby degrading (halophilic) environments, rice fields play an important ecological role by functioning as artificial wetlands, sustaining bird populations and aquatic species (although the modern methods of agriculture with have reduced habitat suitability). They also filter nutrients, can improve connectivity, and regulate soil salinity by irrigation, and have important cultural and aesthetic implications (also attracting tourists) (Ibáñez & Caiola, 2016a). In that sense, socio-ecological sustainability is achieved with a healthy combination of both rice paddies and natural habitats. Thus, next to the dense integration of the social and economic dimension with the ecological, ambiguous relations complicate the problem context.

5.3. Morphological evolution

The Ebro delta morphology is mainly conditioned by the balance between the sediment contribution from the Ebro river and wave (storm)-induced erosion moulding the deposits, as the local tide is very weak (microtidal) (Ibáñez & Caiola, 2016b; Rodríguez-Santalla & Somoza, 2018). The progradation of the current delta goes back 6000 years, with the last millennium introducing a shift in the delta's evolution towards a morphology controlled by both human and natural factors (Gorostiza et al., 2023). During this period, the Ebro basin saw high rates of erosion due to human activity (e.g. agriculture, deforestation) coupled with high flows, which led to growth rates at the mouth of up to 50 m/year (Ibáñez & Caiola, 2021a; Nienhuis et al., 2017). The significant growth is demonstrated by the 4th century seaport Amposta, now located 25 km from the river mouth (Barcelona Field Studies Centre, n.d.-a).

Both progradation and volatile river discharges were put to a halt after the construction of river dams

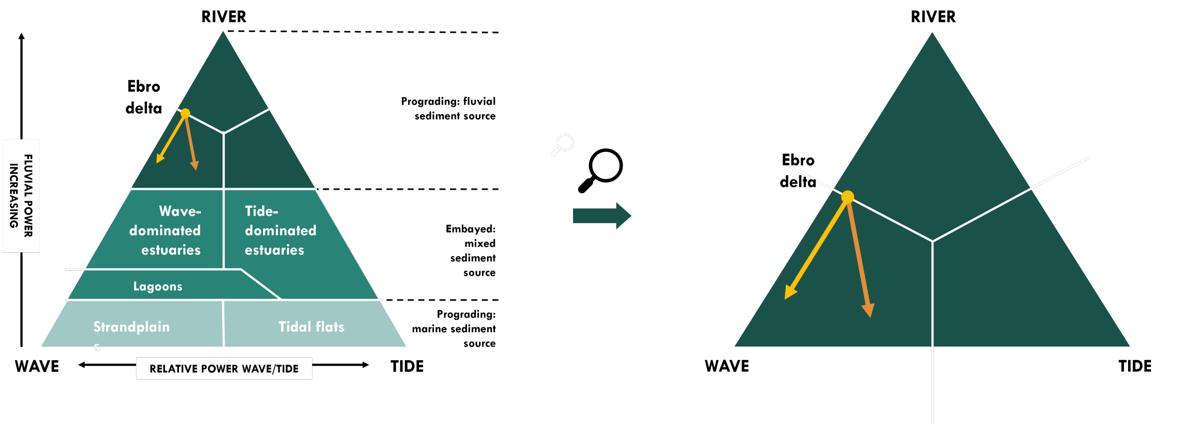


Figure 5.3: Delta classification prism as adapted from (Jiménez et al., 1997), which includes a temporal (dynamic) scale captured in the arrow length. The light orange arrow depicts the shift relative to the original Ebro delta classification, which is a consequence of the depleted fluvial sediment supply. The orange arrow considers mean water-level influence rather than tides, resulting in a shift towards 'tidal' influence. The influence of mean-water level is increasing over time in the face of climate change.

in the 20th century, eliminating the dominating formative processes. Especially the larger and lower course located Flix (1948), Mequinenza (1966), and Ribarroja (1969) dam nearly eliminated river flooding and sediment supply to both the delta plain and river mouth, with sediment transport falling by more than 99%. See Appendix B for the changes in fluvial discharge and transported sediment. This has led to the increasingly dominating effect of wave-induced erosion, shifting the deltaic morphology from an intermediate fluvial-wave-dominated system towards being primarily wave-dominated (Jiménez et al., 1997), see figure 5.3. In the face of climate change impacts, Jiménez et al. argued that the effects of water-level oscillations gain importance, even in the micro-tidal Ebro delta. Classically, only astronomical tides are considered in delta classification, but impacts from climate change - through increased storm surge occurrence & magnitude and relative sea level - will impact mean water-level influence short term and long term respectively (especially if one considers the synergetic effects of waves and water-level). Even though there is no new influx, the total sediment volume is relatively stable (balance between accretion and erosion) meaning the delta is mainly subject to reshaping processes. As storm surges and relative sea-level rise (RSLR) act synergistic with waves and flooding, they play a non-negligible role in the morphology. Figure 5.3 summarizes the morphological evolution.

As of today, the single threaded Ebro river splits the delta, forming two hemi-deltas which both feature a distinctive spit (see 5.1a) believed to have been shaped by wave-induced reworking of historic delta lobes (Nienhuis et al., 2017). Eastern wave energy is dominant, meaning that the position of the mouth generates currents resulting in NW and SW longitudinal sediment drift which nourish respective spits (Rodríguez-Santalla & Navarro, 2021). See Rodríguez-Santalla and Navarro for wind/wave roses and additional information on morphology.

5.4. Main Threats facing the Ebro Delta

The delicate balance between river sediment supply, wave energy and RSLR governing the morphology of the Ebro delta has been drastically tilted by the construction of dams, which eliminated both coastal and delta plain accretion. Intensive land-use has caused further environmental degradation, resulting in a heavily modified structure and functioning. These have made the area more vulnerable to the impacts of climate change: sea-level rise, temperature increases, and increased storminess are already heavily impacting the delta.

These changes to the balance may be too steep for the delta's resilience capacities, threatening its survival. If resilience shows to be holding up to change, the change in stability may have disastrous consequences for the current social-ecological system. To that end, the overarching challenge would be to grow the deltaic social-ecological capital and its resilience to climate and sediment threats. The sections below discussing the main threats are based on Rodríguez-Santalla and Navarro (2021), unless stated otherwise.

5.4.1. Change in sediment and fluvial discharge

The lower river discharge and decimated sediment transport impact several important processes. A balanced sediment input enables the system to prograde and aggrade in accordance with natural behaviour, even allowing compensation of SLR; the negative budget has resulted in net erosion and subsidence moving the delta's horizontal and vertical boundary back and down respectively. The delta experiences an average net subsidence of 3 mm, with erosion prominently featured in Figure 5.4, and Appendix B.2 and B.3. Notably, the mouth undergoes the most significant erosion, amounting to approximately 2.8 km over a period of 90 years, while the today the erosion is less extreme but still high, exceeding 15 m/year locally. On the other hand, the lower fluvial discharge means the marine waters penetrate the river to a greater extent, extending the 'salt-wedge'. The salt wedge - jargon for the penetration of a stratified layer of saline water into the river - influences both ecology and economy, by reducing suitable habitat extent and increasing saline intrusion (Ibáñez et al., 2020). Furthermore, with flood events nearly eliminated, the only way sediment is deposited on the delta plain - thereby countering subsidence - is by irrigation of the rice fields. Yet, in the absence of sediment, there is not much counterbalance.

5.4.2. Environmental degradation

Agricultural and urban activity has degraded the Ebro delta ecosystems. Although significant efforts have been made, eutrophication and pollution continue to pressure the deltaic wetlands. Altered geomorphological or hydrological conditions further affect the conditions of these habitats, which include the reduced fluvial discharge and lack of sediments and nutrients. Change in conditions will invariably lead to a change in species diversity and distribution, often paving the ground for invasive species or unstable tropic structures like algae blooms. It should be noted that the marshes, the most extensive environments before the human colonization, today occupy less than 5% of the territory, surface equivalent to that of urban areas.

5.4.3. Global changes in climate

Climate change effects exacerbate the pressures the delta already faces, and with effects expected to accelerate it poses a serious threat. Main impacts are an increase in sea level, the magnitude and frequency of storms, and temperature, but droughts or extreme rainfall cannot be neglected either. As coastal wetlands are fragile and low-lying systems, they are very sensitive to these changes, and because they play such a crucial role in the delta system, any alteration will result in significant feedback effects. Furthermore, their significant role as carbon sinks will be challenged. The disappearance of natural buffers and resilience worsens this outlook, meaning the feedback of pressures goes both ways.

Storms not only elevate the risk of flooding but also accelerate erosive processes by raising water levels through storm surges and intensifying wave energy. In some cases the system naturally recovers, but this recovery is slower than the frequency of erosive events or exceeds socio-economic viability, especially with the frequency expected to increase further. Temperature increases influence the productivity of agriculture to the point of financial unsuitability, exacerbate pollution impacts on the ecosystem, and directly degrade or alter ecosystem conditions.

The IPCC's Sixth Assessment Report projects sea level to rise between 0.38 m and 0.77 m[2] by 2100, depending on the scenario (on Climate Change (IPCC), 2023). Still, it is mainly the combination of subsidence and SLR (RSLR) that dictates the magnitude of the threat. With an estimated 50 cm SLR and 2 mm/y subsidence, RSLR could potentially submerge roughly 50% of the delta plain by 2100, degrading wetlands and causing polder formation (Ibáñez & Caiola, 2016a). Worst case scenarios could mean 90% of rice paddies will be below mean sea level by this time (Genua-Olmedo et al., 2022). However, the anticipated impacts of sea-level rise on coastal changes up to 2050 are considered insignificant compared to erosion resulting from alongshore sediment transport. To that end, climate accelerated erosion emerges as the primary concern in the immediate future, whereas over the long term, the main threat shifts to RSLR.

5.4.4. Political landscape

A rudimentary analysis of the political landscape helps us to contextualize the problem in its chronological place. It is not intended to be exhaustive in any regard, and further analysis should be carried out to map out values and objectives of stakeholders, potentially including them in a participatory process.

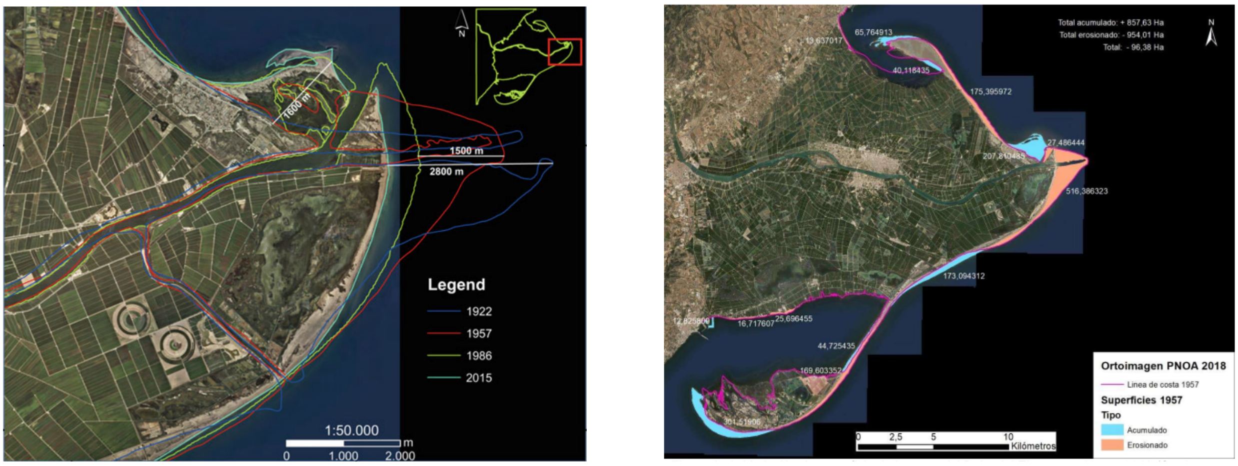
Momentum

Awareness of existential threats has been rising, and has sharply risen after the intense 2020 Gloria storm (Gorostiza et al., 2023). Penetrating 3 km inland, the storm surge flooded 3300 ha of rice fields and irrigation canals, destroyed aquaculture facilities, broke through the Trabocador barrier, and significantly eroded beaches. The damage was heterogeneous: most affected areas had narrow, eroded beaches that provided little wave energy dissipation (Ibáñez & Caiola, 2021b). Gloria and other storms, together with the visible effects of erosion, have started to change the perspective to a resilience-guided coastal protective strategy. Herein, the importance of sediment is increasingly recognized, leading to the concept of "sediment justice" and a growing social demand for increased sediment to mitigate delta subsidence, sea level rise, and coastal erosion (Gorostiza et al., 2023). The need for action is evident among all, but the means of action are still discussed and disputed.

Governance complexity

Related governance is hugely complex due to the multitude of stakeholders, which will in term shape the trade-offs NbS strategies create. Different administrative levels (state, regional, local) intersect with a diverse array of private stakeholders (such as rice growers, fishermen, hunters, tourism companies, foundations, and NGOs), across both upstream and downstream arena's. Contrasting views and values are prevalent. At the same time, public and private agents must reach an understanding if they are to jointly tackle the huge sustainability challenges of this fragile area.
Furthermore, the delta is already experiencing a sectoral shift: The tourism sector, in terms of both companies and visitors, is more and more important to the delta (Roca & Villares, 2012). Yet, the sector has to coexist alongside an agricultural sector that preserves the authenticity and sustainability of this space. As is clear from section 5.2 and from cases globally, traditions can form powerful social anchors resisting the currents of change (which is good nor bad necessarily). As an example, the intense local conflict provoked by managed realignment strategies illustrates this phenomenon (Roca & Villares, 2012). Managed realignment allows the sea to gain ground in a controlled manner, reducing vulnerability to RSLR and extreme events, e.g. by creating salt marshes as a natural coping mechanism. Such strategies provide additional ESS like recreation, carbon storage or saline seepage reduction, but will conflict with the hold-the-line tradition leading locals to strongly prefer maintenance or improvement of the existing line of defence.

[2] 0.38 m (0.28–0.55 m, likely range; SSP1-1.9) and 0.77 m (0.63–1.01 m, likely range; SSP5-8.5). Likely range denotes the 66% confidence interval



(a) River mouth retreat (Rodríguez-Santalla & Somoza, 2018) **(b)** Distribution of erosion and accretion (CEDEX, 2021)

Figure 5.4: Coastline changes

5.5. Overview of proposed Nature-based Solutions

There have been numerous studies and (proposed) interventions to alleviate the threats faced in the Ebro delta. The majority of these target the sediment deficit and subsequent erosive processes. A sufficient sediment budget counters erosion, but additionally has the potential to successfully counter RSLR even in worst-case scenarios (Although a hybrid manner together with traditional structures and local retreat may be necessary) (Ibáñez et al., 2014). Many of the proposed interventions can be considered NbS, and below the most important categories are listed. Note that many of the measures aim to restore natural conditions and processes to establish a stronger social-ecological resilience.

- **Environmental flows or e-flows** are defined as the "quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being" (Arthington et al., 2018). As the important social-ecological functions and values in the delta are heavily dependent on sufficient flows, e-flow strategies could help overcome the strong negative impacts of the dams upstream. Aside from habitat and biological process maintaining flows, inclusion of flood events and sufficient sediment or nutrient carrying capacity are considered in the Ebro delta, see Ibáñez et al. (2020).
- **Sediment by-pass**
  The extensive sediment volume trapped in the reservoirs could be released downstream though a sediment by-pass, restoring the historic route and natural destination. In that sense, sediment transport could be considered as an important component of e-flows. However, technical feasibility is still uncertain, and sediment in the dams has also been polluted over time, further complicating the strategy (Gorostiza et al., 2023). The option would however potentially greatly improve vertical accretion by distributing sediment over the delta plain, which can be transported through the irrigation canals.
- **Building up the coastline** Coastal squeezing, the result of agricultural encroachment and coastal erosion, has reduced the protective coastal strip significantly, negatively impacting flood safety. A sufficient buffer allows the free movement of the coast and can be attained both by converting financially unsustainable rice fields to salt marshes/intertidal habitats (expanding inward) or sand nourishment (expanding outward/strengthening dunes). The former carries a significant social impact which should be considered, but is also effective against saline intrusion. Nourishment is primarily envisioned by taking sand from accretion to erosive areas (CEDEX, 2021). Sediment

traps - e.g. attained by densifying vegetation - can improve sediment attainment, stabilizing the buffer.

- **Habitat restoration** Many forms of habitat restoration will likely increase resilience against sea level rise and other climate effects. Examples are the restoration of hydrological connections between the lagoons and the sea resulting in increased sediment inputs to the lagoons during marine storms, or the re-naturalisation of rice fields and/or improving habitat conditions. E.g. benefits of healthy wetlands include but are not limited to boosting the decomposition of organic matter, consequently speeding up vertical accretion, regulating extreme weather events (both floods and droughts), supporting a healthy and resilient water balance, and purification of water and soil (Barbier et al., 2011; Ferreira et al., 2023).

Other proposed measures include the improvement of recreational infrastructure such as foot and bike-baths, to promote tourism (Zografos, 2017).

5.6. The ICE-Ebro

By detailing the ICE-model with insights from this chapter, the ICE-Ebro is attained for our problem definition, see figure 5.5. Main case-specific subsystems include agriculture (primarily rice cultivation), the exploitative provisioning ESS consisting of fishing, hunting, and salt extraction, and (Eco-)tourism as the primary stand-alone cultural ESS. Others not less important, but are included indirectly in other relations (e.g. rice farming as a cultural activity is captured in agriculture and the positive relation to social well-being). As we are primarily concerned with the area downstream of the dams, this is included in the model, see section 6.2 where we elaborate on this. The importance of sediment is not visible at a first glance, but strongly substantiated by the causal relations; note how if sediment is retained in the dam compound, the impacts propagate throughout all subsystems. To see this effect visualized, see appendix D, which depicts the internal relations in a bit more detail.

The NbS categories have been added as measures, but note that as categories these are very general. Both e-flows and a sediment by-pass would imply mainly positive impacts downstream of the dam compound, while affecting a number of aspects negatively upstream. Widening the coastal buffer zone would restore important coastal habitats, subsequently improving the coastal flood defence. Yet, it trades off with agriculture due to the effects of coastal squeeze having left no inward room to actually expand to (beach nourishment would not create this trade-off, as the buffer zone would expand outwards). The same relations are true for habitat restoration, albeit in a more general manner.

5.7. Conclusions

This completes the formulation of the ICE-Ebro. We set out to map where the social, economic, and ecological trade-offs associated with Nbs for CCA lie in the Ebro Delta. This was done through the merging of the theoretical knowledge base with the Ebro delta contextual understanding (i.e. detailing the ICE-model to the Ebro). In that regard, we employed a literature study, semi-structured interviews, and a field trip to develop a strong contextual understanding. Additionally, insights from SDM were used to refine the synthesis, see chapter 6.

To that end, section 5.1 to 5.4 summarized the system and problem context by detailing the social, economic, and ecological dimensions, describing the socio-ecological and morphological evolution, and delineating (resultant) threats. Ecologically, the delta is notable for its high density and diversity of habitats and species, many of which are rare or endangered. The ecological wealth is crucially supportive for many socio-economic functions and values. Namely, besides vital regulative ESS like flood protection and coastal stabilization, the social and economic structure are deeply connected to and dependent on the landscape, and ultimately on the varying influxes of water, nutrients, and especially

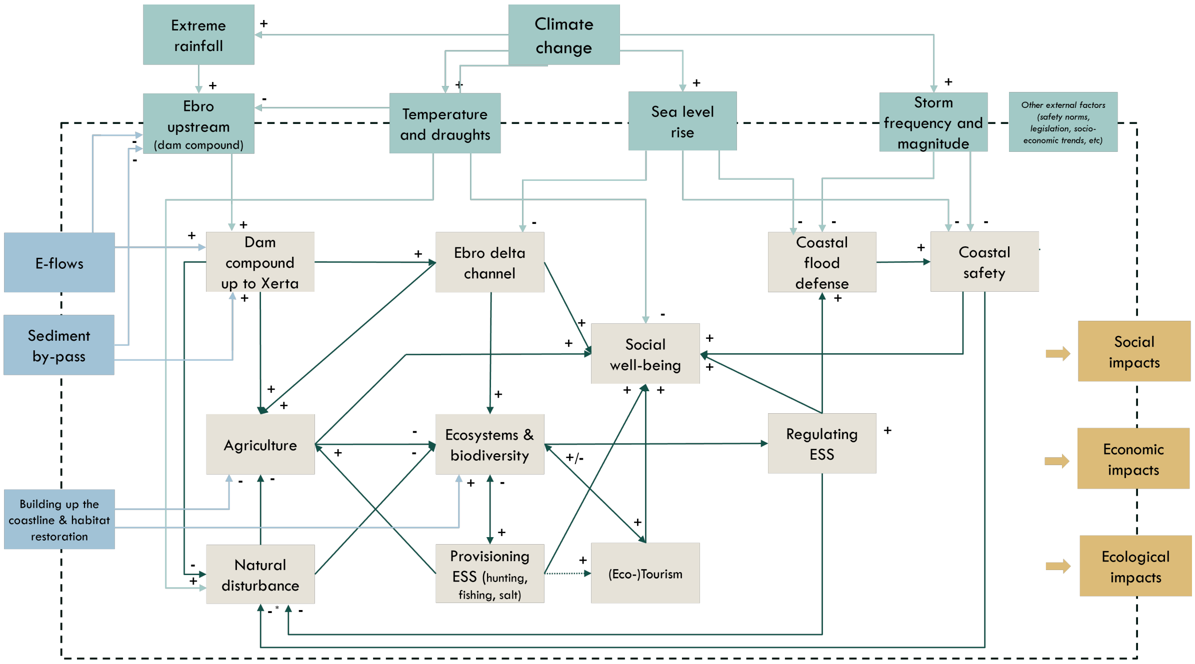


Figure 5.5: The ICE-Ebro.

sediments transported by the Ebro. Main (traditional) activities include rice cultivation, fishing, hunting, and salt production. Subsequently, gastronomy is a major social aspect, and eco-tourism has developed into a cornerstone of the economy. As such, dependency on climate-sensitive income sources is large. Since the 1960s, the social-ecological regime shifted significantly, primarily through dam construction and intensified agricultural practices. The delicate balance between river sediment supply, wave energy and RSLR governing the morphology of the Ebro delta has been drastically tilted by the construction of these dams which compound >99% of sediment and nearly eliminated volatile river discharges, which halted both coastal and delta plain accretion. Besides the drastically tilted morphological balance, intensive land-use has caused further environmental degradation, resulting in a heavily modified system structure and functioning. These have made the area more vulnerable to the impacts of climate change: sea-level rise, temperature increases, and increased storminess are already heavily impacting the delta. These changes and impacts may be too steep for the delta's resilience capacities, threatening the social-ecological sectors. To that end, the overarching challenge would be to grow the deltaic social-ecological capital and its resilience to climate threats. Herein, sediment takes a leading role. Moreover, the (social, economic, and ecological) importance of sediment is so significant in the Ebro delta that the concept of 'sediment equity' is starting to gain traction.

Section 5.5 listed the most important NbS strategy categories considered to adapt to these challenges. Main categories include but are not limited to ecological flows which restore the river's natural dynamics, sediment by-passes to restore the flow of sediment, building up the coastline, both through sediment nourishment and restoration of coastal salt marshes, and other forms of habitat restoration to enhance (regulative) ESS. Associated trade-offs are plenty however, many related to ingrained traditions and cultural activities or upstream and downstream conflicts. We found that understanding of the (historic) context and inclusion of local stakeholders is imperative to uncover hidden relations and ingrained values that are missed at a first glance.

Subsequently, the ICE-model was detailed to the Ebro delta by synthesizing the analysis above, resulting in the ICE-Ebro (section 5.6). The ICE-Ebro is able to comprehensively map the social, economic, and ecological dynamics associated with NbS for CCA in the Ebro delta. Underlying flows can be hidden at a first glance, of which sediment is the prime example. However, the ICE-Ebro can be rapidly used to communicate this important flow by guiding the listener/reader through structure and behaviour, especially by in-person communication. The system-wide impacts of sediment are thereby visually mapped out. Very few adjustments had to be made, mainly filling in land use (agriculture), provisioning ESS (fishing, hunting, salt extraction), and cultural ESS ((Eco-)Tourism). The easy of adaptation suggests that coupled with the contextual-SES understanding, the ICE-model can be effectively used 'scaffold'-like. Although the Ebro-case was used to refine the general ICE-model and will therefore be naturally aligned, this implies that the ICE-model is likely to be modular for different uses and adaptive for other contexts. Additional case-applications are needed to substantiate this claim, preferably on deltas with different morphological and social-ecological regimes to test if the ICE-model holds under changing contexts. Moreover, using the ICE-Ebro (in a participatory environment) will help to identify best practices and use cases, along with potential overlooked biases or failing/missing elements. Essentially, the model needs to be applied in practice to surpass the theoretical aspect of use-cases.

6

Model formalisation

In this chapter the model is formalized by conceptualizing and specifying simultaneously, building on the theoretical understanding (chapter 4) with the system description (chapter 5).

First, we delineate the modelling considerations in section 6.1. Subsequently, the conceptual overview which delineating the system boundary is given in section 6.2. Section 5.6 follows, and presents dynamic hypothesis building on the main archetypes identified. The intertwined formalisation of the different sub-systems is delineated in section 6.4 and section 6.5. We end with a hypothesis of the axes on which trade-offs vary in section 6.6, and conclude in section 6.7.

6.1. Modelling considerations

The model setup process essentially entails the creation of an appropriate model; have we chosen the right aggregation level and boundary, are all relevant concepts included without redundancy, do assumptions align with reality, and is the model fit for its intended use? For our context, this means the model should accurately reflect the Ebro delta SES structure and its long-term behaviour under climate scenarios, while facilitating the inclusion of a wide array of NbS interventions. This includes the ability of the model to show all modes of (extreme) behaviour. Note that these requirements are generic, but in our research context they present a significant hurdle as we have set out to integrate social, economic, and ecological dynamics. As the scope is very broad and envelops the entire SES, the guiding challenge is to successfully integrate all relevant structure and behaviour, while remaining comprehensive and relatively compact.

Furthermore, we aim for the model to be communicative and flexible to increase adaptive capacity. As NbS are inherently and systemically complex, this adaptability facilitates accommodation of the diverse and evolving nature of SES, allowing for the inclusion of more (context-specific) solutions, additional and/or detailed modelling of subsystems, and the inclusion of various stakeholder perspectives ex post. These align with the models goal, which places less emphasis on exact prediction and forecasting, and more on exploration, developing greater system understanding, and facilitating better decision-making under uncertainty.

By prioritizing these principles, we can create a comprehensive tool that not only enhances understanding and learning but also supports effective decision-making and adaptability in the face of the inherent and systemic complexity of NbS.

6.2. Conceptual overview

In this section we will delineate the boundary of the model, which consists of the geographical scope and the array of chosen aspects of the related system that are essential for analysis.

6.2.1. Geographical scope

To model the trade-offs of NbS that concern the Ebro delta, We need to expand our scope to include not only the delta surface area but also the upstream river, extending at least up to the dam compound. With the dam compound, we collectively refer to the Mequinenza, Ribarroja, and Flix dams as they are the most influential for the Ebro delta. The dam compound and associated trade-offs govern the dynamics of the lower Ebro.

Still, we consider a fine-grained trade-off analysis of the dam compound out of our scope, as modelling the far-reaching upstream and downstream impacts of dams represents another significant research effort and would shift the focus from the delta. Regardless, impacts of dams have been extensively studied in the past, including SDM applications (e.g. (Hassanzadeh et al., 2012; Jiang et al., 2020)). Thus, we only include the main derivatives for the lower Ebro of these trade-offs: the discharge and the transported volumes of sediment. The NbS that are associated with the dam compound, like ecological flows and sediment by-passes, can still be modelled by capturing associated trade-offs heuristically without including the feedback that propagates outside of the system boundary. An example is the sediment by-pass, which - among other impacts - would affect the function of the dam and the sediment-based ecosystems that have emerged due to sediment impounding. In that sense, we chose to recognize these trade-offs, but refrain from modelling an upstream system structure and developing deeper insights here.

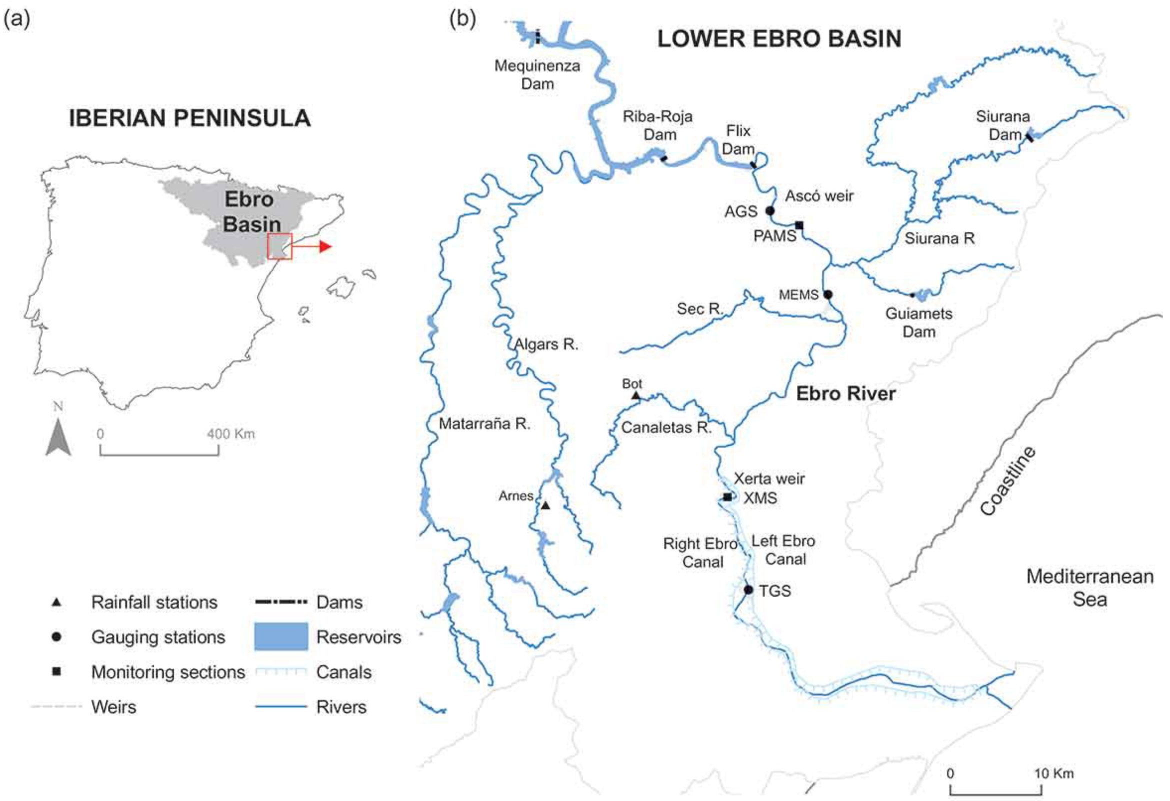


Figure 6.1: Geographic scope, depicting the dams composing the dam compound, the main irrigation canals, and main tributaries (Tena et al., 2012).

An important location downstream of the dam but upstream of the Ebro delta demanding further description is the town of Xerta. Specifically, the irrigation channels divert water from the Ebro near this location, see figure 6.1 and 5.2. To address this, we extend the boundary of what we consider the Ebro delta channel in this model up to Xerta.

In conclusion, we consider three spatial aggregations which are guided by the Ebro river; upstream, midstream, and downstream. Downstream from Xerta is the Ebro delta itself, of which the terrestrial boundary is demarcated by the towns of La Ràpita, Amposta, and L'Ampolla (see figure 5.1a). This region is modelled in detail, see figure 6.2 for this geographic scope of the model. The stretch of river from the dam compound up to Xerta is referred to as midstream, and is coarsely modelled (only conceptualising the midstream channel). The model boundary lies on the dam compound, and trade-offs propagating from and to upstream of the dam compound are considered external factors.

6.2.2. Temporal scope

We have opted to extend our analysis up to the year 2100. The reasons are twofold. Firstly, NbS are generally considered to be long-term strategies, with many of their benefits only emerging after some time. Secondly, climate projections for this time horizon are readily available, facilitating a comprehensive assessment of the potential impacts and effectiveness of NbS interventions in addressing future climate adaptation in the Ebro delta.

The model will not be including historical data. The goal is not to mimic reality or historical data, but to assist stakeholders in their understanding of the internal system structure that drives (problematic) behaviour. Regardless, comparing historical data to model outputs is among the least powerful methods for model confidence building (Featherston, Doolan, et al., 2012). We do make use of historical data in our understanding of the SES, as is evident from section 5.2. This historical understanding is needed to correctly assess current values and explain why system structure and behaviour have emerged as such.

6.2.3. Bull's eye diagram

Based on the problem description and geographical demarcation, the model boundary diagram or bull's eye diagram is constructed, depicting endogenous, exogenous and excluded aspects of the model, see figure 6.3. Endogenous aspects lie within the model boundary (e.g. sediment), whereas exogenous aspects are on the boundary (e.g. climate change). Excluded aspects can be important for the problem context, but are out of scope (e.g. political stability). This distinction helps the modeller to create an overview of included elements and their relative endogenicity.

A few choices demand explanation. Firstly, supporting ESS are not included directly as they only *support* the other categories of ESS (although sometimes biodiversity is seen as a supporting ESS). Inclusion would unnecessarily complicate the model. Secondly, we have set out to maintain a high level of aggregation while still capturing crucial system behaviours, albeit at the expense of heterogeneity. As discussed, SDM is not suited to model non-homogeneous aspects and disaggregating (spatially, sectorally, naturally) would diminish the transferability of the model to other deltas, while also greatly increasing model complexity.

6.3. Dynamic hypothesis

A dynamic hypothesis is a conceptualisation of the causal relationships, feedback loops, delays, and decision rules that are thought to generate system behaviour, or in other words a theory of how a problem arises from a system structure (Kelly et al., 2013). It is helpful to make use of systems theory to describe this conceptualisation of (problematic) behaviour, where especially system archetypes can be of use. System archetypes classify and describe generic structure and behaviour over time, and can

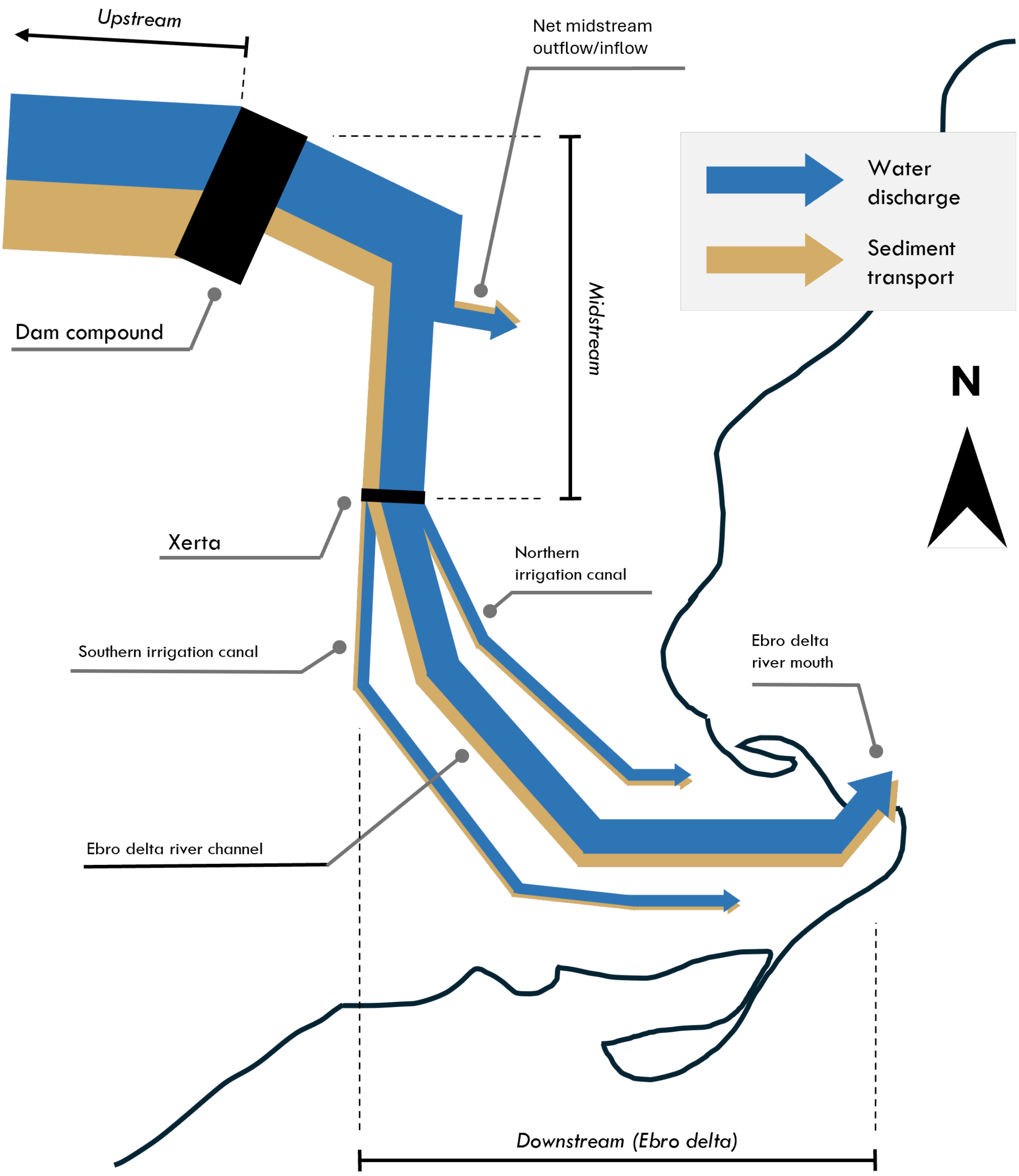


Figure 6.2: Merged geographic scope and flow diagram. The width of the water and sediment flows represents the relative magnitude (not to scale). The net flow from/into the midstream section is mainly determined by anthropogenic demand and tributaries in the respective basin. This flow can either be positive or negative depending on midstream rainfall/evaporation/demand.

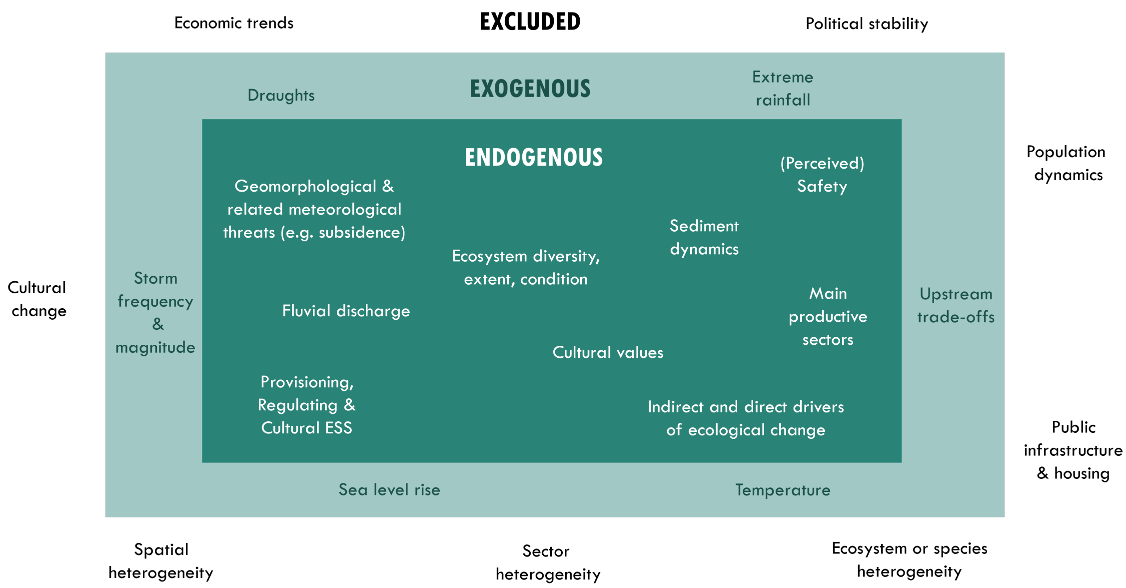


Figure 6.3: Boundary diagram

therefore be used for both model conceptualisation and communicating model behaviour through a storyline (Kim & Anderson, 1998). We can identify two main system archetypes governing the SES of the Ebro delta; tragedy of the commons & limits to growth. We consider the latter archetype to be endogenous in our defined system boundary, whereas the former is seen as exogenous. The line of reasoning for this identification is explained below.

6.3.1. The main archetypes in the Ebro delta

A top-down perspective allows identification of the tragedy of the commons archetype. Although the scope of this research considers the lower Ebro downstream from the dam compound, the area is significantly influenced by upstream aspects of the Ebro basin. Historically, exclusively positive impacts like flood regulation, hydropower, and water provisioning have been ascribed to dams, and only from the 21st century the perspective has shifted to recognition that strong trade-offs are inherent to dams; when water availability is improved for one, it is reduced for the other (Owusu, 2022). We argue that in general, the Ebro delta included, dams can be partially considered as a tragedy of the commons. Tragedy of the commons relates to scenarios where individual motivations or narrowly-focused objectives result in collectively catastrophic dynamics, often associated with unsustainable resource depletion. Although fluvial discharge is not necessarily limited, exploitation of this ESS through damming lead to negative impacts including but limited to: disruption of natural river flow and sediment transport, alteration or fragmentation of habitats and loss of biodiversity, and community displacement due to reservoir inundation (Botelho et al., 2017; Owusu, 2022). These have social, economic, and ecological repercussions (often through impacted ESS), and especially aspects to equity and environmental impacts are often overlooked or neglected. In that sense, multiple parties compete for (management of) the same 'resource' - water and sediment - deriving different ESS from it.

Now, in the face of climate change and the biodiversity collapse, many of these impacts have become more pressing or visible, although the climate adapting capacities of dams cannot be neglected[1].

[1]The impacts of climate change bring implications for dams (Pittock & Hartmann, 2011). Firstly, dams can prevent affected flora and fauna from migrating to new habitats. Secondly, the risk of dam failures may increase, especially with the likelihood of more frequent high flood events. Thirdly, dams may no longer provide the intended services as hydrological patterns change.

The consequences for deltas are evident, see also section 4.1.2. The sediment-starved Ebro delta is a primary example. The commons - water and sediment - have been poorly managed primarily benefiting interests of upstream stakeholders. To that end, our argument can be summarized as follows: The costs paid by the environment, taxpayers, and downstream communities (including the rice farmers) to contribute to human development *through poor management of water and sediment* by building dams are tragic, especially in the face of climate change and the degradation of biodiversity.

Zooming in on the defined system conceptualisation, we are able to distinctly recognize a limits to growth archetype. It relates to scenarios of rapid growth, followed by stagnation after reaching a limit, and potentially by a collapse. The limit is often driven by a balancing process (such as overgrazing leading to starvation). In the Ebro delta we have seen this structure and behaviour unfold when irrigation canals facilitated the rapid conversion of natural habitats to rice paddies, driving socio-economic growth, see section 5.2. For climate adaptation, these habitats could have provided a crucial role through their regulative ESS: Sea level rise and/or marine storms protection, shoreline stabilisation, vertical accretion, saline intrusion prevention, water quality improvements, temperature regulation, and more. Initially, the coastline has acted as a limit to agricultural and other socio-economic expansion, but as consequentially resilience of the system was lost, natural hazards - cranked up by climate change - now dominate the balancing processes. Coastal squeeze leaves minimal room for the coast to move and accommodate to climate change impacts, and RSLR not only exacerbates these threats, but introduces higher saline gradients too which cannot be dampened by salt marshes and subsequently reduce rice yields over time. If no action is taken, (partial) collapse is imminent, even under moderate climate scenarios.

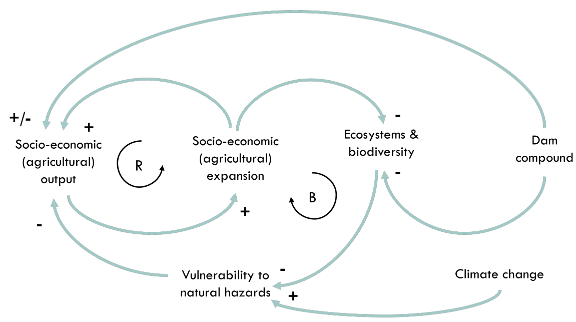


Figure 6.4: Merged archetypes, resulting in a CLD with a socio-economic reinforcing feedback loop, balanced by the resilience provided through regulative ESS of ecosystems & biodiversity.

Merging these tho archetypes yields figure 6.4, which is - not surprising - quite similar to figure 5.5 but illustrates the essence of the problem in a simple way. See also figure 6.2 for the flow diagram, which helps to illustrate how flows of sediment (and water) are distributed within the system boundary. The relation between the two archetypes is reinforcing. Namely, the upstream tragedy of the commons structure exacerbates the balancing/limiting feedback of the downstream limits to growth structure: without sediment, the delta cannot prograde and accrete vertically efficiently. Together, the archetypes provide a storyline that is illustrative, but quite susceptible to framing by stakeholders with conflicting interests. We want to point out this vulnerability as it has been applied extensively. Although it has benefited upstream (and some downstream) interests, refraining from better sediment management has been an aberration to cultural irrigation and has led to decreased human security downstream (Gorostiza et al., 2023; Zografos, 2017). The latter has to be improved through site-specific alternatives, of which some include expropriations of agricultural land (see section 5.4.4 and 5.5), adding insult to injury by suggesting farmers are to blame for their climate change vulnerability. Thus, although we believe extensive

Modification may also be needed to meet new demands brought by climate change.

deltaic agricultural expansion has been part of the problem, we want to explicitly refrain from framing local stakeholders as the scapegoats.

6.3.2. Influence on KPIs

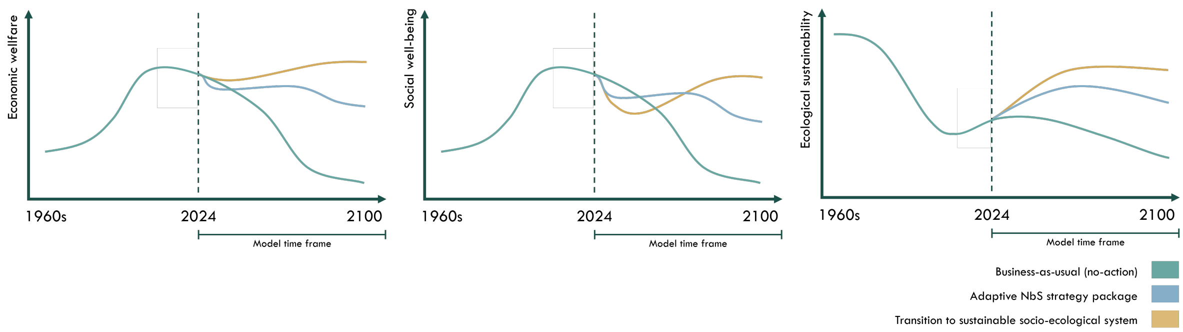


Figure 6.5: Aggregated impacts on the economic, social, and ecological dimensions in the Ebro delta. The farther we look into the future, the greater the uncertainty in impacts (i.e. broader bandwidth of confidence). Would extreme climate scenarios unfold, perhaps strategies need to include more hybrid measures.

The resulting multi-functional impacts of the system structure and behaviour under the effects of climate change are visualized in an aggregated manner in figure 6.5, which communicates the expected effects of the problem and how we expect NbS for CCA to be contributing to the solution. We have opted to highlight aggregated behaviour of interventions, as it allows for basic insights without too many distinctions between individual NbS measures. The model results will actually give a more nuanced perspective, also distinguishing trade-offs within the three dimensions. Three levels of interventions have been described; business-as-usual where no or minimal/traditional action is taken, an adaptive NbS strategy package which delivers an array of resilience-promoting NbS interventions, and a holistic full scale transition to a more sustainable SES which makes use of NbS.

Business-as-usual

As the Ebro delta grew socio-economically, a coupled decline was seen on the ecological dimension. However, the last two decades have seen ecological improvements, with some habitat restoration as well. Still, much work remains to be done to ensure that the region's resilience is sufficiently robust to withstand the impacts of climate change. Implementation of NbS is expected to strengthen resilience, but only up to moderate impacts of climate change. Thus, without any further work the impacts of climate change gradually weaken the ecological dimension through degradation and hazard stress, thereby increasing socio-economic vulnerability to climate change until a certain threshold is reached which significantly impacts both the social and the economic dimension (e.g. a heavy storm, or RSLR reaching over-topping heights). As environmental conditions shift, ecosystems typically undergo adaptive changes as well, resulting in a gradual rather than steep decline in their condition, extent, and diversity.

Adaptive NbS strategy package

With this strategy package, we intend to describe aggregated effects of NbS interventions. Generally, we see some financial implementation costs and trade-offs, but they are not very steep compared to traditional options. They will, however, greatly improve resilience of the ecological dimension, which will create a buffer against climate change impacts for all three dimensions. In that sense, there won't be necessarily an improvement in aggregated impacts, but stabilisation. We expect the steep decline in the social and economic dimension to be shifted to the future (to a point where even NbS strategies cannot adapt fully to impacts), and to be of a lesser magnitude.

Transition to sustainable socio-ecological system

Among other goals, the Rest-Coast project envisions a sustainable socio-ecological shift where the system transitions to a greener socio-economic model. This could entail regenerative agriculture, or a shift from agriculture to eco-tourism. As this model would holistically strengthen and tighten the link with the ecological dimension from the ground up rather than just adapting to impacts using functions of the ecological dimension, we expect the resilience of the system to be stronger than a solution package of adaptive NbS. However, this transition will carry social trade-offs and conflict which take a while to settle: it implies a livelihood shift, a partial loss of rice paddy surface, and a new way of life among others.

6.4. Intertwined conceptualisation and specification

In this section, the different subsystems are discussed and formalized. The structure of the model is followed, roughly from left to right. We use the ICE-Ebro model to guide the modelling effort, but note that the model structures different subsystems slightly differently, as the specification of subsystems like sediment demand significantly more variables. Six main subsystems are defined; Fluvial discharge, Sediment - channel & delta plain, Sediment - shoreline dynamics, Coastal processes & climate effects, Agriculture, and finally Ecosystems & Tourism. Figure 6.6 relates these subsystems to the earlier defined subsystems in the system diagram of the Ebro delta by applying the colours of the model. Before detailing the formalisation of the subsystems, we expand on the use of multiplier functions within our model.

Substantiation of relationships is drawn from the system synthesis (5). In the delineation of the subsystems below, formalisation descriptions are paired with stock-flow diagrams, which are the visual representation of SDM. See Appendix H for a screenprint of the total model. See Appendix I for the tables with the model equations.

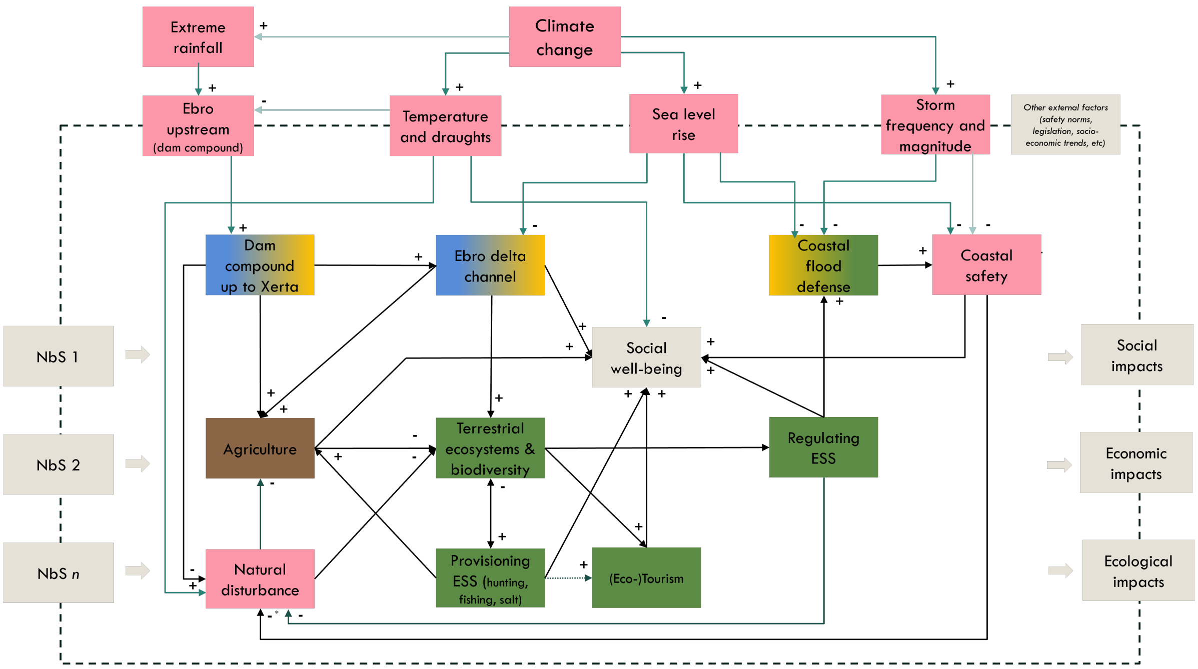


Figure 6.6: Adapted ICE-Ebro, with colours corresponding to model subsystems used in the model. Blue = Fluvial discharge, orange = Sediment, brown = Agriculture, pink = Coastal processes & climate effects, and green = Ecosystems & Tourism

6.4.1. Multiplier functions

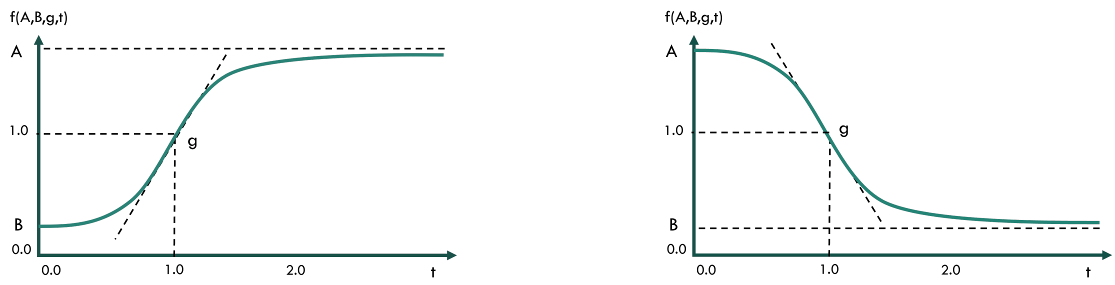
The adequate integration of multiple highly contrasting disciplines is one of the largest challenges that arise when trying to successfully model social, economic, and ecological dimensions and associated trade-offs. As we aim to remain comprehensive and insightful, the difficulty is found in achieving the right level of aggregation while correctly interrelating different aspects. In that regard, the trade-off between model boundary and (dis-)aggregation needs to be carefully navigated in this research, i.e., the abstraction level of the model is key for success. To that end, we have already discussed the benefits of the ad hoc approach to describe highly complex relations that is favoured by many system dynamic modellers (see section 4.2.2.

In this context, multiplier functions are very useful, allowing for accurate representation of proportional relationships. J. Slinger (1988) has expanded on the multiplier function initially developed by Uys et al. (1985), which describes the continuous form of the table functions commonly used in SD to capture proportional relationships. The function utilizes just three parameters, and can therefore rapidly be used to quantify relations in our model. To capture both increasing ($f(A,B,g,t)_{increasing}$) and decreasing ($f(A,B,g,t)_{decreasing}$) table functions continuously, the inverse of the original function around the asymptote is taken. See the table and figure 6.7 below.

$$\begin{aligned}
f(A,B,g,t)_{increasing} &= \frac{A}{1+(\frac{A}{B}-1)\,exp(-C\cdot t^{s})} \\
f(A,B,g,t)_{\text{decreasing}} &= A - f(A,B,g,t)_{\text{increasing}} \\
C &= \log\left[\frac{E}{A-1}\right] \\
s &= \frac{g\cdot A}{(A-1)\cdot C}
\end{aligned}$$

$$where$$

$$\begin{aligned}
f(A,B,g,t) &= \text{function value [no unit]} \\
A &= \text{horizontal asymptote [no unit]} \\
B &= \text{value at t = 0 [no unit]} \\
g &= \text{gradient at t = 1 [no unit]} \\
t &= \text{independent value [no unit]}
\end{aligned}$$



(a) Continuous increasing table function (CTF_{dec})

(b) Continuous decreasing table function (CTF_{dec})

Figure 6.7: Continuous multiplier function (table function) graphs

We adopt the multiplier functions to streamline the modelling effort. The primary use lies in the comparison of value t_i to a baseline t_{base} where if $t_i = t_{base}$, $t = 1.0$. I.e., to compute a *relative* or *multiplier* effect, independent value $t = \frac{t_i}{t_{base}}$. Naming of these multiplier functions is done with respect to what they represent, e.g. *relative* erosion rate compared to a *normal* erosion rate, or *relative* biodiversity compared to a *baseline* 'sustainable' level of biodiversity).

6.4.2. Subsystem: Fluvial discharge

The fluvial discharge submodel describes the flow of water from the dam compound down the lower Ebro and intro the channel and irrigation channels. Main aspects modelled include the basic structure of the dam compound and derived midstream flow to Xerta, the relation between irrigation and river channel flow, as well as the option for a fluvial flood flow, and the salt wedge dynamics.

Dam compound up to Xerta

Figure 6.8 shows the stock-flow diagram of the dam compound up to Xerta. As we have opted to exogenously model trade-offs at the dam compound, the structure and equations depicting this section are relatively simple, and many of the flows (like evaporation and precipitation) are aggregated.

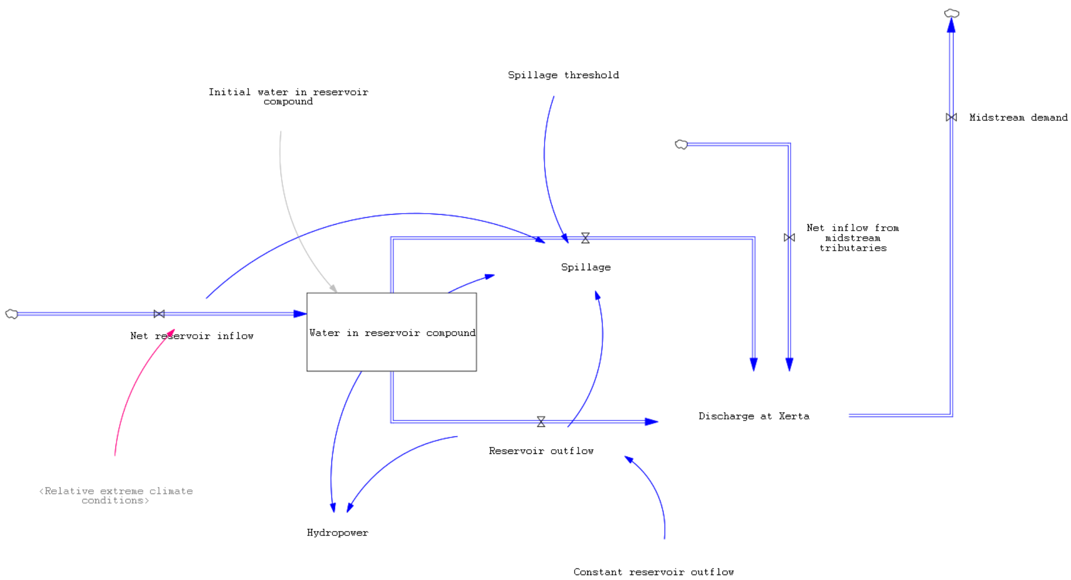


Figure 6.8: Stock-flow diagram of the dam compound up the Xerta

The *water in reservoir compound* describes the volume of water stored in the reservoirs, which is essentially the balance between in- and outflows. We aggregate upstream discharge and evaporation & precipitation from and in the reservoir within the *net reservoir inflow*. Extreme rainfall and droughts, of which the magnitude and/or frequency are expected to increase with climate change (Officina Catalana del canvi climàtic, 2018), affect this inflow through an increasing multiplier effect (*Relative extreme climate conditions*). *Reservoir outflow* is the normal discharge from the reservoir, with *Spillage* governing the threshold at which the reservoirs either overflow or even potentially fail. Thus, the *Discharge at Xerta* is given by the midstream flows, which are the reservoir outflow (normal or spillage), the *Net inflow from midstream tributaries*, and the *Midstream demand*. The latter aggregates all outflows from the midstream section (e.g. irrigation, drinking water, evaporation). *Hydropower* is primarily given by reservoir head and outflow, although exact computation is outside of scope.

Irrigation and the delta channel

Figure 6.9 shows the structure downstream of Xerta, describing irrigation, delta channel discharge, and the fluvial flood flow.

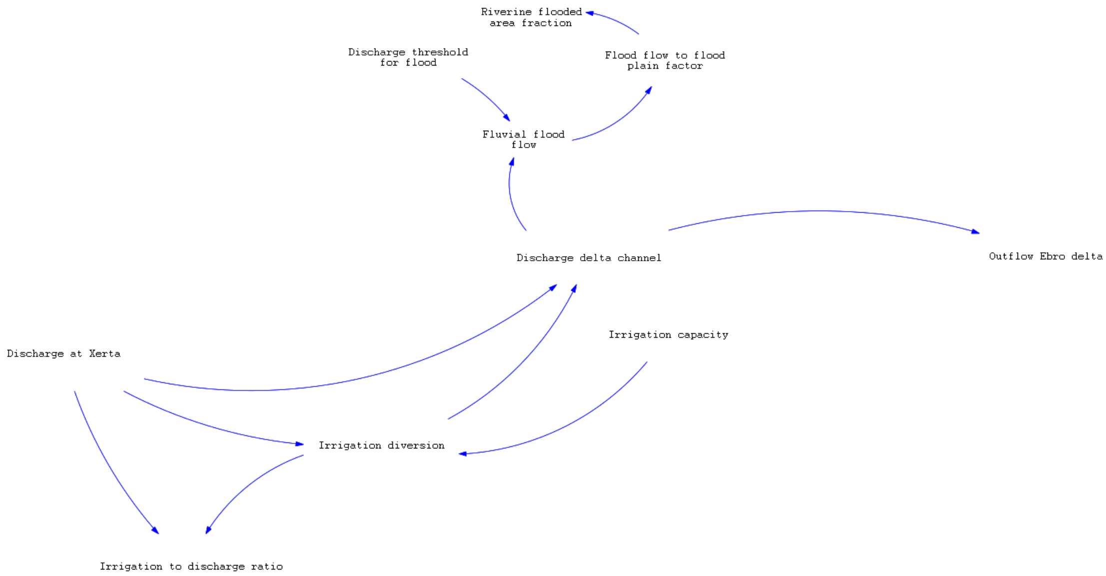


Figure 6.9: Stock-flow diagram of the irrigation canals, the delta channel discharge, and the fluvial flood flow.

At Xerta, the *Irrigation diversion* determines the water that is diverted to the irrigation channels at max canal capacity, given by *Irrigation capacity* (equals irrigation water allocation rights). To determine if the remaining discharge exceeds the capacity of the channel resulting in a *Fluvial flood flow*, a simple threshold sets the minimum of the maximum run-off capacity of the channel (i.e. the bottleneck); no river bed morphology is included. In turn, the *Flood flow to flood plain factor* relates this discharge to a flooded delta plain as an increasing multiplier function which is used to compute the *Riverine flooded area fraction*, which is equal to the flood plain factor for now. This relation is extremely straightforward, simply relating a maximum peak flood flow at time *t* to an inundated area. It does not include hydraulic, hydrological, topographic, and other components, and does not consider the total flood peak volume. This simplification was motivated by the current absence of fluvial floods and the scope of the model.

It is assumed that the full discharge through the channel reaches the mouth, i.e. *Discharge delta channel* = *Outflow Ebro delta* (consequentially, we set evaporation and precipitation on the delta plain to null).

Salt wedge dynamics

Figure 6.10 shows the salt wedge dynamics stock-flow diagram. The *Salt wedge position* is determined depending mainly on the discharge, sea level and bed bathymetry which can introduce local sills.
There are basically three positions to where the stratified salt layer penetrates relative to the mouth of the delta, ; debits higher than 342-410 m^3/s wash away the salt wedge completely, discharges between 120-150 m^3/s stop the salt wedge at Gràcia island (18 km), and lower discharges result in propagation to the maximum distance (32 km) (Ibáñez et al., 2020). Additional factors influencing this position are mouth conditions (a high sill obstructs inflow of saline water, dampening the saline intrusion (J. H. Slinger, 2017)), the sea level relative to the river level (A high gradient speeds up saline intrusion. Note however that astronomical tides are negligible; it is SLR and meteorological tides that govern this tidal level), and a memory effect (inertia due to previous positions) (Sierra et al., 2004). The latter is captured

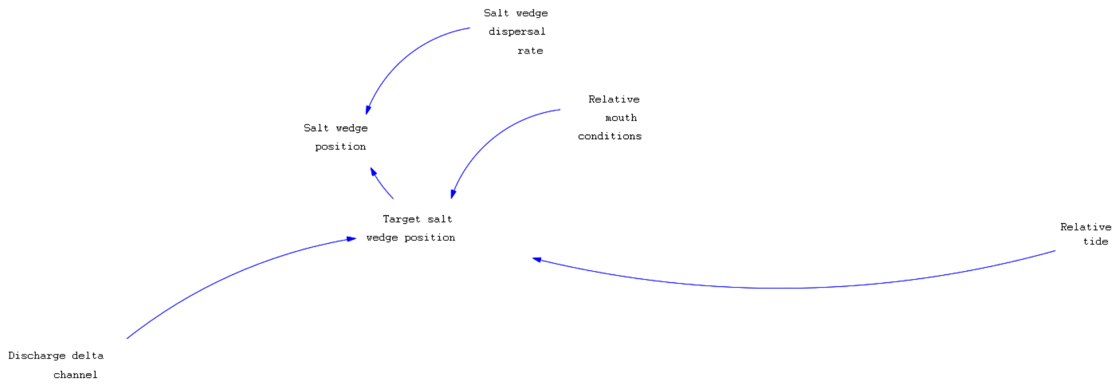


Figure 6.10: Stock-flow diagram of the salt wedge dynamics

with the *salt wedge dispersal rate*, which is a simple time delay, while sea level and mouth conditions are captured through multiplier effects on the discharge (determining a relative discharge). This relative discharge is the input for the *Target salt wedge position* that determines theoretical position based on the discharge thresholds positions. The equations below help to illustrate these relations.

$$Salt\ Wedge\ Position = \frac{Target\ Salt\ Wedge\ Position}{Salt\ Wedge\ Dispersal\ Rate} \qquad [km]$$

$$Target\ Salt\ Wedge\ Position(x) = \begin{cases} 32 & for\ 0 \leq x < 90 \\ 32 - \frac{14}{10}(x-90) & for\ 90 \leq x < 100 \\ 18 & for\ 100 \leq x < 300 \\ 18 - \frac{18}{50}(x-300) & for\ 300 \leq x < 350 \\ 0 & for\ x \geq 350 \end{cases}$$

$$[km]$$

$$x = Relative\ Discharge \qquad [m^3/Month]$$

$$Relative\ Discharge = Relative\ tide\ (CTF_{dec}) \cdot Relative\ Sill\ Height\ (CTF_{inc}) \cdot Discharge\ delta\ channel \qquad [m^3/Month]$$

6.4.3. Sediment

The formalized sediment subsystem is the largest in our model, and essentially describes the journey of sediment particles downstream from the dam compound. The sediment submodel consists of two smaller submodels to improve clarity; the *Channel & delta plain*, and the *Shoreline dynamics*. See figure 6.1 for the graphical representation of the sediment journey, which helps in understanding. First, we discuss how we have simplified the sediment dynamics, after which the two smaller subsets of the sediment submodel will be discussed.

Sediment dynamics simplification

Sediment dynamics are complex, and we have opted to trade broadness of scope for accurate modelling of dynamics, resulting in the aggregation of varying characteristics of sediment particles. First, we aggregate the modes of fluvial sediment transportation, only considering the total sediment load. See

Appendix E for a description of the different modes[2]. This simplification extends to particle behaviour: e.g. coastal deposits primarily consist of fine sand particles (diameter < 0.2 mm), the delta plain of silt and clay (≤ 0.062 mm) (Genua-Olmedo et al., 2022). In conclusion, we consider only one type of sediment of which characteristics, behaviour, and effects are distributed equally. Therefore, we also assume that the sediment is dispersed directly proportional to the discharge, instead of sediment transport capacity being dependent on variables like grain size distribution, discharge, channel profile, vegetation, and others. Note that even with this maximum aggregation, the sediment structure and dynamics constitute most of the formalized model.

6.4.4. Subsystem: Sediment - channel & delta plain

The submodel *Sediment - channel & delta plain* describes the flow of sediment from upstream up to the coastline. Main aspects modelled include the upstream and midstream section (the sediment impounded in the reservoirs and the sediment released downstream to Xerta), the sediment transport on and through the delta (distribution via irrigation canals and river channel), and the subsidence processes (sediment deposits leading to vertical accretion).

Dam compound up to Xerta

Figure 6.11 shows the stock-flow diagram representing sediment from the dam compound up to Xerta.

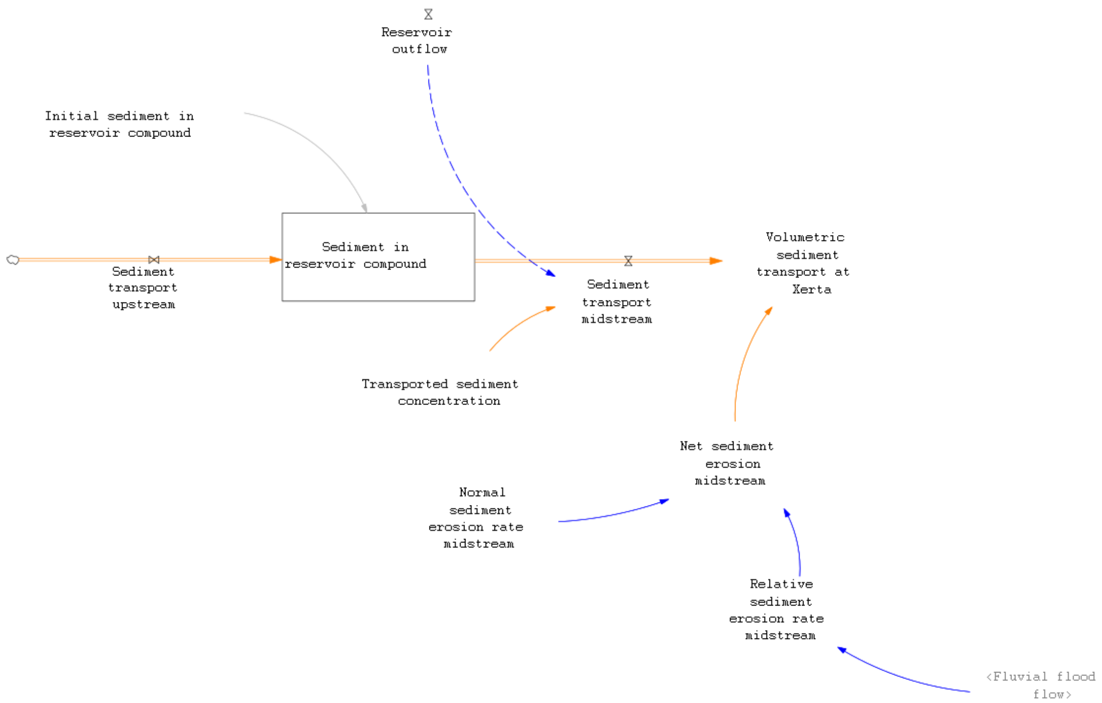


Figure 6.11: Stock flow diagram of sediment from the dam compound up to Xerta

As the dam compound retains >99% of sediment, the *Sediment in reservoir compound* increases rapidly over time through *Sediment transport upstream*. Subsequently, the *Volumetric sediment transport at Xerta* consists of the transported sediment that is passed through the dam, and the sediment that is eroded from the midstream section (mainly from the channel and tributaries).
The transported sediment from the dam compound is determined by multiplying the *Reservoir outflow* times the *Transported sediment concentration* which is still allowed to pass through; this describes

[2]It's important to note that the dam compound retains 100% of the bedload, while any bedload still transported in the river channel results from channel erosion (Vericat & Batalla, 2006)

a heuristic co-flow between fluvial discharge and sediment transport where we assume that sediment transport increases linearly with discharge (See Appendix E.2 for a more accurate relationship). The *Net sediment erosion midstream* is given by constant *Normal sediment erosion rate midstream* times an increasing multiplier effect *Relative sediment erosion rate midstream* acts. This increasing multiplier effect is related to the magnitude of a *fluvial flood flow*.

Sediment transport on and through the delta

Figure 6.12 shows the stock-flow diagram representing the sediment flows through the delta channel, through the mouth, and through the irrigation canals. A sediment particle at Xerta can take three routes. Either it flows through one of the two irrigation canals, or it continues its journey to see through the delta channel, where it may (temporarily) deposit, see figure 6.2. The *Irrigation to discharge ratio* linearly distributes the total *Volumetric sediment transport at Xerta* as was assumed.

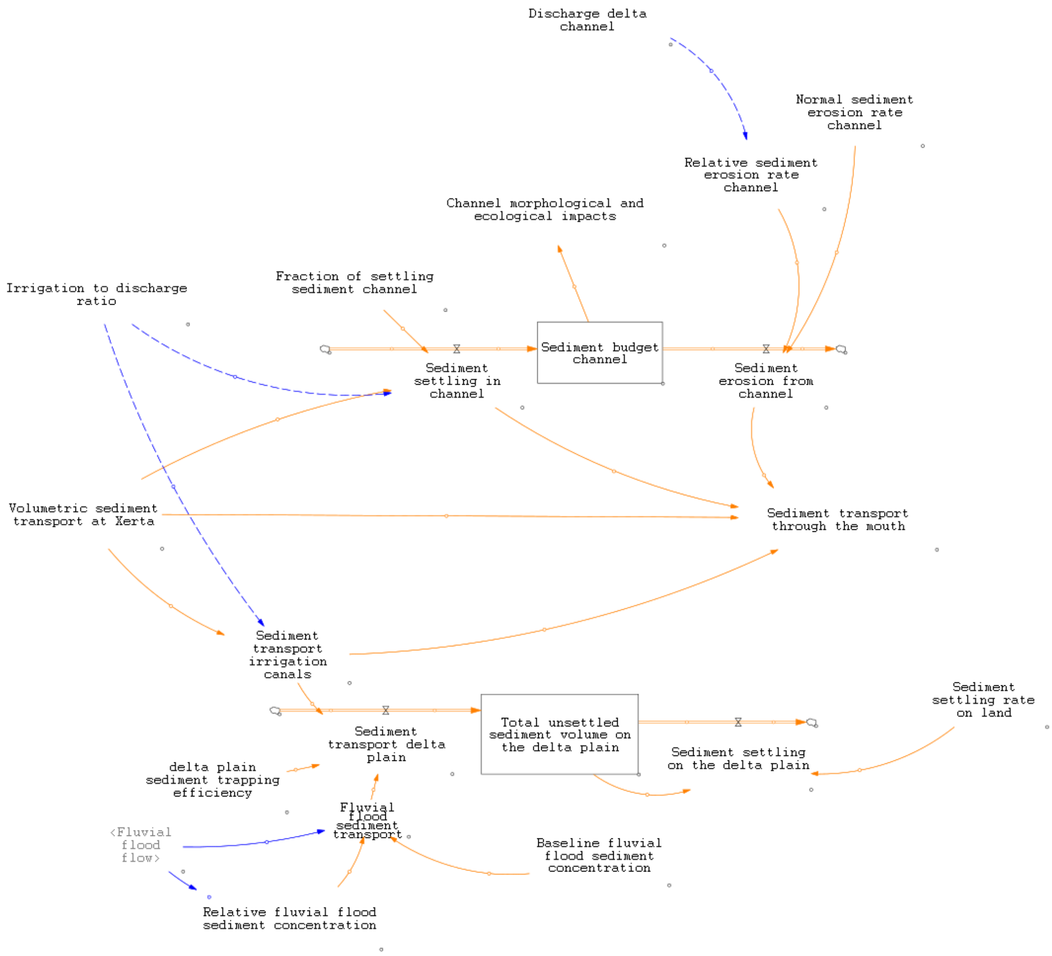


Figure 6.12: Stock flow diagram of the sediment transport on and through the delta

If a grain of sediment is transported through the irrigation canals (*Sediment transport farmland)*, it ends up on the irrigated rice paddies where the *Total unsettled sediment volume on the delta plain* slowly settles due to the slow moving water and sediment trapping effect of crops/vegetation. Thus, we assume 100% of this sediment settles down after a certain delay (*Sediment settling rate on land*), contributing to fertility and vertical accretion of the delta plain.

The grain of sediment travelling through the delta channel has a small chance of settling based on the *Fraction of settling sediment channel*. In reality there is a non-linear relationship between the discharge rate, sediment concentration, profile of the channel, and other variables that govern settling sediment; we chose to simplify as these variations have no important implications for variables of interest. Regardless, over the long-term time horizon, bed morphology achieves a dynamic equilibrium where exported sediment roughly equals imported sediment (Vericat & Batalla, 2006). The sediment budget of a riverbed can be expressed by $I_n - O_n = \Delta S_n$, where I_n describes the incoming sediment in the n^{th} reach, and O_n the outgoing (Vericat & Batalla, 2006). Thus, the flows of *Sediment settling in channel* minus the *Sediment erosion from channel* governs the *Sediment budget channel* in our model. A negative budget is the result of 'hungry water' (i.e. high flows) transporting sediment downstream without upstream replacement ($I_n \approx 0$), leading to geomorphological (e.g. riverbed incision or armouring, where only coarse sediment remains after fine sediments have been eroded) and ecological degradation of the riverbed if left unchecked. These are captured in the *Channel morphological and ecological impacts* multiplier. The erosion in the channel is given by a *Normal sediment erosion rate channel* times an increasing multiplier function *Relative sediment erosion rate channel* related to the *Discharge delta channel*.

Sediment from up to Xerta that has not settled down, OR has been eroded from the channel bed, will eventually be transported out through the mouth. This *Sediment transport through the mouth* will end up at the coastline, where it contributes to a coastal sediment budget. This transport through the mouth is therefore given by the following equation and figure 6.13:

$$\begin{aligned} \textit{Sediment transport through the mouth} = & \textit{ Volumetric sediment transport at Xerta} \\ & - \textit{Sediment transport irrigation canals} \\ & - \textit{Sediment settling in channel} \\ & + \textit{Sediment erosion from channel} \end{aligned}$$

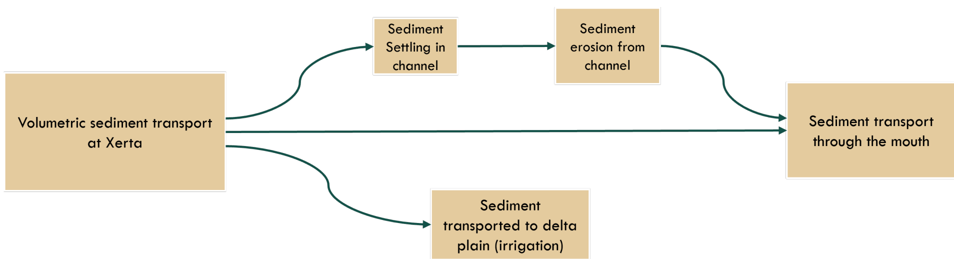


Figure 6.13: Flows of sediment on and through the delta. Flows are scaled to current relative magnitude (not to scale). Note that *Sediment settling in channel* (I_n) - *Sediment erosion from channel* (O_n) = *Sediment budget channel* (ΔS_n)

Subsidence

Figure 6.14 shows the stock-flow diagram depicting processes related to subsidence of the delta plain. Namely, the surface level of the delta plain is determined by the vertical accretion, minus the natural subsidence rate.

Vertical accretion is facilitated through two main mechanisms: sediment (mineral) and organic matter accumulation (Belenguer-Manzanedo et al., 2023; Ibáñez et al., 2010). The former can - besides artificially through irrigation of rice paddies - be achieved naturally through fluvial flooding. Organic decomposition counters subsidence through the decomposition of plant matter (Belenguer-Manzanedo et al., 2023; Ibáñez et al., 2010). Organic matter accumulation can be dis-aggregated into two main components; that originating from natural habitats, and that of crop residues which is tilled back in

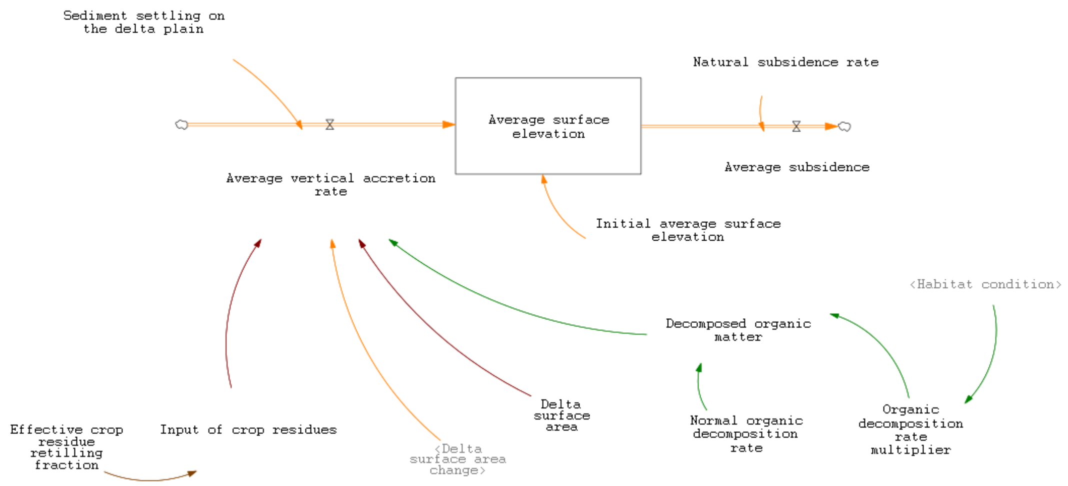


Figure 6.14: Stock-flow diagram of the subsidence processes.

the soil (both also increasing carbon sequestration). Modelling results suggest rice fields and wetlands are relatively comparable in terms of vertical accretion rates in the Ebro delta, where 100% of straw is tilled back into the soil since 1990 (Belenguer-Manzanedo et al., 2023)[3]. Organic and mineral accumulation are synergetic: sediment accumulation provides nutrients and an additional hazard buffer, while vegetation (natural and crop) increases sediment trapping efficiency.

We capture these effects by dividing the volume of incoming mineral and organic matter by the total surface area to attain the *Average vertical accretion rate* of the *Average surface elevation*. Average, because SDM does not allow us to model spatially heterogeneous accretion rates; we divide by the total delta plain for both mineral and organic matter accumulation. Here, these volumes are normalized in relation to the accretion rate, meaning dividing by the area yields the correct accretion for each component. This normalization accounts for the different densities of the components. Thus, the normalisation captures the proportional difference in the rates of accretion between respective mechanisms. Organic matter input is calculated with an increasing multiplier function *Organic decomposition rate multiplier* based on the *Habitat condition* input. Subsequently, only the *Natural subsidence rate* determines the speed of subsidence (*Average subsidence*) as no water other resources are extracted from the delta subsoil, meaning artificial subsidence can be set to zero (Rodriguez-Lloveras et al., 2020). The equations below help clarify the computation of the *Average vertical accretion rate*:

$$\begin{aligned} \textit{Average vertical accretion rate} &= \frac{\textit{Normalized input volume rate}}{\textit{Surface area}} && [m/Month] \\ \textit{Normalized input volume rate} &= \textit{Sediment settling on the delta plain} && [m^3/Month] \\ &+ \textit{Input of crop residues} \\ &+ \textit{Decomposed organic matter} \\ \textit{Surface area} &= \textit{Delta surface area} - \textit{Delta surface area change} && [m^2] \end{aligned}$$

[3]However, restoring wetland habitats in the most vulnerable rice fields could be an effective strategy to mitigate SLR (and promote carbon sequestration). This is supported by evidence showing that accretion in rice fields converted back to wetlands can reach significantly higher rates temporarily, primarily due to the accumulation of organic matter following the establishment of plant communities

6.4.5. Subsystem: Sediment - coastal dynamics

The submodel *Sediment - Shoreline dynamics* describes the flow of sediment from upstream up to the coastline. Main aspects modelled include the coastal sediment budget and the natural flood defence capacity (which relies heavily on sediment). As this part of the formalisation takes a while to build, we first provide a summary. Following, the formalisation of main modelled aspects is discussed. To clarify the progression of the argumentation, we will first discuss the formalization of natural flood defence capacity and then work back to the coastal sediment budget.

Summary of main aspects modelled

After sediment has been transported through the mouth, it contributes to a coastal sediment budget, which increases resilience against coastal processes. We are essentially looking to capture two main aspects. Firstly, how to capture the capacity of the coastal flood defence and the change in capacity because of a deficit in sediment, and secondly, how to quantify the resulting change in capacity. Below, our conceptualisation of these aspects is summarized.

- **Relative natural flood defence capacity**
  We conceptualize the natural flood defence capacity as a buffer zone consisting of beaches, dunes, and wetlands that absorb and dissipate coastal processes. The unit of analysis used is surface area, where a negative change in surface area represents coastal retreat. I.e. we use a change in the surface area of these assets to determine the relative capacity change of the natural flood defence. Coastal vegetation increases the dissipating capacity of the natural flood defence. A deficit in sediment means erosive processes dominate, degrading the flood defence capacity.
- **The coastal sediment budget**
  To quantify the change in surface area of beaches (which lie at the forefront of the shoreline) we relate the change to a volume of sediment; the coastal sediment budget. Here, we focus on net erosive stretches of coast. These erosive stretches are the most vulnerable points, and therefore determine the maximum flood defence capacity. The sediment budget of the erosive zone is given by splitting the total sediment budget of the coastline into the sum of eroding stretches, and the sum of accreting stretches.
- **Relation between flood defence and sediment budget**
  The sediment budget can be related to a sediment deficit, namely, if the sediment budget of the erosive zone = 0, then the erosion = 0, and the sediment deficit = 0; the coastline neither retreats nor progrades. A stable coastline equals a stable flood defence in this conceptualisation (keeping all other variables constant).

The natural flood defence capacity

Reducing the complexity of natural flood defences into a few variables that still capture their effectiveness requires some significant assumptions. Our goal is to compute a simple flood defence capacity and determine if it can withstand storm-induced hydraulic loads and wave overtopping. The variable we use is based on relative surface area, allowing us to combine the effects of sandy and vegetated habitats into one measure of capacity that can be compared to a baseline. First, we explain the basics of how natural flood defences function and how mainly erosive processes threaten this functioning, after which we will construct our conceptualisation.

Regulating ESS for coastal flood protection can either absorb or dissipate coastal processes, resulting in coastal protection and erosion control. Whereas dunes primarily fulfil the function of man-made barrier structures like dikes that absorb and store excess water during high tides and storm surges, vegetated habitats like salt marshes or wide beaches can dissipate wave energy, reducing their intensity and erosive force (Barbier et al., 2011; Toimil et al., 2023; Vuik et al., 2016). Essentially, the combined dune, beach and wetland system provides a buffer zone that protects the hinterland and accommodates for inward shoreline translation caused by the combined impact of storms and RSLR. As erosion degrades the buffer, the coupling of flooding and erosion of these systems over time is crucial for assessing beach protection benefits (Toimil et al., 2023). Appendix F discusses natural flood defences in more detail.

To conceptualize this, we classify two components that together form the total relative coastal flood defence: 1) a sandy coastal flood defence stock which consolidates the beach and dune system, and 2) a vegetated coastal flood defence stock which consolidates coastal vegetated habitats. This relative coastal flood defence is related to the most vulnerable points, i.e. the erosive coastline sections, as we are interested in potential failure and a chain is no stronger than its weakest link. The Ebro coastline is a mosaic stretch of net accreting and net erosive sections which are the result of both morphology and coastal processes, see Appendix B.3. The summation of these erosive stretches determines the total coastline erosion in retreat, which can be directly related to a volumetric sediment deficit (sediment deficit = 0 if erosion = 0).

Figure 6.15 shows the stock-flow diagram depicting the components of the natural flood defence, which are a sandy and vegetated habitat stock primarily.

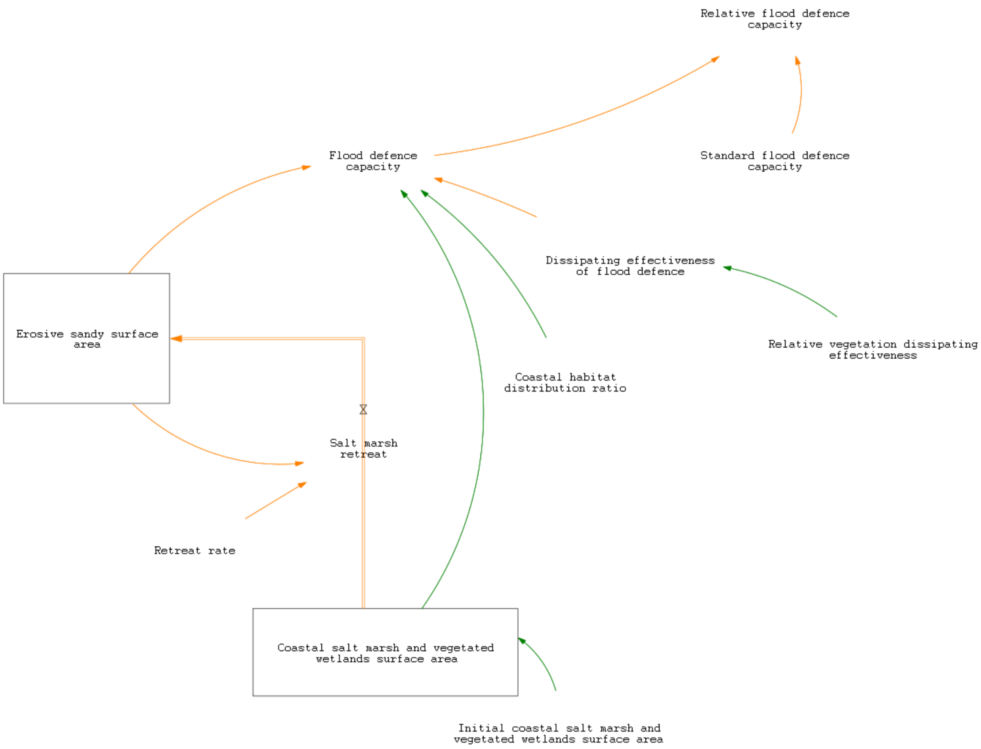


Figure 6.15: Stock-flow diagram of the natural flood defence.

The unit used to represent relative coastal flood defence is relative surface area (both for the sandy and vegetated components). Our choice for representation by relative surface area has three reasons; Firstly, this simplification allows us to reduce a complex three-dimensional engineering problem to two homogeneous and relatable variables. Secondly, a unit of analysis that is commonly observable (Surface area loss of natural flood defence assets is readily monitored) enables a comprehensive and communicative assessment. Thirdly, we can comparatively easily translate a change in the volume of sediment to a corresponding surface area gain or loss; i.e. compute a sediment surplus or deficit. The volume change is related to the balance of inflows (accretion) and outflows (erosion) of sediment in the coastal section under inquiry. To summarize, we can link the surface area change - which is directly related to erosion - to a change in the *relative* flood defence capacity.

We consider the vegetated coastal habitats to be slightly more effective in their flood defence capacity as the vegetation of dunes and coastal salt marshes provides a wave attenuating effectiveness increase, see Appendix F. Additionally, as in the Ebro delta the beaches are in front of salt marshes primarily, erosion and accretion initially affect the sandy coastal flood defence. If coastal retreat leads to the degradation of sandy coastal flood defence and nears null (i.e. $0\ m^2$), the vegetated habitats will degrade to beach as the vegetation cannot withstand the shore frontline conditions. In other words, surface area of the vegetation stock converts to sandy stock through a flow. To compute the *Flood defence capacity*, we add the sandy (A_s) and vegetated (A_v) area, where a multiplier (α) favours the latter and is for this research only based on *Relative vegetation dissipating effectiveness*.

Finally, in order to compute the relative capacity of the flood defence, the comparison with a functional standard or baseline needs to be made. Thus, dividing the *flood defence capacity* by the *Standard flood defence capacity* yields the *relative flood defence capacity* The final equation determining the relative flood defence capacity is given below, and is visualized in figure 6.16.

$$\begin{aligned}
\textit{Relative flood defence capacity} &= \frac{\textit{Flood defence capacity}}{\textit{Standard flood defence capacity}} && [m^2] \\
\textit{Flood defence capacity} &= A_s + \alpha A_v && [m^2] \\
&\textit{where:} \\
A_s &= \textit{Erosive sandy surface area} && [m^2] \\
A_v &= \textit{Coastal salt marsh and vegetated wetlands surface area} && [m^2] \\
\alpha &= \textit{Dissipating effectiveness of flood defense} && [no\ unit] \\
&= \textit{Relative vegetation dissipating effectiveness } (CTF_{inc})
\end{aligned}$$

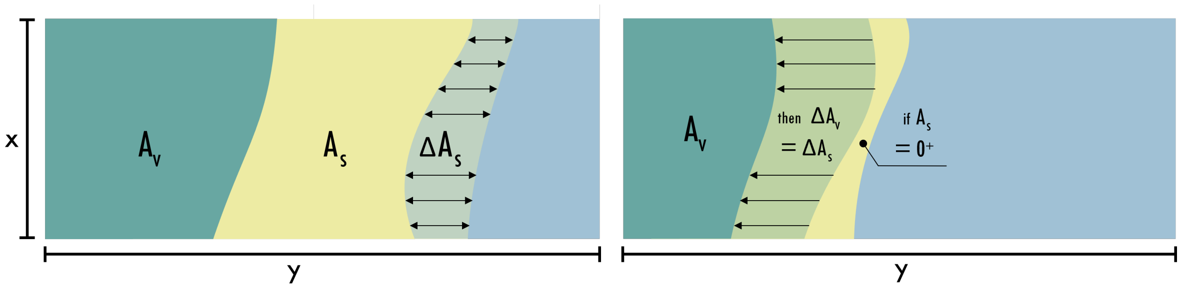


Figure 6.16: Conceptualisation of relative flood defence capacity as a function of sandy (A_s) and vegetated (A_v) surface area (change). If A_s is almost zero, A_v starts degrading to sandy shoreline.

The coastal sediment budget

In coastal science and engineering, the sediment budget is fundamental. The most important concepts and definitions have been summarized and streamlined by Rosati (2005), which we will use in this paragraph. The sediment budget is defined as the "balance of volumes (or volume rates of change) for sediments entering (source) and leaving (sink) a selected region of coast, and the resulting erosion or accretion in the coastal area under consideration". Expressed in consistent variables, it describes the difference between the sources and sinks equalling the sediment volume change (rate) ΔV of a specific coastal stretch or 'cell', see equation 6.1. Herein, we assume Residual equals 0 and the equation is balanced (i.e. no measurement errors or unconsidered processes).

$$\sum Q_{\text{source}} - \sum Q_{\text{sink}} - \Delta V + P + R = \textit{Residual} \qquad [m^3] \tag{6.1}$$

where:

$$\sum Q_{\text{source}} = \textit{Sum of inflows} \qquad [m^3]$$
$$\sum Q_{\text{sink}} = \textit{Sum of outflows} \qquad [m^3]$$
$$\Delta V = \textit{Net change in volume} \qquad [m^3]$$
$$P = \textit{Sum of artificial deposition} \qquad [m^3]$$
$$R = \textit{Sum of artificial removal} \qquad [m^3]$$
$$\textit{Residual} = \textit{Degree to which cell is balanced} \qquad [m^3]$$

In this context, non-exhaustive examples of sources can be incoming longshore or cross-shore sediment transport, river sediment, sand nourishment, and relative sea level declines. Sinks, on the other hand, may be outgoing longshore or crosshore sediment transport, dredging, and RSLR. *Net* transport rates[4] can be determined by using sums of sources and sinks, where for instance the (non-directional) net longshore sediment transport (rate) is the difference between the source and sink longshore transport (rates) over a time interval. Translating equation 6.1 into an illustrative figure representing the components of a coastal sediment budget yields figure 6.17.

Rosati (2005) proposes the concept of the macrobudget. The macrobudget essentially collapses all cells under study into one large cell to attain a quantitative balance of a larger coastal region, encompassing the entire longshore and cross-shore extents of interest. We adopt a slightly adapted version of his concept to assess the sediment deficit of the Ebro delta coastline. Our version defines two halves of the macrobudget: the erosive zone (where coastal processes mainly erode sediment from beaches) and the accretion zone (where sediment is mainly accreted) as argued for in the paragraphs on flood defence capacity. In this context, the accretion zone can be seen as a large sink *within our boundary* where sediment accretes, meaning the sediment is not lost to the macrobudget. The sediment budget of the erosive zone (which is essentially the sediment deficit) can be computed by calculating the difference between sources and sinks. If the sediment transport into the erosive zone is larger than the erosive processes taking it back out, a negative deficit (surplus) results in a prograding delta[5]. The main source in our conceptualisation is the sediment originating from the Ebro river. Eroded sediment that is not transported out of our system boundary (by either cross-shore transport or longshore drift) ends up in the accretion zone sink (most of it in the Northern and Southern spits). Sediment that is transported outside the boundary is truly 'lost' and reduces the macrobudget. This conceptualisation results in equation 6.2, and is visualized in figure 6.18:

[4] the *gross* transport rate relates to the total and absolute volume of sediment transported both left and right

[5] A negative deficit or neutral budget could be a target for policy

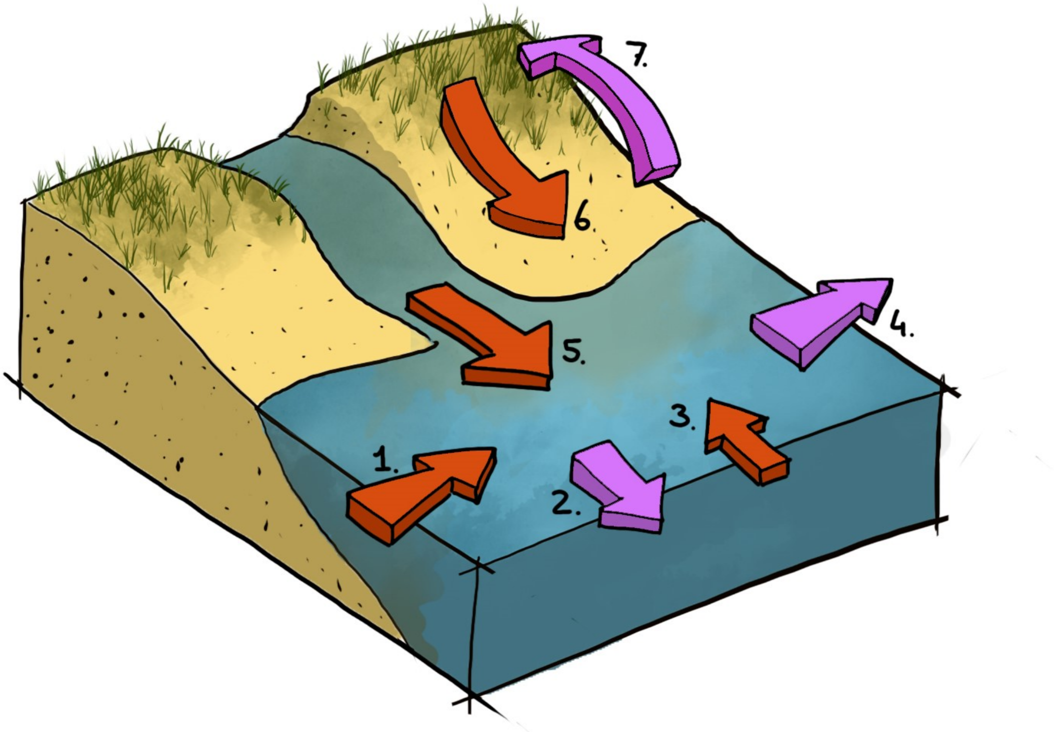


Figure 6.17: Basic components of a coastal sediment budget. In red the sediment flows gained by the beach section, and in purple the sediment lost from the beach section. 1 = longshore drift into system. 2 = Offshore transport by waves and currents (especially during storms). 3 = Shorewards transport by waves and currents. 4 = Longshore drift from system. 5 = Sediment from river channel. 6 = Dune erosion; sediment redistributed from dunes to beach during/after storms. 7 = Wind transport or wave washover.

$$\Delta V_E + \Delta V_A = \Delta V_I - \Delta V_O \quad = \text{Macrobudget} \quad [m^3] \tag{6.2}$$

where:

$$\Delta V_E = \Delta V_I - \Delta V_A - \Delta V_O \quad = \textit{Sediment budget erosive zone} \quad [m^3]$$

$$\Delta V_A = \Delta V_{\text{drift}} \quad = \textit{Sediment budget accreting zone} \quad [m^3]$$

$$\Delta V_I = \sum Q_{\text{source}} \quad = \textit{Net incoming sediment transport} \quad [m^3]$$

$$\Delta V_O = \sum Q_{\text{sink}} \quad = \textit{Net outgoing sediment transport} \quad [m^3]$$

In this conceptualization, the accreting zone represents the accumulation of sediment eroded from the erosive zone. Thus, only the *Net sediment longshore drift* (or drift) (ΔV_{drift}) from the erosive zone to the accreting zone defines the change in volume.

Equation 6.1 can be applied to solve for volume change magnitudes and rates with estimates of net longshore transport rates, which allows us to estimate the respective shoreline change magnitudes and rates. Namely, for a given coastal transect, the volumetric shoreline change rate ΔV can be related to the rates of shoreline change, assuming horizontal translation of the shoreline without alteration of its shape over an active depth (A_D). The active depth represents the vertical extent of the beach profile that

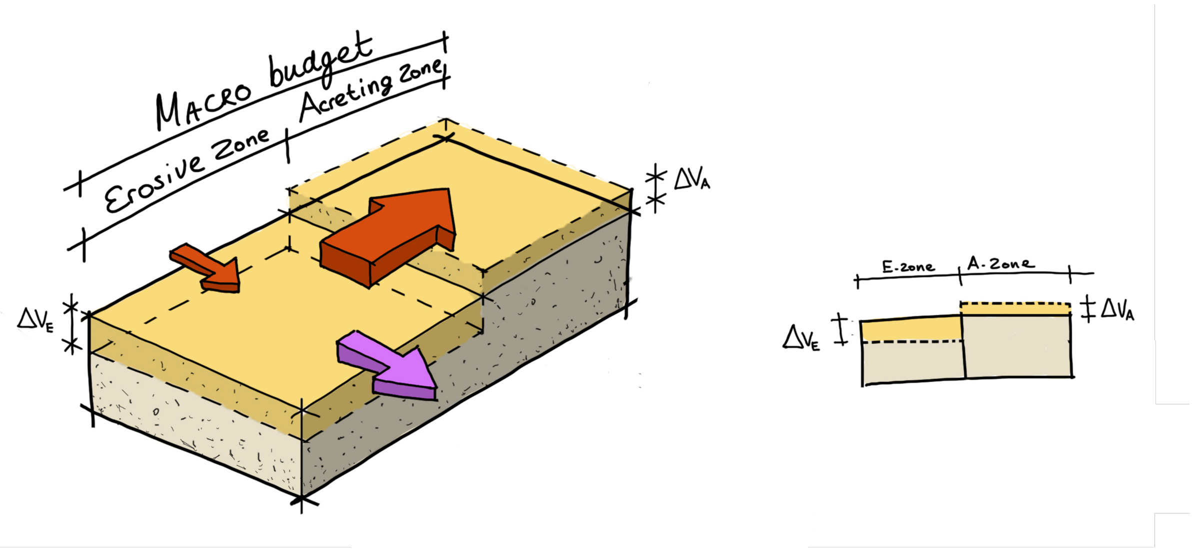


Figure 6.18: The erosive zone and accreting zone making up the macrobudget in the Ebro delta. Currently, only a small volume of sediment ΔV_I is transported to the coast, represented by the small red arrow. Longshore erosion transports a larger volume of sediment (ΔV_A) from the erosive zone to the accreting zone. The purple arrow represents the volume of outgoing sediment ΔV_O, which is a true sink. The macrobudget represents the change in volume of sediment stored in the Ebro delta coastline.

is eroding or accreting. Typically, it is defined as the sum of the berm crest or dune elevation (B) and the closure depth (D_c), which marks the theoretical depth line along a beach profile at which sediment transport is very small or non-existent.

$$\Delta V = \Delta x \Delta y A_D \qquad [m^3] \qquad (6.3)$$

where:

$$\Delta x = \text{Transect spacing} \qquad [m]$$
$$\Delta y = \text{Shoreline change rate} \qquad [m]$$
$$A_D = B + D_c = \text{Active depth} \qquad [m]$$

Given that we have set our flood defence capacity to a relative surface area, we are not interested in the beach profile width change but rather an aggregated surface area change of the *Erosive sandy surface area*. This yields equation 6.4.

$$\Delta A_E = \Delta x \Delta y \qquad (6.4)$$

We now have all information needed to calculate the surface area change of the beach profile. As we are interested only in the eroding beach profiles (representing the weakest link in the flood defence, thereby governing the flood defence capacity), the sediment budget of the erosive zone is used to solve for the surface area change rate of the eroding beach profile. Merging our conceptualisation (flood defence equals a certain surface area), and equation 6.1 to 6.4 (setting *P* & *R* to zero) yields equation 6.5 which describes the surface area change rate of the erosive beach profile. Erosion is accelerated by relative coastal dynamics (tidal level and wave impacts), i.e. through a multiplier effect.

$$\Delta A_E = \frac{\Delta V_E}{A_D} = \frac{\Delta V_I - \Delta V_A - \Delta V_O}{B + D_c} \qquad (6.5)$$

Finally, we can specify the conceptualisation. Figure 6.19 shows the stock-flow diagram of the macrobudget and related coastal retreat.

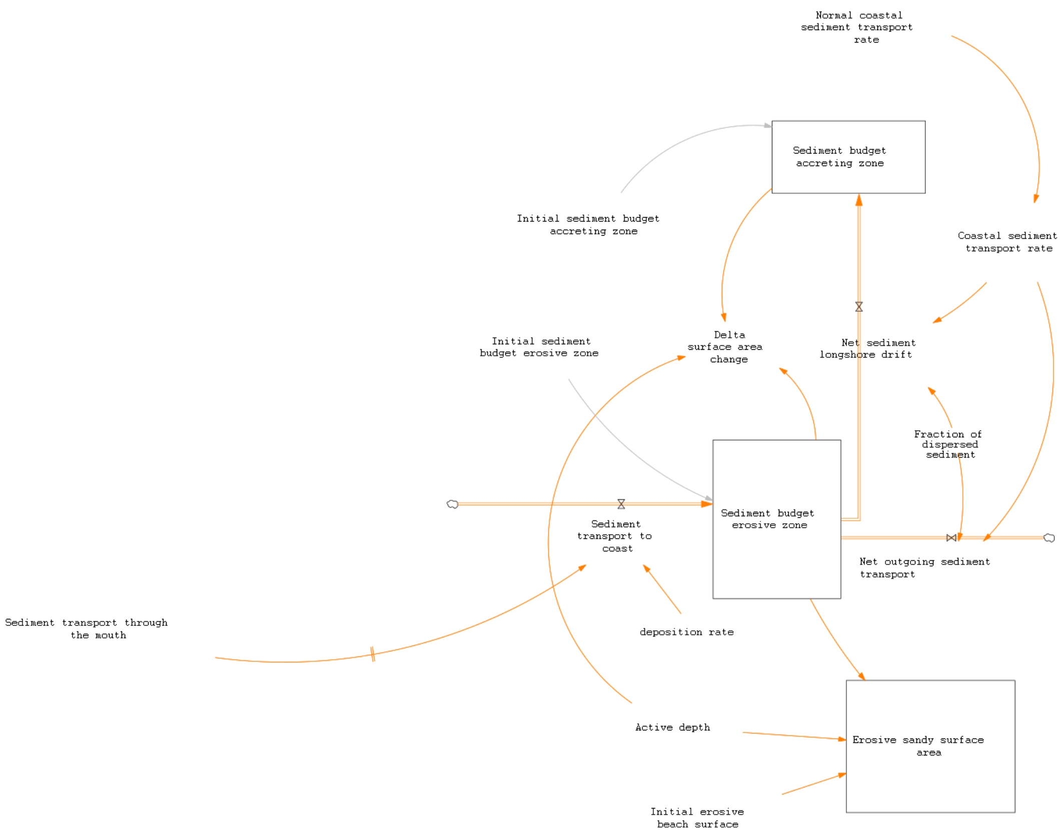


Figure 6.19: Stock-flow diagram of the macrobudget (given by the*Sediment budget erosive zone* + *Sediment budget accreting zone*). The *Sediment budget erosive zone* is used to calculate the coastal retreat expressed in the *Erosive sandy surface area*.

The coastal retreat is represented by the change in the variable *Erosive sandy surface area*, and is calculated by dividing the *Sediment budget erosive zone* by the *Active depth* (in this way the total *Delta surface area change* is calculated as well). The *Sediment transport to coast* represents the only source, and is given by the *Sediment transport through the mouth* with a small delay Deposition rate as sediment takes a while to deposit. Not all sediment deposits, but in the conceptualisation we aggregate the sediment sink transport *Net outgoing sediment transport*, i.e. the sediment that is directly transported to the sink, or the sediment that deposits, then erodes, then is transported to the sink. The *Fraction of dispersed sediment* sets the distribution of transported sediment to the *Sediment budget accreting zone* via the *Net sediment longshore drift* (sink within boundary macrobudget) and *Net outgoing sediment transport* (sink outside boundary macrobudget). The rate of transport is determined by a multiplier effect, see the paragraphs on the flood defence and the coastal processes.

6.4.6. Coastal processes & climate effects

The coastal processes & climate effects submodel describes the dynamics of the coastal processes and how climate impacts exacerbate these processes. Main aspects modelled include the processes acting on the shoreline, their interaction with the shoreline, marine flooding & consequences of marine flooding, and finally the impacts of climate change.

Shoreline shaping processes

Figure 6.20 shows the stock-flow diagram of the main coastal processes, describing wave energy and mean-water-level oscillations as the primary shoreline shaping processes,

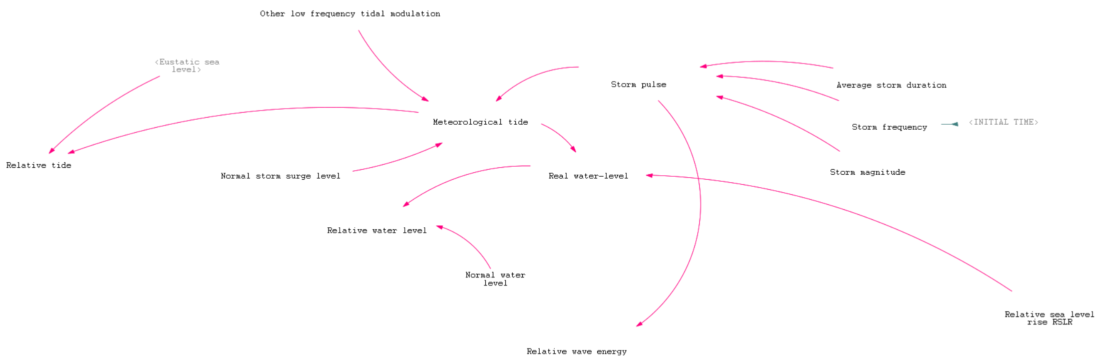


Figure 6.20: Stock-flow diagram depicting the relative wave energy and water-level.

The main processes acting on the shoreline are either waves or mean-water-level oscillations (or their synergetic action) (Grases et al., 2020; Jiménez et al., 1997). Wave energy and direction are influenced by meteorological conditions (i.e. heavy winds, storms, low frequency tidal modulation). We opt to aggregate all wave characteristics (magnitude, direction, frequency, etc) into one *Relative wave energy* multiplier. The mean-water-level is primarily governed by either meteorological tides or RSLR as the Mediterranean is microtidal. Real water-level is related to a *Relative water-level* multiplier for calculations. Note that to capture the increasingly significant impacts of wave energy and mean water-level at higher values, their respective multipliers require a high upper asymptote. Namely, with sufficiently high RSLR or storm magnitudes, the probability of flooding will approach 100% (even with improved natural flood defences).

The relative magnitude of the above multipliers is affected by meteorological processes. Namely, storms raise both wave energy and mean-water-level (through the storm surge). We define storms as pulses; the *Storm pulse* is simply given by a *Storm frequency*, an *Average storm duration*, and a *Storm magnitude*. Other meteorological processes are aggregated in the *Other low frequency tidal modulation* variable.

Interaction with the shoreline

Figure 6.21 shows the stock-flow diagram of the influence of the main coastal processes on the shoreline through inducement of flooding and erosion.
The main influence that the coastal processes exert on the coastline is by inducing flooding risks and by accelerating erosion. Two main ways govern flooding. Either the coastline directly exposed to coastal processes fails, or the inland coastal defence fails due to RSLR, as there are no significant coastal meteorological influence acting on the sheltered bay/lagoon area (The coastal lagoons are connected to the sea, aligning their water-level. While basic dikes currently protect inland areas from rising sea levels, they may become inadequate as sea levels continue to rise). Note again that we see the *Relative flood defence capacity* as the capacity of the most vulnerable points, see section 6.4.5. A simple threshold determines risk of failure; if hydraulic loads (wave energy and water-level) are bigger than the capacity, the flood defence fails. A similar threshold is adopted for inland crest height overtopping

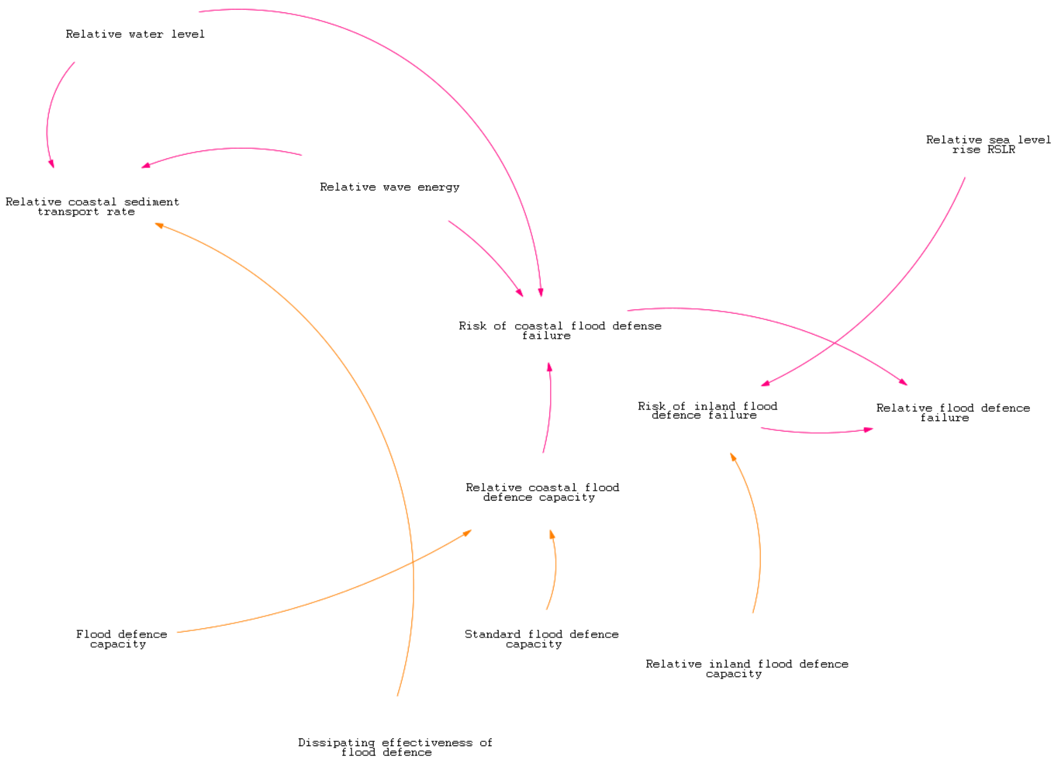


Figure 6.21: Stock-flow diagram depicting the interaction of main coastal processes with the shoreline.

(RSLR > *Flood defence of inland bays*).

Waves are the primary mechanism driving erosion (Grases et al., 2020; Jiménez et al., 1997). However, while high water levels can dampen the impact of wave trains on the seabed, mean water levels still synergize with wave action by effectively increasing wave heights. This enables waves to reach more vulnerable parts of the coastline, exacerbating dune erosion. Thus, the coastal processes act as erosion-accelerating, meaning relative increase in either will also relatively increase erosion (although more so for wave energy increase). The balancing element in this equation is the wave-dissipating effectiveness of the coastal flood defence. Moreover, sediment trapping efficiency is increased by vegetation, see Appendix F. The final equations determining the *Relative coastal sediment transport rate* ($Relative\ V_{drift}$), the *Risk of coastal flood defence failure* ($Risk_{coastal}$), and the *Risk of inland flood defence failure* ($Risk_{inland}$) are given below.

$$
\begin{aligned}
Relative\ V_{drift} &= F_{\text{wave}} \cdot F_{\text{level}} - \alpha && [no\ unit] \\
Risk_{coastal} &= F_{\text{wave}} \cdot F_{\text{level}} - U_{\text{coastal}} && [no\ unit] \\
Risk_{inland} &= RSLR - U_{\text{inland}} && [m] \\
&\textit{where:} \\
F_{\text{wave}} &= Relative\ wave\ energy\ (CTF_{inc}) && [no\ unit] \\
F_{\text{level}} &= Relative\ water\text{-}level\ (CTF_{inc}) && [no\ unit] \\
U_{\text{coastal}} &= Relative\ coastal\ flood\ defence\ capacity && [no\ unit] \\
U_{\text{inland}} &= Relative\ inland\ flood\ defence\ capacity && [m] \\
\alpha &= Dissipating\ effectiveness\ of\ flood\ defence && [no\ unit]
\end{aligned}
$$

Risk of coastal flood defence failure ($Risk_{coastal}$) and the *Risk of inland flood defence failure* ($Risk_{inland}$) are used to collectively compute the total risk of failure (which can't go negative).

$$\textit{Relative flood defence failure} = \max\{0, (Risk_{coastal} + Risk_{inland})\}$$

Climate impacts

Figure 6.22 shows the stock-flow diagram of the impacts of climate change, mainly describing RSLR and extreme climate conditions.

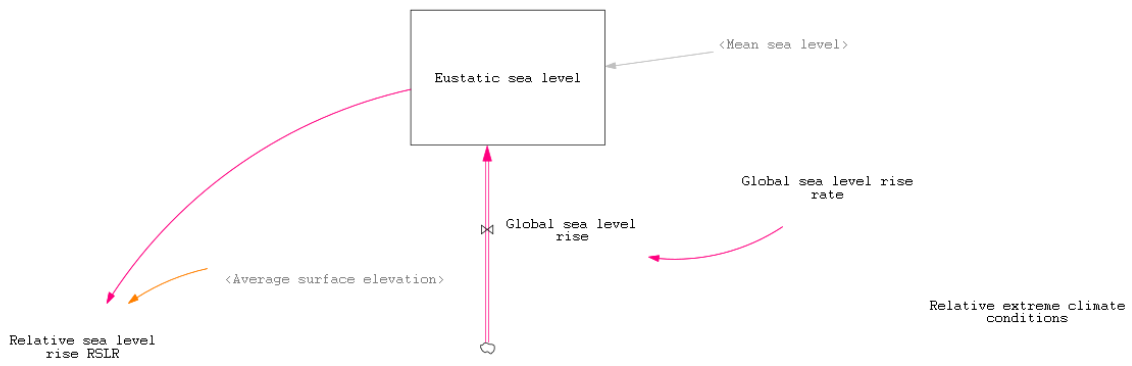


Figure 6.22: Stock-flow diagram of climate impacts. The *Relative extreme climate conditions* acts at different locations in the model, but has been included in the screenprint for clarity.

Climate effects do three main things: they increase SLR, they increase storm magnitude and frequency, and they increase the increasing multiplier *Relative extreme climate conditions* which impacts various other variables in the model through drought, temperatures or heavy rainfall. RSLR is given by substraction of *Average surface level elevation* of the delta plain from *Eustatic sea level*, relative to a baseline set to 0. The increase in storm magnitude and frequency is not captured within the model, but would include *external* preset (or randomly set) climate scenarios affecting storm surges.

Marine flooding

Figure 6.23 shows the stock-flow diagram of marine flooding and resulting consequences, describing flooded area, safety, and perceived safety.

If a larger section of the delta surface level is below sea level, the inundation potential of a flood increases (CEDEX, 2021), which we captured in the variable *Loss of land above sea level per m SLR*. This potential also increases if the flood is allowed to propagate further inland. The latter is mainly facilitated by the conduit effect that the irrigation canals have, which we captured in the increasing multiplier *Irrigation canal amplification*, see also Appendix B.1. A function of these thereby determines the *fraction of flood-susceptible land*. To account for the magnitude of failure, we multiply this fraction with *Relative flood defence failure*, which is normalized (value between 0 and 1.25) to determine the actual *fraction of flooded surface area*, as the magnitude of the storm surge strongly relates to flooded area (Grases et al., 2020). The normalisation scaling surpasses 100% (125%) as extreme events can also inundate insusceptible land if storm surges are sufficiently high. See the equation below that helps clarify this paragraph.

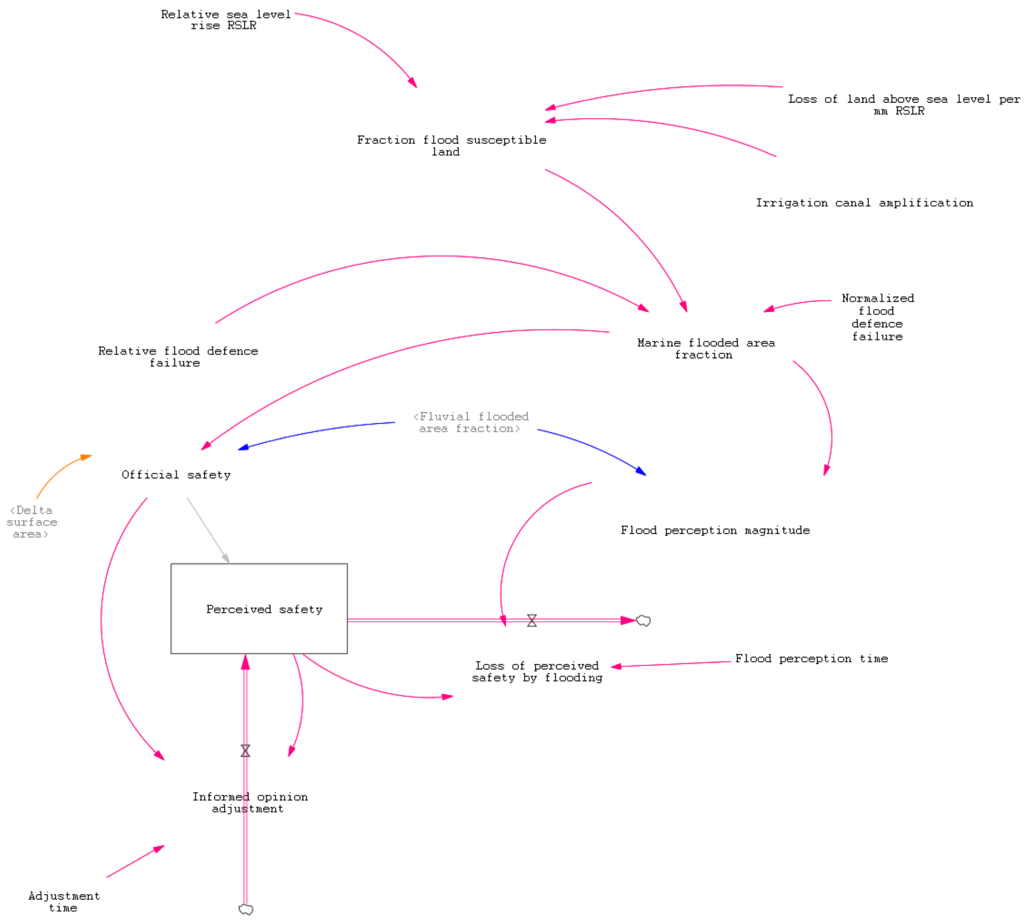


Figure 6.23: Stock-flow diagram of marine flooding, official safety, and perceived safety

$$\begin{aligned}
\textit{Marine flooded area fraction} &= \min\left\{1.25, \left(\frac{\textit{Relative flood defence failure}}{\textit{Normalized flood defence failure}}\right)\right\} && [\textit{no unit}]\\
&\quad \cdot \textit{Fraction flood susceptible land}\\
&\textit{where:}\\
\textit{Fraction flood susceptible land} &= && [\textit{no unit}]\\
&\quad \textit{RSLR} && [m]\\
&\quad \cdot \textit{Loss of land above sea level per m RSLR} && [1/m]\\
&\quad \cdot \textit{Irrigation canal amplification } (\textit{CTF}_{inc}) && [\textit{no unit}]
\end{aligned}$$

In the event of a flooding, there is a physical and a psychological consequence. Physically, there is a loss of (official) safety, besides direct and indirect damage to ecosystems, agriculture, and the built environment. This is captured within a decreasing multiplier *Official safety*, which has as input the sum of fluvial and marine flooded area. Psychologically, there is a loss of *Perceived safety*. Perceived safety accumulates towards a level where is matches the *Official safety*. In the absence of floods, residents feel assured and secure. However, when a flood strikes (fluvial or marine), the degree of perceived safety drops abruptly, relative to its magnitude. Subsequently, confidence gradually rebuilds during periods without floods. The distinction between the two types of safety, and the SD modelling of the dynamics of perceived safety are adapted from Klein et al. (2016). For an extended explanation of this mechanism, see their work. In the model, physical or official safety is inversely proportional to the fraction of flooded surface area (therefore the *decreasing* multiplier for *Official safety*. When 100% of the surface area is flooded, the safety level is 0%.

6.4.7. Agriculture

The agriculture submodel mainly models the magnitude of the rice sector and its output, and how different impacts affect this output. Main aspects modelled include the annual rice production, the average paddy productivity which leads to this production, and the average soil salinity which is a component of average paddy productivity.

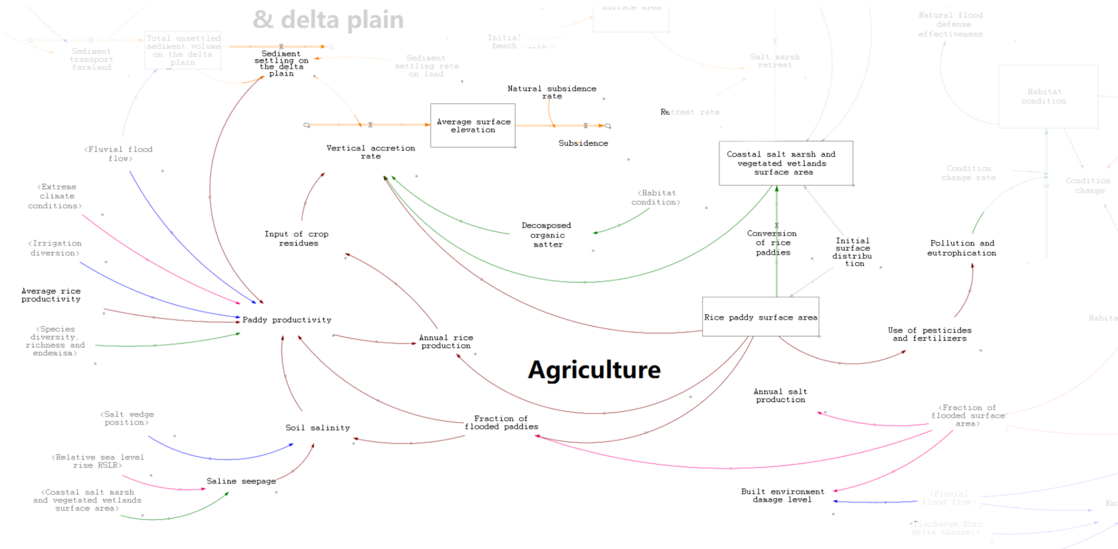


Figure 6.24: Subsystem agriculture

Annual rice production

See figure 6.25, which shows the stock-flow diagram of the annual rice production, describing total production as a function of productivity and surface area, physical crop damage from flooding, and the input of crop residues for vertical accretion.

As rice constitutes more than 80% of agricultural practices in the Ebro delta, we model this crop exclusively. The main structure that governs *Annual rice production* is the total *Rice paddy surface area*, multiplied by the *Average paddy productivity* per hectare. . Herein, we additionally include no delays or crop cycles for simplicity. That means we compute a theoretical constant rice productivity output at time t (it has no memory of past events). This also means any physical impacts of flooding are instant, and do not perpetuate over time.

Flooding is assumed to instantly damage the rice crop, where we additionally assume fraction of flooding over the entire delta plain equals fraction of flooding of the rice fields (i.e. equal distribution). Furthermore, we do not make a distinction between fluvial and marine flooding for *physical* damage to the crop (marine flooding increases soil salinity while fluvial flooding decreases it). The equations below help clarify the above:

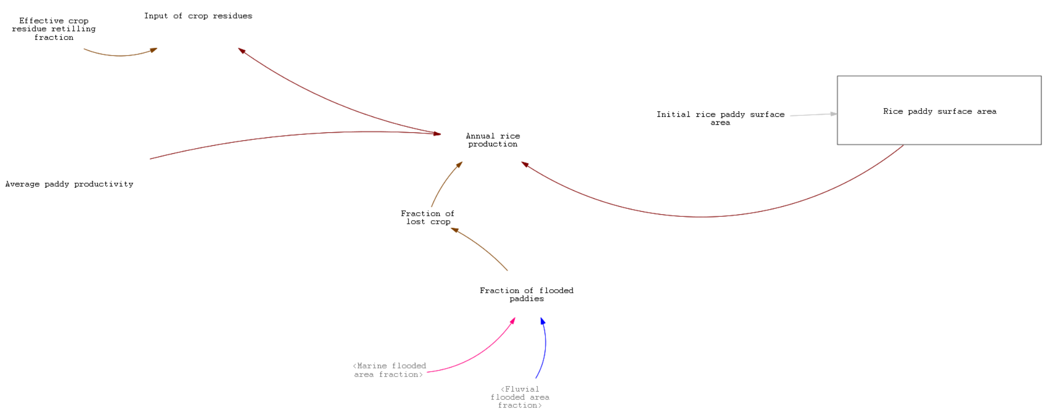


Figure 6.25: Stock-flow diagram of the annual rice production

$$\begin{aligned} \textit{Annual prod.} &= (1 - \%\ \textit{of lost crop}) \cdot (\textit{Avg. productivity} \cdot \textit{Paddy surface area}) \quad [mT/Month] \\ &\textit{where:} \\ \%\ \textit{of lost crop} &= \textit{Fraction of flooded paddies} \quad [\textit{no unit}] \\ &= \textit{Marine flooded area fraction} + \textit{Fluvial flooded area fraction} \end{aligned}$$

As was discussed in the subsidence component of the sediment submodel, rice yields not only improve economic output but also, depending on the quantity of organic matter tilled back in the soil, improve vertical accretion rates Belenguer-Manzanedo et al. (2023). Through this vertical accretion, rice fields decrease RSLR.

Average rice productivity

See figure 6.26, which shows the stock-flow diagram of the average paddy productivity, which consists of a range of multipliers.

This productivity is influenced by various factors, some positive and some negative. Among the positive contributors in this system conceptualization are primarily the amount of irrigation (*not* capturing its use for flushing salt, see the paragraph on average soil salinity) and sediment (nutrient-rich, and counters RSLR thereby reducing flood and salinization risks) (Ibáñez & Caiola, 2016a). Furthermore, the use of pesticides and fertilisation chemicals increases the productivity significantly (Belenguer-Manzanedo et al., 2023) (although with a long-term dampening effect through the negatively feedback to biodiversity). Rice farming faces multiple threats from climate change, including water scarcity, sea level rise and flooding, soil salinization, and increased pest activity due to higher temperatures (Officina Catalana del canvi climàtic, 2018). Additionally, non-climate-related factors like the invasion of alien species, such as the apple snail, further exacerbate these challenges (Ibáñez & Caiola, 2016a) (thus, biodiversity is an increasing multiplier, more equals a higher productivity). We conceptualize these factor in a range of multipliers to an *average rice productivity*:

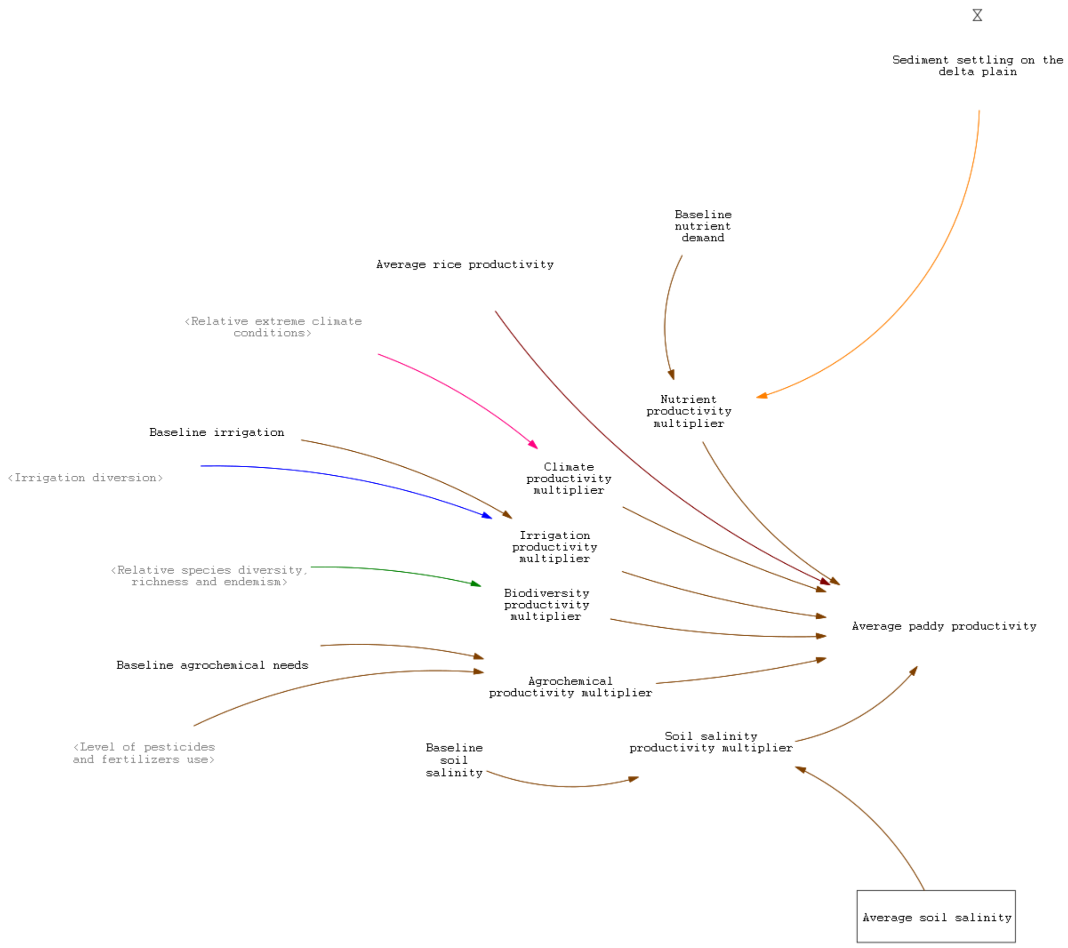


Figure 6.26: Stock-flow diagram of the average paddy productivity

$$Average\ paddy\ productivity = Average\ rice\ productivity \cdot \prod productivity\ multipliers \quad [\frac{mT}{m^2 \cdot Month}]$$

$$where:$$

$$\prod productivity\ multipliers = Nutrient\ productivity\ multiplier\ (CTF_{inc}) \quad [no\ unit]$$
$$\cdot\ Climate\ productivity\ multiplier\ (CTF_{dec}) \quad [no\ unit]$$
$$\cdot\ textitIrrigationproductivitymultiplier\ (CTF_{inc}) \quad [no\ unit]$$
$$\cdot\ Biodiversity\ productivity\ multiplier\ (CTF_{inc}) \quad [no\ unit]$$
$$\cdot\ Agrochemical\ productivity\ multiplier\ (CTF_{inc}) \quad [no\ unit]$$
$$\cdot\ Soil\ salinity\ productivity\ multiplier\ (CTF_{dec}) \quad [no\ unit]$$

Average soil salinity

See figure 6.27, which shows the stock-flow diagram of the average soil salinity. Soil salinization can occur through either saline flooding or saline seepage.

If a rice field is flooded with saline water, the salt will be absorbed by the soil[6]. The higher the concen-

[6]Salinity is expressed in electrical conductivity (which is a proxy) (EC) or deciSiemens per meter (dS/m) (D. Slinger & Tenison, 2005).

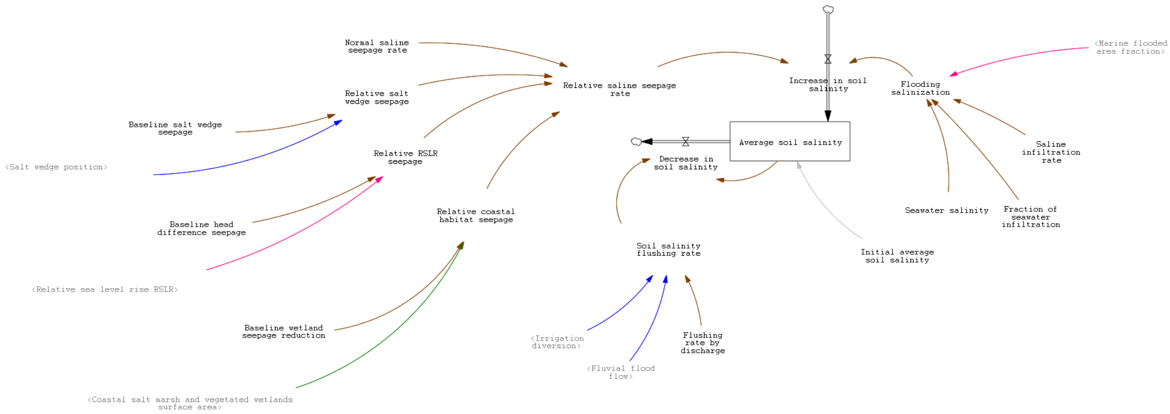


Figure 6.27: Stock-flow diagram of soil salinity.

tration of salt in the floodwater and the faster the rate of infiltration, the quicker the soil salinity will rise. We heuristically determine the increase over time based on the average *Seawater salinity*, the amount of infiltrated water, and the *Saline infiltration rate*. We linearly relate the amount of infiltrated water to the *Marine flooded area fraction* with the *Fraction of seawater infiltration* as a dimensionless unit (not considering depth, hydrological processes, time of inundation, etc). Essentially we say heuristically, during marine flooding, a linear increase in soil salinity is seen:

$$Flooding\ salinization = \frac{Seawater\ salinity \cdot Marine\ flooded\ area\ fraction \cdot Fraction\ of\ seawater\ infiltration}{Saline\ infiltration\ rate} \quad \left[\frac{dS}{m \cdot Month}\right]$$

Marine floods indirectly impact rice productivity through desalinization, but fluvial floods actually improve yields after a delay due to the fertilisation and saline flushing of soils (Gorostiza et al., 2023; Ibáñez & Caiola, 2016a). The same use is found in irrigation, which primarily flushes salt and pollutants if the sediment concentrations are low. Combining these effects and relating it to a *Flushing rate by discharge* yields the *Soil salinity flushing rate* which reduces the *Average soil salinity*:

$$Decrease\ in\ soil\ salinity = \frac{Average\ soil\ salinity}{Soil\ salinity\ flushing\ rate} \quad \left[\frac{dS}{m \cdot Month}\right]$$

$$where:$$

$$Soil\ salinity\ flushing\ rate = \frac{Irrigation\ diversion + Fluvial\ flood\ flow}{Flushing\ rate\ by\ discharge} \quad [Month]$$

Saline seepage endangers rice productivity from both inward and outward: The salt wedge increases saltwater intrusion of deltaic aquifers (Sierra et al., 2004), whereas seawater intrusion originates from sea. Consequently, with climate impacts expected to rise, soil salinity is expected to increase and cause rice yields to decrease (Belenguer-Manzanedo et al., 2023). Besides the absorption of saline floodwaters, wetlands can act as a buffer by absorbing saline groundwater flows, thereby reducing saline seepage (Herbert et al., 2015). We again make use of a range of multipliers to capture these effects within the*Relative saline seepage rate* while maintaining simplicity:

$$\textit{Relative saline seepage rate} = \textit{Normal saline seepage rate} \cdot \prod \textit{seepage multipliers} \quad [\frac{dS}{m \cdot Month}]$$

$$\textit{where:}$$

$$\prod \textit{seepage multipliers} = \textit{Relative salt wedge seepage } (CTF_{inc}) \quad [\textit{no unit}]$$
$$\cdot \textit{ Relative RSLR seepage } (CTF_{inc}) \quad [\textit{no unit}]$$
$$\cdot \textit{ Relative coastal habitat seepage } (CTF_{dec}) \quad [\textit{no unit}]$$

6.4.8. Ecosystems & Tourism

Main aspects modelled in the ecosystems & tourism subsystem include the status of ecosystems (condition, extent, diversity), the drivers impacting habitat condition change, the stocks of exploitative ESS, and how the tourism sector interacts with these structures. Modelling ecosystems and biodiversity is extremely complex, especially from a top-down perspective, where current advancements are just beginning to scratch the surface. Although we have formulated a list of KPIs that heuristically describe its status (see 4.2, quantified indicators are out of reach for this model's scope (and respectfully, that of many others). We therefore make extensive use of multiplier effects in this subsystem, which relate changes relative to a healthy and endemic baseline that *can* be quantified roughly and has been done in literature (e.g. (Ibáñez et al., 2020) on the Ebro delta).

Ecosystem status and drivers of condition change

Figure 6.28 shows the stock-flow diagram of the ecosystem status, consisting of the habitat condition, habitat extent, and species diversity, richness, and endemism. Furthermore, the five drivers of change are modelled. The ecosystem status modelling closely follows the indicators formalized in section 4.2.

The extent of habitat is defined as the sum of the coastal vegetated surface area and the total surface area of all other ecosystems not encompassed by this vegetative stock. The distinction between vegetated and non-vegetated habitats arose from our coastal flood defence conceptualisation and is primarily practical. Species diversity, richness, and endemism is a function multiplying habitat condition and extent. Habitat condition is influenced by the condition change rate, which is determined by the five main drivers of direct (human) impact on ecosystems. (See, (IPBES, 2019)). These are all described in multiplier effects. Naturally, the condition change can be positive or negative. Note for instance the *Habitat degradation* driver, where conditions close to the endemic situation *negatively degrade* habitat (i.e. habitat restoration, mind the counter-intuitive wording).

- **Habitat degradation** is globally the main human influence on habitats, and describes the changes in land cover, management of ecosystems, or spatial configuration (e.g. fragmentation). We capture these aspects in the relative endemic conditions to a baseline, the influence of tourism, habitat extent (in which changes in land use and connectivity are captured (Hodgson et al., 2009)), and protective legislation and restoration. Multiple variables make up the relative endemic conditions, see the next section.
- **Climate change**, mainly through temperature and weather patterns, impacts local ecosystem functioning and creates unfavourable conditions for healthy endemic habitats.
- **Pollution** is especially devastating to freshwater and marine habitats, and in our model originates primarily from agriculture.
- **Overexploitation** of wildlife threatens population viability directly and indirectly. In the Ebro delta, these mainly include fish, game, and aquaculture. The latter is not necessarily *wildlife* per se as it is farmed, but for simplification purposes we have aggregated the exploitative natural resources into one stock.

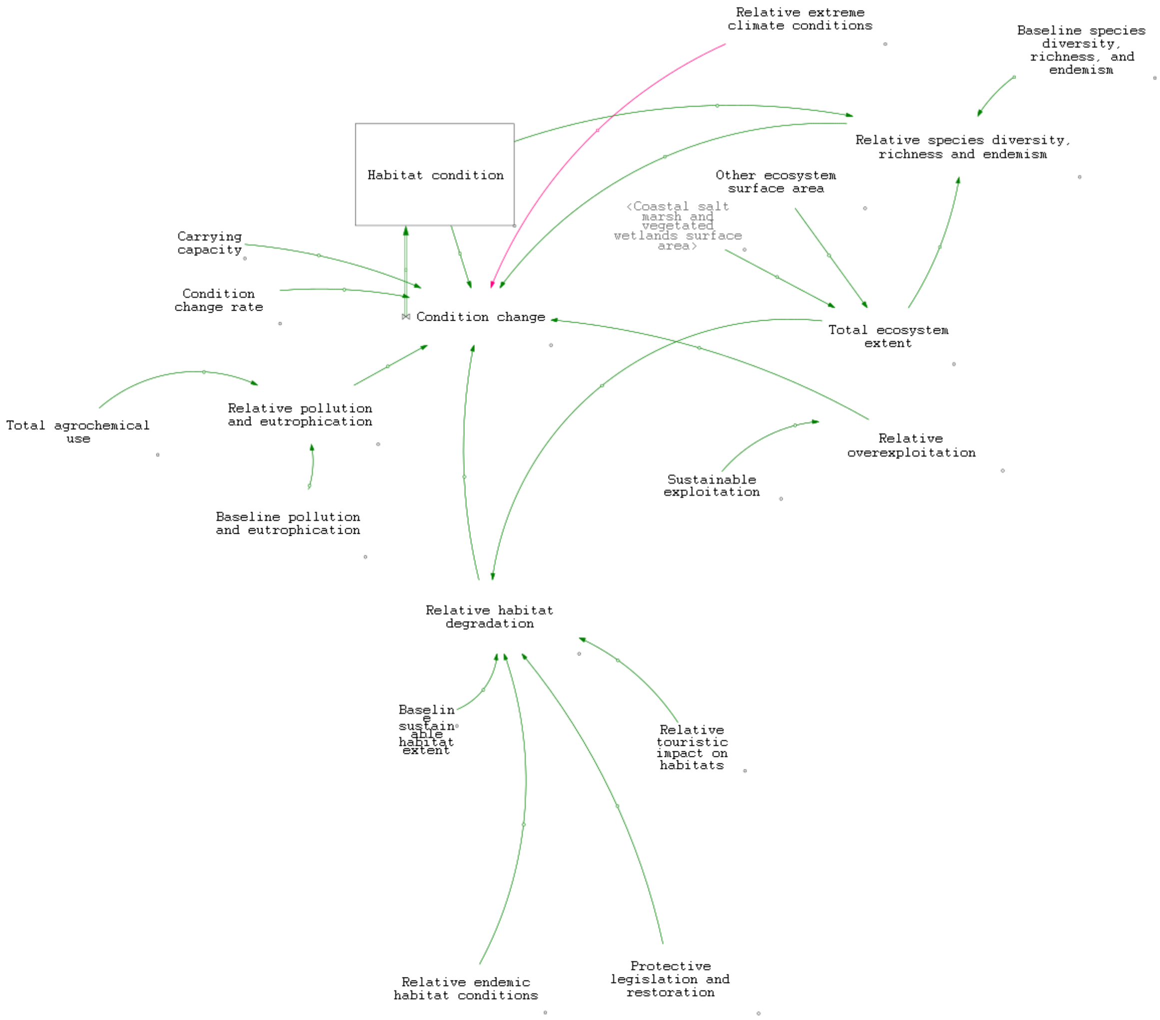


Figure 6.28: Stock-flow diagram of the ecosystem state and main anthropogenic drivers of change.

- **Invasive species** disrupt the functioning of endemic ecological functioning mainly through the out competition of local species, impacting both ecosystems and human activities. To not unnecessarily complicate the ecological structure, we capture the relative impacts of invasive species (Invasive exotic species) within the *Species diversity, richness, and endemism* (non-invasive endemic species) factor, where a lower value relates to a bigger issue.

To quantify the *Condition change rate*, we use the logistic curve. Essentially, logistic functions model growth which is limited by constraining factors. In ecology, these bounds are referred to as the carrying capacity (maximum population size that the environment can sustain). These processes are found everywhere, from populations growth to the spread of disease, and for these reasons, the curve has been heavily promoted despite criticism (Kingsland, 1982) (It is no coincidence that the multiplier functions follow this shape). Indeed, the curve simplifies complexity and carries some heavy assumptions. Still, because it represents the basic principles of bounded growth, we opt to adopt the logistic curve to model habitat condition change (essentially modelling habitat restoration and decline). Written as a differential equation it looks as follows, see also figure 6.29:

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right)$$

where:

$$N = \textit{Population or quantity of interest}$$
$$t = \textit{time}$$
$$r = \textit{Intrinsic growth rate}$$
$$K = \textit{Carrying capacity.}$$

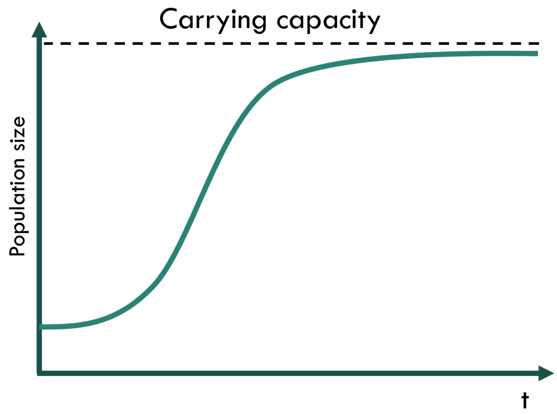


Figure 6.29: The theoretical bounded growth of a population over time.

The recovery of a disturbed ecosystem can be represented by the logistic function, where we chose to capture this recovery in the condition instead of in population sizes. The condition then influences habitat extent and diversity. Initially, positive interventions might result in slow recovery due to factors like limited species populations, poor soil health, or other degraded ecosystem functions. Subsequently, these functions are restored and see exponential growth through positive feedback. Beyond that point, saturation may be reached as the ecosystem nears carrying capacity, and its productivity may begin to decline as resources or space become limited. For a healthy degrading ecosystem the same function is used. Initially, the high level of ecosystem functions provides resilience to change, but starts depleting more rapidly under heavy disturbance. Once the ecosystem assets are depleted, not much is left to degrade (and some species will adapt or provide surprising resilience), slowing decline. See appendix G for the modelled visualisation of these changes in condition for different scenarios. The equations below show the adapted logistic function for our formalisation, where we link the product of the five drivers of change to the *Condition change rate*.

$$\frac{dC}{dt} = \frac{1}{r} \cdot C\left(1 - \frac{C}{K}\right) \cdot \left(\prod drivers - 1\right) \qquad \left[\frac{1}{Month}\right]$$

where:

$$C = \textit{Habitat condition} \qquad [\textit{no unit}]$$
$$r = \textit{Condition change rate} \qquad [\textit{Month}]$$
$$K = \textit{Carrying capacity} \qquad [\textit{no unit}]$$
$$\prod drivers = \textit{Relative pollution and eutrophication } (CTF_{dec}) \qquad [\textit{no unit}]$$
$$\cdot \textit{ Relative species diversity, richness and endemism } (CTF_{inc}) \qquad [\textit{no unit}]$$
$$\cdot \textit{ Relative habitat degradation } (CTF_{dec}) \qquad [\textit{no unit}]$$
$$\cdot \textit{ Relative overexploitation } (CTF_{dec}) \qquad [\textit{no unit}]$$
$$\cdot \textit{ Relative extreme climate conditions } (CTF_{dec}) \qquad [\textit{no unit}]$$

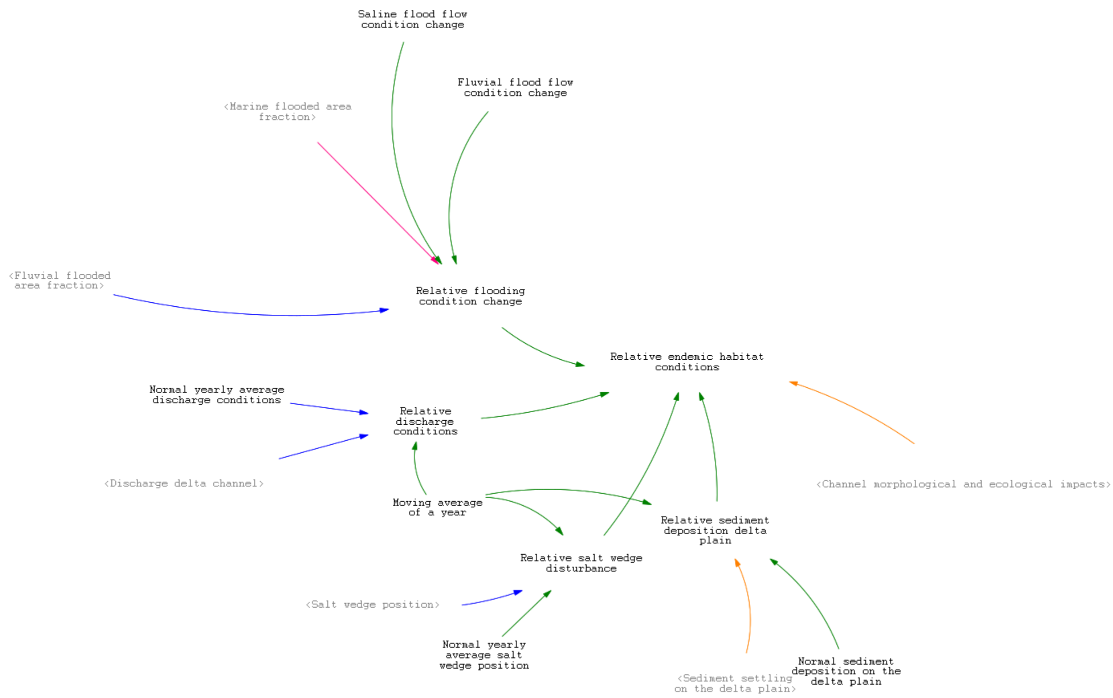


Figure 6.30: Stock-flow diagram of the relative endemic habitat conditions

If $\prod drivers \leq 1$, a negative habitat change is seen. Values higher than one indicate a positive habitat change. Note that most of the multipliers are decreasing continuous table functions (CTF_{dec}) as they capture drivers of negative change. For example, high pollution implies a multiplier value smaller than 1 $\prod drivers$. The exception is the *Relative species diversity, richness and endemism* as we captured the invasive species driver within the biodiversity variable. I.e. high biodiversity = a multiplier above 1. Again, the function used is an abstraction, only capturing the main principle of bounded change. We do not consider tipping points, change in carrying capacity, detailed internal feedback, etc.

Relative endemic conditions

Figure 6.31 shows the stock-flow diagram of the *Relative endemic habitat conditions*.

A high level of endemic conditions relates to a high level of suitability of habitat for endemic species, thereby directly improving the *Habitat condition*, and thus indirectly improving *Species diversity, richness, and endemism*. Factors influencing the endemic condition are also described as multipliers, i.e. the *Relative endemic habitat conditions* is a product of a subset of multipliers. These are:

- Flood flows ((CTF_{inc})/(CTF_{dec})) (consisting of marine and fluvial flooding).
- The fluvial discharge (CTF_{inc})
- The salt wedge position (CTF_{dec}). The presence of the salt wedge with respect to the natural flow regime leads to hypoxic conditions and increasing accumulation of organic matter, deteriorating the ecological status (Ibáñez et al., 2020).
- Sediment deposition on the delta plain (CTF_{inc}).
- Channel morphological and ecological impacts (CTF_{dec}).

A yearly moving average is calculated for fluvial discharge, the salt wedge position, and the sediment deposition, as naturally these flows vary over the year. The moving average of these values is used as input for respective the multiplier functions.

Tourism and ESS

Figure 6.31 shows the stock-flow diagram of tourism and the exploitative provisioning ESS, where we primarily model the growth of the tourism sector, the fish, aquaculture, game stock, and their interaction.

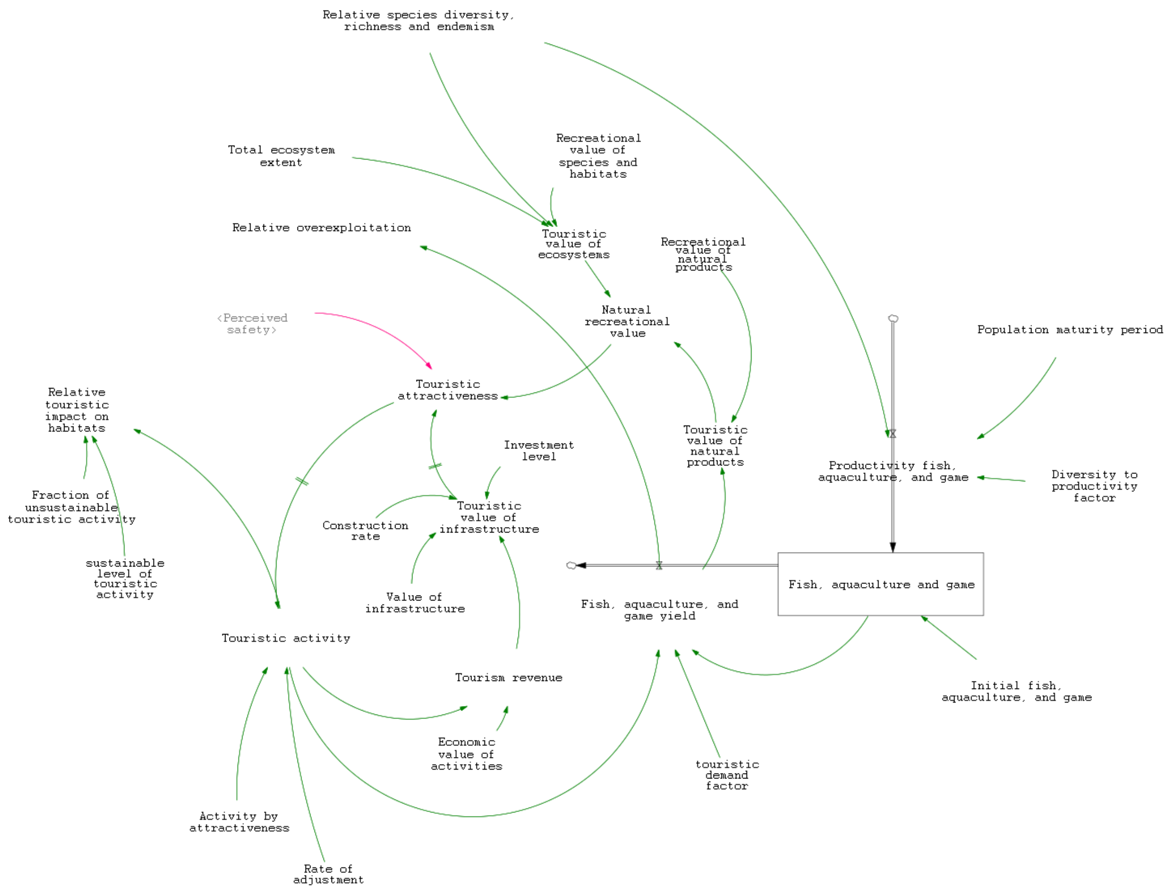


Figure 6.31: Stock-flow diagram of the tourism sector and related exploitative provisioning ESS.

Essentially, the various components of the tourism industry interact with each other to collectively provide tourists with attractions and experiences, but their resulting impacts on the socio-economic dynamics and the natural environment should not be neglected (Sedarati et al., 2019). Below these are formalized.

Biodiversity has a direct and indirect aspect, which drives tourism growth by increasing *Natural recreational value*. Directly, it increases *Touristic value of ecosystems* (coupled with the habitat extent), drawing in tourists. Birds are an especially strong driver of this aspect in the Ebro delta. Secondly, as higher levels of biodiversity increase ecosystem functioning (and resilience), the productivity of exploitative ESS (*Fish, aquaculture, and game*) is increased. The stock of these ESS is depleted through exploitation (fishing, hunting, and farming). Tourism has a feedback effect on these stocks: a higher yield attracts tourists drawn in by the gastronomy of the Ebro (*Touristic value of natural products*, but a higher number of tourists can result in higher demands leading to unsustainable exploitation (*Relative overexploitation)*. Tourism growth also drives itself: A reinforcing feedback is found in the sector's compounding effect. As tourism infrastructure, services, and attractions develop, *Touristic value of infrastructure* grows, which attracts more visitors, leading to increased revenue, investment in the tourism sector, and word-of-mouth promotion. However, if the *Perceived safety* of the area is low, tourists will be wary of choosing this destination. The total *Touristic attractiveness* is given by the following equation, where we express this attractiveness in *value*:

$$\begin{aligned} \textit{Touristic attractiveness} &= (\textit{Touristic value of infrastructure} + \textit{Natural recreational value}) \quad [\textit{Value}] \\ &\cdot \textit{Perceived safety} \\ \textit{where:} & \\ \textit{Natural recreational value} &= \textit{Touristic value of ecosystems} \quad [\textit{Value}] \\ &+ \textit{Touristic value of natural products} \end{aligned}$$

Increased attraction is not immediately evident for the potential tourist, and needs to be ”discovered”. To that end, the following equation gives the *Touristic activity*, which captures this delay. As in this scope the touristic activity is not captured within a stock for simplicity, it is only and directly related to attractiveness.

$$\begin{aligned} \textit{Touristic activity} &= \frac{\gamma \cdot \textit{Touristic attractiveness}}{r} \quad [\frac{\textit{Tourists}}{\textit{Month}}] \\ \textit{where:} & \\ \gamma &= \textit{Activity by attractiveness} \quad [\frac{\textit{Tourists}}{\textit{Value}}] \\ r &= \textit{Rate of adjustment} \quad [\textit{Month}] \end{aligned}$$

6.5. Formalized KPIs on the social, economic, and ecological dimension

With the previously defined KPIs, the flow of ESS, and the system description in hand, we can now begin to map out how impacts on the three impact dimensions of NbS emerge in our formalized model. The overview of these is given in table 6.1. Note that the social impact assessment framework was used to guide impacts on the social dimension, but we refrained from comprehensively mapping impacts along the eight categories as this would greatly increase complexity of an already complex dimension, especially because many of the impacts are interrelated or span multiple categories. To that end, the most relevant impacts are described, but we remain aware that social impacts are more extensive in reality.

Two of the categories of the framework are mostly outside of model scope: *political systems* (describing to which extent people are able to partition in life-governing decisions, the level of democratisation, and dedicated resources to both) and *community* (capturing impacts like cohesion, stability, services) categories (Vanclay et al., 2015). Still, they are certainly impacted by the problem (and potential solutions). Namely, local communities can suffer under degrading climate or livelihood conditions, and the intense local conflicts around the managed retreat strategies or the concept of sediment equity proves (impacts and aspects of) political systems are highly ingrained in the problem structure.

6.6. Multi-functional trade-off variation

Although we cannot show the variation in trade-offs between different NbS under different climate scenarios without running the model, we *can* show the axis along which these variations move.

The social dimension has proven to be relatively complex, as expected. A multitude of relative indicators needs to be established based on an extensive analysis of (the evolution of) the system and

Social wellbeing	Economic welfare	Ecological state

• Way of life & cultural activities
  • Δ traditional way of life
    • Δ Fish, aquaculture and game yield [mT/Month]
    • Δ Annual rice production [mT/Month]
    • Δ Annual salt production [mT/Month]
  • Natural recreational value [€/Month]
• Environment, health and wellbeing
  • Official safety [dmnl]
  • Extreme climate [dmnl]
  • Touristic activity (nuisance) [dmnl]
• Personal and property rights, fears and aspirations
  • Perceived safety [dmnl]
  • Δ Erosive sandy surface (coastal retreat) [ha\m^2]
  • Δ Species diversity, richness, and endemism [dmnl]
  • Conversion of rice paddies (land attachment loss) [ha\m^2]
  • Sediment settling on farmland (Raising ground culture) [m^3\Month]
	• Productive activities
	  • Fish, aquaculture and game yield [€/Month]
	  • Annual rice production [€/Month]
	  • Annual salt production [€/Month]
	  • Tourism revenue [€/Month]
	• Direct costs
	  • Expected damage built environment [€]
	  • Costs of interventions (NbS) (includes maintenance and monitioring) [€]
		• Total ecosystem extent [ha\m^2]
		• Habitat condition [dmnl]
		• Species diversity, richness, and endemism [dmnl]

Table 6.1: Formalized KPIs on the social, economic, and ecological dimension. Note how the economic welfare gives provisioning ESS in monetary values. As it stands, the model gives these outputs in mT/Month, but they could be easily linked with the market prices to compute the financial output.

associated values. Main impacts under a business-as-usual scenario will be related to loss of safety (perceived & official) and worsened living conditions, loss or change of cultural activities, and coastal retreat and degradation of natural assets which result in land attachment issues. Implemented NbS will (over the long-term) likely enhance resilience of the natural system, decreasing social vulnerability to hazards and dampening the above-mentioned losses. Consequently, it is likely that short-term negative social consequences (mostly cultural, and equity-related) are traded for the preservation of long-term social resilience. These temporal trade-offs can be especially high if long-term resilience requires a shift to a different socio-ecological system (i.e. more eco-tourism instead of rice cultivation).

Economically, business-as-usual will see a gradual decline of the productive activities due to worsening climate conditions, with a higher chance of steep declines or collapse in the event of flooding. Trade-offs resulting from the adoption of NbS strategies to negate these declines might follow two structures. Firstly, there could be a sacrifice or decrease in productive activities or efficiency, aimed at safeguarding the remaining sector from collapse (e.g. converting financially unsustainable rice fields to protective coastal habitats reducing saline seepage and flooding risks, or implementing environmental flows which are non-optimal for agriculture but enhance ecological resilience). Secondly, there could be a change in the distribution of economic sectors, where overall the economic output is similar, yet with variations between sectors (e.g. from agriculture to eco-tourism as main sector, or a shift towards regenerative agriculture with a new crop type). These trade-offs likely require social and economic adaptability and flexibility, and enhanced recognition of ESS.

Ecologically, the region will continue to degrade if no or minimal actions are taken and business-as-usual scenarios unfold. Yet, although there will very likely be a (steep) decline of species diversity, richness and endemism, paired with a loss of resilience, nature will adapt to the new conditions. However, these changes can be detrimental to the social and economic dimension, which have come to rely on a certain SES equilibrium. NbS interventions will likely enhance the resilience of the ecological system, or will directly improve environmental conditions which strengthen the endemic ecology. Yet in order for these strategies to succeed, nature will have to be given more room, which (likely in the short-term) is disbeneficial for social wellbeing and economic welfare. An internal trade-off arises from eco-tourism, which is positively related with increased biodiversity, but if not handled sustainably, has a negative effect on ecosystem conditions.

6.7. Conclusion

This completes the formalisation of the model. We set out to capture the social, economic, and ecological dynamics associated with NbS for CCA in the Ebro delta in a SDM. The coupling of the contextual understanding and the ICE-Ebro through the SDM methodology guided the modelling effort. This boiled down to an integration of the (scientific) data and expert mental models through system science to arrive at an abstraction of the Ebro SES that is able to assess multi-functional trade-offs of different NbS strategies over time. We opted to formalize in a concurrent manner (intertwined conceptualisation and specification) to increase the alignment with available data. As the model was not finished to the point of running, validation targeted the model formalisation, and was primarily executed by semi-quantitative interviews with local and scientific experts at multiple stages of the iterative process. Naturally, as the SDM was built on the ICE-Ebro, this iteration also included insights from chapter 5 and 6.
To that end, we initially stated the modelling considerations in section 6.1, after which section 6.2delineated the system boundary. We aimed to formulate a model that captured and integrated all relevant SES aspects in a comprehensive manner, and was able to facilitate learning and adaptation in the face of the inherent and systemic complexity of NbS. The formulation of the dynamic hypothesis followed in section 6.3. We concluded that the system structure and behaviour are governed by the synergistic working of a limits to growth and tragedy of the commons archetype. The former is found in the intensified agricultural activities, while the latter is seen in the construction of dams which have decimated sediment transports. Together, they have led to increased vulnerability to natural hazards. The expected aggregated behaviour of the social, economic, and ecological dimension was hypothesized for three scenarios with making increasing use of NbS. We expect NbS strategies to enhance ecologic sustainability, which creates economic and especially social negative impacts short term, but strengthens resilience to climate change of all dimensions long term. Still, worst-case climate scenarios would eventually surpass this capacity.

The formalisation was described in section 6.4, 6.5 and 6.6, where we built on the ICE-Ebro to guide the modelling effort, formalized the KPIs, and delineated the main trade-off axes. The key observations on the model formalisation include the following:

- The model formalisation succeeded in comprehensively capturing the social, economic, and ecological dynamics associated with NbS for CCA in the Ebro delta. Furthermore, the model provides a high degree of flexibility and modularity, as it is able to accommodate for various NbS or different measures and perspectives, and could be easily expanded or detailed. Despite its size, the formalized model remains communicable by coupling it with the ICE-Ebro. Together, these lead us to conclude that the aggregation level is right.
- Still, quantitatively modelling of NbS' multi-functionality (social, economic, ecological impacts) results in a broad and complex model, even at a high level of abstraction. This highlights the inherent and systemic complexity of NbS, which is further underscored by the difference in magnitude between the Ebro-ICE model and the SDM. The SDM illustrates the high degree of integration among different aspects of a SES, emphasizing the complex feedback and consequential varying trade-offs that NbS interventions create. As an example, the multiple impacts of sediment are only truly captured and understood by relating the different dimensions. This indicates that an isolated analysis may be far from the truth, and sheds light on the non-monetizable values of NbS. In that sense, the formalisation partially substantiates our earlier proposed statement; thorough understanding of NbS trade-offs requires a comprehensive understanding of system structure *and behaviour*. The final part of this statement cannot be fully supported without a functioning model that has verified and validated this behaviour.
- The most difficult aspect of the formalisation was correctly aggregating and integrating heterogeneity, especially spatially, where heavy assumptions had to be made to be able to link different disciplines, sectors, and processes. Still, the model should not and was not intended to be used

for precise heterogeneous results, but rather enhance understanding of system-wide relations and behaviour. The comprehensive, communicative and versatile character of the model suggests that the high abstraction has been effective in that regard.

- Quantitatively assessing impacts across social, economic, and ecological dimensions can be effective if heuristics are adopted, especially given the challenges in (quantitative) valuation of NbS. Valuation of behaviour of the most important aspects and/or relative to a (substantiated) baseline can be more insightful than striving for precision and risking inaccuracy. The formalisation illustrated that the flow of ESS can be effectively used to link long-term or hidden benefits of NbS. However, it remains to be seen if a running model and its behavioural output can be validated and verified.
- The highly contrasting number of indicators for each dimension offers two key insights on impact valuation. Firstly, social impacts can be difficult to capture comprehensively. However, despite (or perhaps because of) this high number of indicators, it remains quite easy to overlook or wrongly assess certain impacts. Secondly, ecological impacts are difficult to capture accurately, requiring extensive aggregation. Real ecological structures and behaviours are heterogeneous, leading to inevitable oversight or mis-assessment of certain aspects, such as species responses to changing conditions
- The formalized model proves, even without outputs, that sediment is the fuel for the functioning of the Ebro delta SES. Sediment and related processes influence social welfare, economic prosperity, and ecological status throughout the system. This leads us to align with emerging concepts on sediment equity and it's multi-functional significance.

With respect to the ICE-model, we conclude that the model formalisation was successfully executed and that a detailed ICE-model is 1) able to effectively guide the modelling effort, 2) helpful in its communication, and 3) able to illustrate the high level of intrinsic and systemic complexity of NbS. Still, this is only one partial practical case-application. To that end, we underscore the need for the completion of a full modelling cycle, and to test the use of the ICE-model and its guiding role in the SDM modelling effort in other contexts.

7

Conclusions

This chapter discusses the answers to the research questions in section 7.1. The limitations follow in section 7.2, and after that section 7.3 addresses the main research objective, applicability, and ethical considerations. Subsequently, section 7.4 discusses the general and case-specific recommendations. Finally, section 7.5 ends with the future research suggestions.

7.1. Research findings

In this thesis we have set out to bridge the notable deficiency in the comprehensive assessment and understanding of the multi-functional (social, economic, and ecological) trade-offs associated with Nature-Based Solutions (NbS) for climate change adaptation (CCA). By employing a system dynamics modelling (SDM) approach and focusing on deltaic regions, we aimed to grow understanding of NbS for CCA in the socio-ecological system (SES) context where they are intended to function. The Catalan Ebro delta - a region facing multiple existential threats, many of which are related to climate change - was selected as a case. This led us to formulate the following objective and progressive research questions:

To explore the application of a system dynamics modelling approach for assessing the social, economic, and ecological trade-offs associated with Nature-based Solutions for climate change adaptation in deltaic regions.

1. What is known on the social, economic, and ecological trade-offs and SDM applications associated with NbS for CCA in deltaic regions?
2. Which factors and interactions yield the social, economic, and ecological dynamics associated with NbS for CCA in deltaic regions?
3. Where do the social, economic, and ecological trade-offs associated with Nbs for CCA lie in the Ebro Delta?
4. Which specification is able to capture the social, economic, and ecological dynamics associated with NbS for CCA in the Ebro delta?

A mixed method approach grounded in the SDM methodology was adopted, and applied to the Ebro delta case study. Question one aimed to deepen the understanding of the knowledge gaps related to the objective. Question two to four entailed a heavily iterative exploration. Herein, question two developed a guiding meta-model (the ICE-model) capable of capturing social, economic, and ecological dynamics associated with NbS for CCA in deltaic regions, question three detailed this model to the case study (the ICE-Ebro), and question four applied the ICE-Ebro to guide the SD modelling effort. The case study, as the object of inquiry, served to refine and illustrate this exploration, next to providing contextual insights that benefit local policy.

7.1.1. Answers to the questions

What is known on the social, economic, and ecological trade-offs and SDM applications associated with NbS for CCA in deltaic regions?

The first research question was answered with a thorough and systematic literature review, which aimed to map out the knowledge gaps related to the multi-functional trade-offs of NbS for CCA (generically and for deltaic regions, examined if employing SDM as an application of the systems approach may help overcome these gaps, and evaluated how SDM has previously been applied to NbS multi-functionality and associated trade-offs.

We found that there is a need for greater integrative understanding and analysis of the multi-functional trade-offs of various NbS strategies - over scale (temporal, spatial), under climate uncertainty and for various stakeholders. The aim is here to surpass single-dimensional assessment and/or implementation of NbS (e.g. focusing exclusively on flood risk management), and incorporating the entire range of associated impacts, both positive and negative. The systems approach and SDM modelling - while highly suited to this research area - have both been sparingly applied. SDM is able to model nonlinear relationships between various sub-elements in a coupled system, include and aggregate both material and information flows, and fits the research area well due to the numerous feedback loops that complex SES inhibit. Benefits such an approach can provide can be summarized in the capacity to investigate complex behaviour over time for different interventions while facilitating wider participation and understanding. To that end, there is a clear need for further exploration of the applicability of SDM approaches in comprehensively assessing NbS multi-functionality and associated trade-offs.

Which factors and interactions yield the social, economic, and ecological dynamics associated with NbS for CCA in deltaic regions?

The second research question was answered by employing a literature study and semi-structured interviews, and was iteratively improved through insights from the case-application. This allowed us to construct a theoretical understanding, formulate guiding concepts and indicators, and a guiding meta-model grounded in systems science.

The theoretical understanding consisted of the (climate related) societal problems deltas face, what role NbS can play in overcoming these, and what is still constraining their potential success. It was shown that deltas serve as hubs of social, economic, and ecological significance; their high heterogeneity and connectivity greatly increase economic and ecological productivity resulting in concentrated human development integrated with important ecosystems. Deltaic evolution is highly dynamic, and is primarily governed by the equilibrium between fluvial and coastal processes. Among these, the river's discharge and sediment play a particularly significant role in shaping delta morphology. However, globally, deltas face serious environmental degradation, threatening their resilience to natural hazards and climate change, and impoverishing natural resource outputs. It was shown that it is likely to be direct human effects (e.g. poor management of sediment, intensive agriculture, groundwater extraction) that pose the greatest threat to deltas, with the impacts of climate change exacerbating these dangers. NbS have emerged as a strong contender to aid in the adaption of deltaic SES to climate change impacts.

Subsequently, we derived heuristic concepts and indicators for capturing varying social, economic, and ecological impacts of NbS. We opted to capture these dynamics through the flow of ecosystem services (ESS) primarily, as it was shown that clear and consistent multi-functional trade-off assessment from the loss of ecosystems and biodiversity requires the linking of biophysical aspects of ecosystems with human benefits through ESS. We argued for the adoption of heuristics to assess social, economic, and ecological behaviour, as we aim to assess trade-off trends rather than provide an exact forecast.

By consolidating the theoretical knowledge base within a system diagram framework, adopting the guiding concepts and indicators, and aligning it with the overarching research objective, the meta-model was formulated (ICE-model). The ICE-model has two main uses. Firstly, it is intended to facilitate problem exploration. To that end, its high level of abstraction and modular structure allow for adaptability to different contexts and use-cases which may enhance NbS scalability. Secondly, it creates a solid foundation and guiding role for the SD modelling effort. Because of this adaptability and guiding role, the ICE-model could be described 'scaffold'-like on which to build on either horizontally (e.g. to different cases) or vertically (detailing to SDM). This nature helps to place NbS in the context where they are intended to function (complex SES), and communicate the broad array of (non-monetary) values of NbS and/or ESS to stakeholders not familiar or reluctant with the concept. In summary, exploration and learning, stakeholder engagement, and policymaking could be facilitated, although the ICE-model should be applied in practice for definite conclusions.

Where do the social, economic, and ecological trade-offs associated with Nbs for CCA lie in the Ebro Delta?

The third research question was answered with a literature study, semi- structured interviews, and field trips to develop a strong contextual understanding. This entailed delineating the system and problem context, and proposed NbS strategies, which were subsequently synthesized into the ICE-Ebro by detailing the general ICE-model. Additionally, insights from SDM were used to iteratively refine the synthesis.

The system and problem context consisted of a detailed social, economic, and ecological dimension, a description of the socio-ecological and morphological evolution, and a delineation of the (resultant) threats. It was shown the Ebro delta SES is tightly integrated across the social, economic, and ecological dimensions. High and unique ecological wealth is crucially supportive for both social and economic functions and values. The community and its activities are deeply ingrained in the landscape, with substantial dependency on climate-sensitive income sources. Rice cultivation, in particular, is the main activity, playing a major social, economic, and non-negligible ecological role. Since the 1960s, the social-ecological regime shifted significantly, primarily through dam construction and intensified agricultural practices. The delicate balance between river sediment supply, wave energy and RSLR governing the morphology of the Ebro delta has been drastically tilted by the construction of these dams which compound >99% of sediment and nearly eliminated volatile river discharges, halting both coastal and delta plain accretion and affecting the environment drastically. Intensive land-use has caused further environmental degradation. These modifications have made the area more vulnerable to the impacts of climate change: sea-level rise, temperature increases, and increased storminess are already heavily impacting the delta. To that end, the overarching challenge would be to grow the deltaic social-ecological capital and its resilience to climate, in which sustainable sediment flows take a leading role.

Although there is consensus found in the need for action, there is not in the definition of the correct guiding strategy. NbS have been extensively proposed to enhance resilience, with main categories relating to environmental flows, sediment by-passes, establishing a coastal buffer, and restoring habitats. Associated trade-offs are plenty however, many related to ingrained traditions and cultural activities or upstream and downstream conflicts. We found that understanding of the (historic) context and inclusion of local stakeholders is imperative to uncover hidden relations and ingrained values that are missed at a first glance.

Subsequently, the ICE-model was detailed to the Ebro delta by synthesizing the analysis above, resulting in the ICE-Ebro. The ICE-Ebro was able to comprehensively map the social, economic, and ecological dynamics associated with NbS for CCA in the Ebro delta. The easy of adaptation suggests that coupled with the contextual SES understanding, the 'scaffold'-like character of the ICE-model is attainable.

Although the Ebro-case was used to refine the general ICE-model and will therefore be naturally aligned, this implies that the ICE-model is likely to be modular for different uses and adaptive for other contexts. Still, the model needs to be applied in practice and different contexts to surpass the theoretical aspect of use-cases.

Which specification is able to capture the social, economic, and ecological dynamics associated with NbS for CCA in the Ebro delta?

The fourth research question's answer was found by coupling the contextual understanding and the ICE-Ebro in a quantitative SDM. This boiled down to an integration of the (scientific) data and expert mental models through the SDM methodology and the author's systems thinking knowledge. We opted to formalize in a concurrent manner (intertwined conceptualisation and specification) to increase the alignment with available data. As the model was not finished to the point of running, validation and verification targeted the model formalisation, and was primarily executed by semi-quantitative interviews with local and scientific experts at multiple stages of the iterative process. Modelling considerations, a system boundary, and dynamic hypothesis preceded the model formalisation. The latter was expanded on by delineating expected trade-offs.

The modelling considerations primarily built on the aim to formalise a model that is able to capture and integrate all relevant SES aspects in a comprehensive manner, and to facilitate learning and adaptation in the face of the inherent and systemic complexity of NbS. The model boundary is primarily delineated by the geographical boundary of the Ebro delta, although it encompasses the Ebro delta channel up to the dam compound. The dynamic hypothesis followed, where we determined that the system's structure and behaviour are shaped by the combined influence of a limits to growth and tragedy of the commons archetype. The former manifests in intensified agricultural activities, while the latter is evident in dam construction, which has significantly reduced sediment transports. Together, these factors have increased vulnerability to natural hazards and subsequently climate change impacts. We then hypothesized the expected aggregated behaviour across the social, economic, and ecological dimensions associated with NbS. We anticipate that NbS strategies will bolster ecological sustainability, resulting in short-term economic and social negative impacts but enhancing resilience to climate change across all dimensions in the long term. However, under worst-case climate scenarios, this capacity would eventually be exceeded. Subsequently, the model formalisation was discussed. Key observations on the model formalisation included the following:

- **Comprehensiveness, versatility, and communication**
  The model was able to successfully capture the social, economic, and ecological dynamics of NbS for CCA in the Ebro delta. It is flexible and modular by accommodating for various NbS and perspectives, and is likely to be relatively easily expanded or detailed as needed. Effective communication is ensured through the coupling with the Ebro-ICE model.The former manifests in intensified agricultural activities, while the latter is evident in dam construction, which has significantly reduced sediment transports. Together, these factors have heightened vulnerability to natural hazards.
- **Embracing complexity of NbS multi-functionality**
  Still, quantitative modelling of NbS multi-functionality results in a broad and complex model, even at a high level of abstraction. This highlights the inherent and systemic complexity of NbS, which is further underscored by the difference in magnitude between the Ebro-ICE model and the SDM. To that end, the SDM illustrates the high degree of integration among different aspects of a SES, emphasizing the complex feedback and consequential varying trade-offs that NbS interventions create. As an example, the multiple impacts of sediment are only truly captured and understood by relating the different dimensions. This indicates that an isolated analysis may be far from the truth, and sheds light on the non-monetizable values of NbS. In that sense, the for-

malisation partially substantiates our earlier proposed statement; thorough understanding of NbS trade-offs requires a comprehensive understanding of system structure *and behaviour*. The final part of this statement cannot be fully supported without a functioning model that has verified and validated this behaviour.

- **Aggregation and Integration Challenges**
  Aggregating and integrating heterogeneity, especially spatially, was challenging and required heavy assumptions to link different disciplines, sectors, and processes. Still, the model should not and was not intended to be used for precise heterogeneous results, but rather aims to enhance the understanding of system-wide relations and behaviour. The model's comprehensive, versatile, and communicative nature suggests the high aggregation level was effective.
- **Effective Impact Assessment**
  The model's successful capture of multi-functional dynamics suggests heuristics can support the quantitative assessment of social, economic, and ecological impacts, especially given the challenges in valuing non-monetizable impacts of NbS. Assessing behaviour relative to a baseline can be more insightful than striving for precision and risking inaccuracy. The formalisation illustrated that the flow of ESS can be effectively used to link long-term or hidden benefits of NbS. However, it remains to be seen if a running model and its behavioural output can be validated and verified.
- **Indicator insights**
  The highly contrasting number of indicators for each dimension offers two key insights on impact valuation. Firstly, social impacts can be difficult to capture comprehensively. However, despite (or perhaps because of) this high number of indicators, it remains quite easy to overlook or wrongly assess certain impacts. Secondly, ecological impacts are difficult to capture accurately, requiring extensive aggregation. Real ecological structures and behaviours are heterogeneous, leading to inevitable oversight or mis-assessment of certain aspects, such as species responses to changing conditions.
- **Sediment significance**
  The formalized model proves, even without outputs, that sediment is the fuel for the functioning of the Ebro delta SES. Sediment and related processes influence social welfare, economic prosperity, and ecological status throughout the system. This leads us to align with emerging concepts on sediment equity and it's multi-functional significance.

With respect to the ICE-model, we conclude that the model formalisation was successfully executed and that a detailed ICE-model is 1) able to effectively guide the modelling effort, 2) helpful in its communication, and 3) able to illustrate the high level of intrinsic and systemic complexity of NbS. Still, this is only one partial practical case-application. To that end, we underscore the need for the completion of a full modelling cycle, and to test the use of the ICE-model and its guiding role in the SDM modelling effort in other contexts.

7.2. Limitations of the research approach

In the following sections, the limitations of the research approach are discussed. These have been divided into process limitations and model limitations (ICE-model & SDM model). Limitations of the SDM approach have been discussed in the methodology, see section 7.2.

7.2.1. Process limitations

First and foremost, no comprehensive modelling cycle has been completed. The literature review already identified the need for an explorative analysis that acknowledges uncertainty and multiple perspectives, and a comprehensive approach would address this need. In practice, our SDM model is semi-formalized (one step further than conceptualisation), and remains non-operational. Our validation and verification are, at best, indicative without reflecting on the model's (extreme) behaviour (Some specification errors will have gone by unnoticed as well). It does not imply that our conclusions and recommendations lack validity, as the formalized model already helps to understand and map multi-functional trade-offs of NbS. It does however necessitate caution; without proper validation and verification, there is a limit to the confidence of insights, especially on hypothesis of future behaviour. Furthermore, incorporating scenario analysis into future research would significantly enhance the ability to manage uncertainty, facilitate informed decision-making, embrace diverse perspectives, identify critical drivers, and develop adaptable strategies. Moreover, without actually using the model, is it difficult to reflect if the model aligns with policy goals. See section 7.5 for the detailed discussion on the recommended future research. Further process related limitations are discussed below.

- The research approach focused on one case application only, and as this case was used to refine and illustrate our exploration, this limits the strength of conclusions. This limitation is exacerbated because the model has not surpassed theory by not having been applied in practice.
- Although one of the main found knowledge gaps is the lack of local stakeholder participation in the design and implementation of NbS, this research only minimally included participatory processes (the field trip included participation of local stakeholders).
- The limiting aspect of bounded rationality and our own bias, especially considering the high complexity of SES, is tightly interwoven with the formalisation of both the SD and ICE-model. Although the authors had a moderate understanding of the related concepts, important aspects will have been overlooked. With iterative external validation we have tried to keep the former limited to a minimum.

7.2.2. ICE-model

As we have only applied and refined the ICE-model to one case study, the distilled general structure and behaviour may be skewed. Furthermore, it remains to be proven if the ICE-model is adaptive enough to be used as a basis for case study analysis, and modular enough to be adjusted for different use cases (e.g. comparing grey and green designs).

Additionally, the high abstraction of the ICE-model has aggregated complex behaviour, which has hidden detailed interrelations or averaged polarity. In that regard, if understanding of the full complex structure and behaviour associated with NbS strategies is desired, the ICE-model should be accompanied by more detailed SD modelling, preferably quantified.

The leading role for the ESS framework in the ICE-model brings with it challenges. In practice, often economic values are prioritized over cultural, social, and intrinsic values of ecosystems, especially because of valuation difficulties, potentially marginalizing non-economic benefits and perspectives. By explicitly taking a holistic multi-functional perspective and adopting heuristics, we hope to surpass this skewed perspective.

7.2.3. Limitations of the model

The formalized model was not indented to be perfect, but acknowledgement of its limitations is important to understand what it can and cannot do. There are several aspects and considerations having significant influence on intended model use, which are discussed below.

- The choice for our high abstraction and broad insights on the entire SES implies an imminent loss of more detailed insights on individual dimensions, aspects, or sectors. It allowed us to attain cross-dimensional and systematic insights, but it remains to be seen if some assumptions hold up and represent the real world system. Aggregation results in an "average" behaviour insensitive to spatial, sectoral, or characteristic heterogeneity. Below, the most significant aggregation assumptions are discussed.

  · It is questionable if our aggregation of sediment dynamics is substantiated. For example, no distinction is made between bedload and suspended load or wash load and bed material load, whereas these behave very differently and have different uses. The large difference in sediment flow volumes (i.e. between fluvial sediment load and longshore drift) limits the resulting error margin as it accentuates trends over precise sediment dynamics.
  · The ecological status - which is a function of habitat condition, habitat extent, and biodiversity - is mainly computed based on relative changes to a baseline. Yet, relative change is not necessarily good nor bad, and the amount of assumptions intruded in this manner carry with them an increasing level of uncertainty.
  · The aggregation of vegetated and sandy coastal flood defence into relative surface area is extremely simple, and perhaps not very communicative for coastal flood defence engineers.

- Although SDM is not suited for spatial heterogeneity, and our goals were not as such, we do believe that coupling insights with spatial models or monitoring is essential. Our model primarily taken an exploitative role, but individual aspects and locations need to be unravelled using more refined methods. This is especially evident in the way flood defence capacity is modelled, where all erosive coastline is aggregated into one vulnerable stock. Possible synergy is found with ABM or hydro- or morphodynamic modelling tools such as Delft3D.
- The scope is focused on the Ebro delta, whereas many trade-offs propagate outside of the geographical boundary. These mainly include the upstream and political trade-offs, and recent conflicts between local communities and higher-level governance have proven trade-offs span larger scales.
- The complexity of ecosystems and the interdependencies between different services can introduce significant uncertainty in assessing and managing ESS. Predicting the outcomes of interventions is challenging in this regard. The high aggregation will have introduced reduced accuracy in these areas.
- The model can be refined and/or expanded upon, as it is comprehensive but not exhaustive. Below the most important considerations are given, although we want to be wary of overcomplifying the model.

  · The integration of more refined social or ecological theory could benefit the model, as we have primarily chosen to work with (validated) heuristics which lead to *relative* system performance. Additionally, a socio-economic submodel could provide more insights into population and livelihood mechanisms.
  · The rice productivity and production are given as a constant insensitive to crop cycles, delays, or longer lasting effects of impacts. Ideally, this component should be expanded to a stock-flow model (instead of just auxiliaries) which includes these aspects.
  · The 'community' of the Ebro delta - which is indirectly modelled through their social and economic activities - is not adaptive. I.e. changes in or outside the system do not invoke behavioural change. In reality, behaviour or structure change dynamically in response to system (condition) change, for example through rising awareness of environmental value. The model implicitly sets values static over time, and as cultural values play a significant role in the trade-offs of NbS, related insights over longer time scales can be reduced as values can change.
  · In this same regard, behaviour related to social and economic activities is modelled rationally, and assumed to reflect perfect understanding of the system. In reality, uncertainty impacts decisions, and irrationality is prevalent in social systems.

- A very simple economic structure was adopted, which mainly focused on the exploitation of ESS and related production volumes. Economical dynamics, markets, operational expenses, etc are not included, but will affect financial sustainability of different sectors.
- NbS for CCA provide mitigating benefits as well, such as carbon sequestration, which were deliberately omitted for scoping purposes. Yet, inclusion of these would improve comprehensiveness of trade-off assessment. Another ESS that was not directly included due to scoping but is considered important is water purification.

7.3. Research contributions and considerations

Below, we first discuss the overarching objective, then discuss how a SDM such as the one in this research may be applied, and finally end by delineating ethical considerations.

7.3.1. Answer to the overarching objective

Collectively, the research activities guided by the four questions contribute to the main objective, which is repeated below. Three main conclusions on this objective have been formulated.

To explore the application of a system dynamics modelling approach for assessing the social, economic, and ecological trade-offs associated with Nature-based Solutions for climate change adaptation in deltaic regions.

1. The literature review underscored the high need for the integrative understanding of the trade-offs of various NbS strategies - over scale (temporal, spatial), under climate uncertainty and for various stakeholders. Additionally, the need for the application of the SDM methodology to this context has been strongly underscored.
2. The results of this research have demonstrated that the SDM methodology is suited to assess the social, economic, and ecological trade-offs associated with NbS for CCA. It is able to include and interrelate the wide range of disciplines, sectors, and processes that describe the SES in which NbS are embedded. Heuristics can support the quantitative assessment of multi-functionality by considering (non-monetizable) impacts in relation to a baseline, offering insights without striving for precision at the risk of inaccuracy. In this way, SDM allows for a comparative and quantitative assessment of social, economic, and ecological impacts. Moreover, it is able to do this in a comprehensive, versatile, and communicative manner. I.e. SDM allows to capture and visualize the inherent and systemic complexity of NbS effectively.
3. The ICE-model has been demonstrated to be suitable to facilitate problem exploration and guide a quantitative SD modelling effort, albeit only for one case. Moreover, the ICE-model is useful in helping communicate formalised models.

One of the disadvantages of the methodology is the time intensiveness; especially for complex SES the right integration demands a thorough and iterative analysis. However, we argue that the time costs are justified: once the model has been built it greatly enhances understanding of the system interactions and responses, facilitates multiple applications, and can be rapidly expanded as needed. Moreover, it may lead to greater alignment, long-term benefits, and reduced overlooked impacts or rebound effects of NbS strategies

In summary, the methodology provides a way to comprehensively quantify multi-functional trade-offs of different NbS for CCA in deltaic regions, while maintaining adaptability for different use cases. We expect that the suitability to assess multi-functionality at the regional scale is not limited to deltas. Although the research has not finished a full modelling cycle and has only moderately included participatory elements, the process itself represents a step forward in the understanding of multi-functionality of NbS and SDM applications on this topic.

7.3.2. Applicability of the SDM methodology

The system-wide level application suits the SDM methodology, and seems highly beneficial for growing high-level systemic understanding and supporting NbS policy and decision-making, mainly through facilitation of exploration and (multi-actor) engagement. However, the combination of the high and homogeneous aggregation of processes means it is not able to model detailed or individual behaviour, especially spatially. In that regard, the approach should assisted by other methods and tools which are able to ’zoom-in’ on or specify individual locations, sectors, or events. In the broad context of this research, the role of SDM is therefore more of a top-down tool, but may even be linked with detailed models.

7.3.3. Ethical considerations

Previous conflicts in the Ebro delta has shown that the political arena is complex and needs to be acknowledged. As the model describes the system in which people live, depend on, and ascribe values to, the model’s use should be carefully considered, as should its description of these values. The possibility for misuse is present, and could for instance take the form of justified exploitation of natural resources under the guise of maximizing certain services. In this regard, the processes to optimize accuracy and transparency are important. Furthermore, we again want to underscore that the aim is to grown understanding, increase engagement, and support policymaking. The objective is to holistically assess multi-functional trade-offs, and explore rather than optimize. The model cannot and should not be used decisively on its own, and social impact assessments should be executed concurrently.

However, the model may bring ’just’ ethical impacts as well, mainly as the result from the holistic assessment of social, economic, and ecological dimensions instead of focusing on singles uses and/or dimensions which is still mostly done in practice. E.g. the effective visualisation of the system-wide importance sediment in the Ebro delta helps to substantiate the sediment-equity argument.

7.4. Recommendations

Although the objective of this study was not to formulate policy recommendations, we aspire to enhance the implementation and delivery of NbS in order to sustainably adapt to climate change, grow and maintain biodiversity, and align solutions with societal needs and values. In essence, we believe NbS can be a key strategy for strengthening SES globally by building a sustainable relationship between people and nature.

In that light, we shortly summarize our overarching key take-aways, which are intended to 1) help bridge current difficulties experienced in the NbS field, and 2) shed light on the NbS policy and decision-making in the Ebro delta.

7.4.1. General recommendations

The trade-offs associated with NbS under climate change depend for a large extent on the existing social, economic, and ecological structure and values of the system where the interventions are intended to function. The trade-offs of NbS arise both between and within the impact dimensions, are highly related to associated values, span short- and long-term temporal scales, and seem highly dependent on stakeholder perspectives. For these reasons, we argue that an extensive understanding of this structure and its behaviour (under changing conditions) is imperative if an accurate and comprehensive assessment of NbS impacts is desired. Accurate, because complex system feedback and relations are recognized and acknowledged, and comprehensive, because the entire array of possible trade-offs is evaluated (not just the main benefits). The aim here is to surpass single-dimensional evaluation and/or implementation of NbS (e.g. focusing exclusively on flood risk management), and incorporating the entire range of associated impacts, both positive and negative.

This integrative system understanding will carry with it a time and resource cost, but will pay off in terms of greater alignment, long-term benefits, and reduced overlooked impacts or rebound effects. Moreover, a solid understanding facilitates flexibility and learning, allows for the comparison of (the impacts of) multiple NbS, and could serve as a strong argument for the multiple values of NbS (especially non-monetizable), resulting in increased scalability *within* a local SES.

As discussed, the SDM methodology is suited for analysing the integrative system structure and behaviour, and exploring over various scenarios. Herein, the ICE-model could speed up the acquisition of the system understanding, and thereby may improve cross-regional scalability as a tool.

Finally, we want to reflect on the notion of complexity. Common sense often promotes the philosophy of 'keeping it simple.'. However, we argue that in the context of regional-scale NbS, policy should be cautious of simplicity. Instead, it should embrace the inherent and systemic complexity of NbS, recognizing and leveraging the wide and multi-functional solution space that spans multiple disciplines and stakeholders.

7.4.2. Recommendations for the Ebro delta

NbS for CCA in the Ebro delta are not perfect strategies. They will invariably carry with them negative impacts, or necessitate friction-inducing social or economic change. Yet, in the face of natural impacts - expected to accelerate in the face of climate change - they do seem to improve long-term resilience and provide multiple benefits aligned with multi-functional values. We hypothesize that under the threats of climate change, a conflict-inducing shift to a sustainable SES may be necessary to sustain desired social, economic, and ecological conditions of the Ebro delta community. Herein, NbS are vital instruments, able to span social, economic, and ecological dimensions thereby aligning with the local SES if executed well. We additionally want to underscore the importance of sediment for the system, and advise that strategies acknowledge its region-spanning multi-functional influence. In conclusion, we believe NbS are essential components in growing the Ebro delta's socio-ecological system resilience and magnitude.

However, besides the structural, financial, and ecological requirements, implementation of NbS strategies in the Ebro necessitates improved consideration of ingrained values, communication and transparency, and participation between local and regional/national stakeholders. Policy that has not recognized the inherent systemic values stands at risk of inefficiency, creating push-back, or missing the essence, as has been shown especially well with the concept of sediment equity. The model confirms this aspect by 'visualizing' these values. As we hypothesize that many of the proposed NbS will hurt socially and economically in the short-term, a long-term vision is essential for a comprehensive assessment of trade-offs.

7.5. Future research

In this section, first the advancement of the research of this thesis is discussed. Subsequently, suggestions for expanding future research are given.

7.5.1. Advancing the research approach

As stated, this research represents a step forward in the comprehensive understanding of multi-functionality of NbS and SDM applications on this topic. As a priority, a full modelling cycle needs to be executed, including using the model in a practical/policy setting. Subsequently, the methodology needs to be applied to multiple cases, preferably different in characteristics, to evaluate the robustness. Below, these essential steps have been listed.

1. Specify the model with data.
2. Validate and verify. (See Senge and Forrester (1980) and Sterman (2002)).
3. Design a range of experiments which are to be evaluated (i.e. scenario analysis).
4. Use the model, aligning with policy goals and fostering engagement and learning.
5. Expand the range of cases both horizontally and vertically. Horizontally, various contexts should be analysed, and vertically, different use cases within the same context should be examined.

Within this process, model exploration, uncertainty, and participatory aspects need to be incorporated, as was identified. The following sections discuss these in more detail.

Uncertainty and exploration

As of now, this approach has not acknowledged uncertainty. An approach that acknowledges uncertainty is imperative if one considers the extreme lack of knowledge associated with our understanding of the world and human behaviour, both in terms of probability distributions and future outcomes (often referred to as ”deep” uncertainty (Walker et al., 2012)). Indeed, the complex characteristics of NbS and the SES where they are intended to function carry with them many structural and behavioural uncertainties, and necessitate an exploratory modelling approach rather than a deterministic one. Therefore, we consider explicit analysis of uncertainty a priority of future research.

Scenario analysis allows researchers to explore and evaluate multiple future scenarios under conditions of uncertainty. By considering a range of possible futures, we can better prepare for and adapt to unexpected changes. By evaluating different strategies, the potential consequences of various actions are better understood. This combination supports policy that is robust under multiple future conditions. Furthermore, it encourages the inclusion of diverse perspectives and values in the research process.

A systematic method for scenario analysis is a design of experiments, where a set of different scenarios to be tested is formulated to explore key drivers, interactions, and outcomes in the model. An approach that surpasses designing experiments is Exploratory System Dynamics Modelling and Analysis approach (ESDMA). ESDMA allows for the methodical examination of various hypotheses concerning model formulation and parameterization and their impact on the types of behavioural dynamics that may emerge (Kwakkel & Pruyt, 2015).

Participatory modelling

Participatory modelling could facilitate collaboration and shared visions, minimizing conflicts and maximize transparency, awareness and comprehension (Pagano et al., 2019). Most importantly, it would address the lack of (local) stakeholders’ engagement, and enhance collaboration among various decision-makers that the NbS concept suffers from (Giordano et al., 2020; Giordano & Pagano, 2023). This is especially imperative considering the alignment of multi-functionality of NbS. Significant steps have been taken within this direction in the SDM field (e.g. Giordano and Pagano (2023), Pagano et al. (2019), or Martín et al. (2021)). This study set out to take a more comprehensive, integrated, and quantitative analysis of multi-functional trade-offs under climate uncertainty, but would greatly benefit from the inclusion of participatory elements along the lines that were described by these authors.

7.5.2. Expanding the research boundary

Multiple future research steps can be taken to expand the research boundary. Below a non-exhaustive list is given:

1. Expanding the SDM by coupling it with methods suited to heterogeneity, such as agent-based modelling or hydro- or morphodynamic modelling tools such as Delft3D, would greatly enhance the utility.
2. This, and previous research (e.g. Gorostiza et al. (2023)), have identified the multi-functional importance of sediment relating to the concept of sediment equity/justice. A SDM model capturing this concept would be of great interest not only to the Ebro delta, but to global cases.
3. The importance of sediment within the system may demand dis-aggregation of sediment transport modes. For instance, sediment deposits at the coastline relates to the fraction of bed load material - wash load will not settle.
4. The geographic scope could be extended to non-deltaic regions to enhance the robustness and scalability of the methodology. Given that the ICE-model is implicitly adaptable to coastal depositional environments, applying a SDM to an estuary could be a logical next step. Similar to deltaic regions, SDM applications on NbS multi-functionality in estuarine contexts have been limited.

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Appendix A: Literature search results

Table A.1: Literature search results

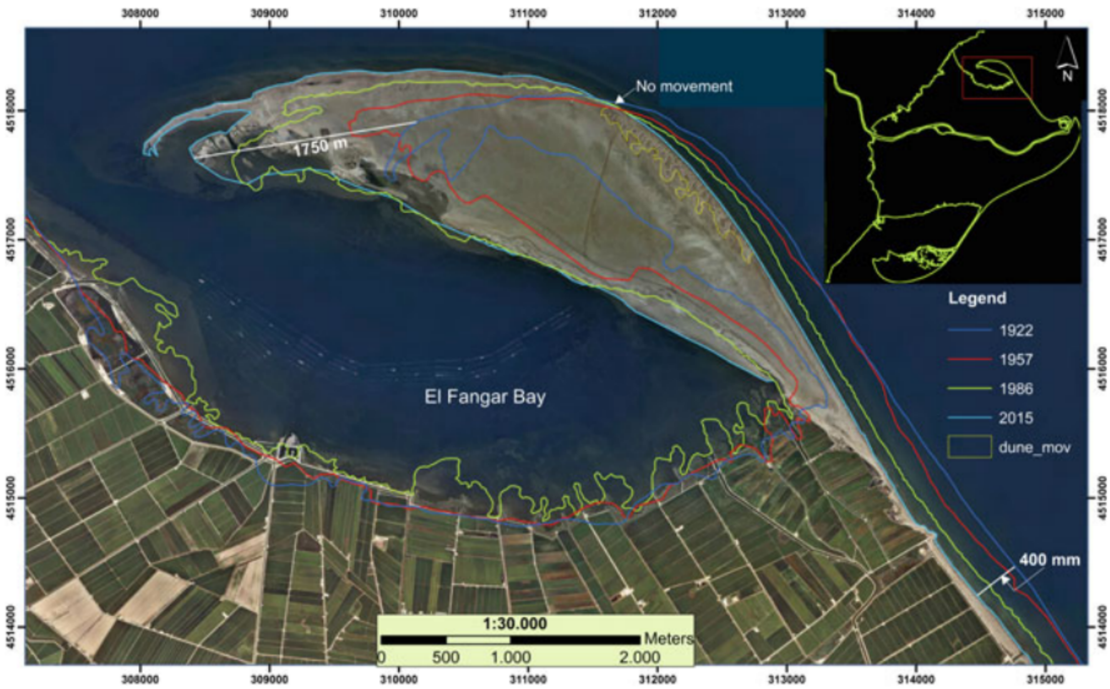
Pino and Marquez, 2023	Complementary ideas for the implementation of nature-based solutions
Viti et al., 2023	Holistic valuation of Nature-Based Solutions accounting for human perceptions and nature benefits
Anguelovski and Corbera, 2023	Integrating justice in Nature-Based Solutions to avoid nature-enabled dispossession
Woroniecki et al., 2023	Contributions of nature-based solutions to reducing people's vulnerabilities to climate change across the rural Global South
Debele et al., 2023	Nature-based solutions can help reduce the impact of natural hazards: A global analysis of NBS case studies
Seddon, 2022	Harnessing the potential of nature-based solutions for mitigating and adapting to climate change
Viti et al., 2022	Knowledge gaps and future research needs for assessing the non-market benefits of Nature-Based Solutions and Nature-Based Solution-like strategies
Cottrell, 2022	Avoiding a new era in biopiracy: Including indigenous and local knowledge in nature-based solutions to climate change
Turner et al., 2022	The Role of Nature-Based Solutions in Supporting Social-Ecological Resilience for Climate Change Adaptation
Welden et al., 2021	Leveraging Nature-based Solutions for transformation: Reconnecting people and nature
Martín et al., 2021	Assessing the long-term effectiveness of Nature-Based Solutions under different climate change scenarios
A. C. Smith et al., 2021	Nature-based Solutions in Bangladesh: Evidence of Effectiveness for Addressing Climate Change and Other Sustainable Development Goals
Gunn et al., 2021	The natural assurance value of nature-based solutions: A layered institutional analysis of socio ecological systems for long term climate resilient transformation
Seddon et al., 2021	Getting the message right on nature-based solutions to climate change
Coletta et al., 2021	Causal Loop Diagrams for supporting Nature Based Solutions participatory design and performance assessment
Hanson et al., 2020	Working on the boundaries—How do science use and interpret the nature-based solution concept?
Giordano et al., 2020	Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis
Ruangpan et al., 2020	Nature-Based Solutions for hydro-meteorological risk reduction: A state-of-the-art review of the research area
Seddon, Daniels, et al., 2020	Global recognition of the importance of nature-based solutions to the impacts of climate change
Seddon, Chausson, et al., 2020	Understanding the value and limits of nature-based solutions to climate change and other global challenges
Chausson et al., 2020	Mapping the effectiveness of nature-based solutions for climate change adaptation
Han and Kuhlicke, 2019	Reducing Hydro-Meteorological Risk by Nature-Based Solutions: What Do We Know about People's Perceptions?
Pagano et al., 2019	Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: A participatory System Dynamics Model for benefits and co-benefits evaluation

Table A.2: Literature search results SDM applications

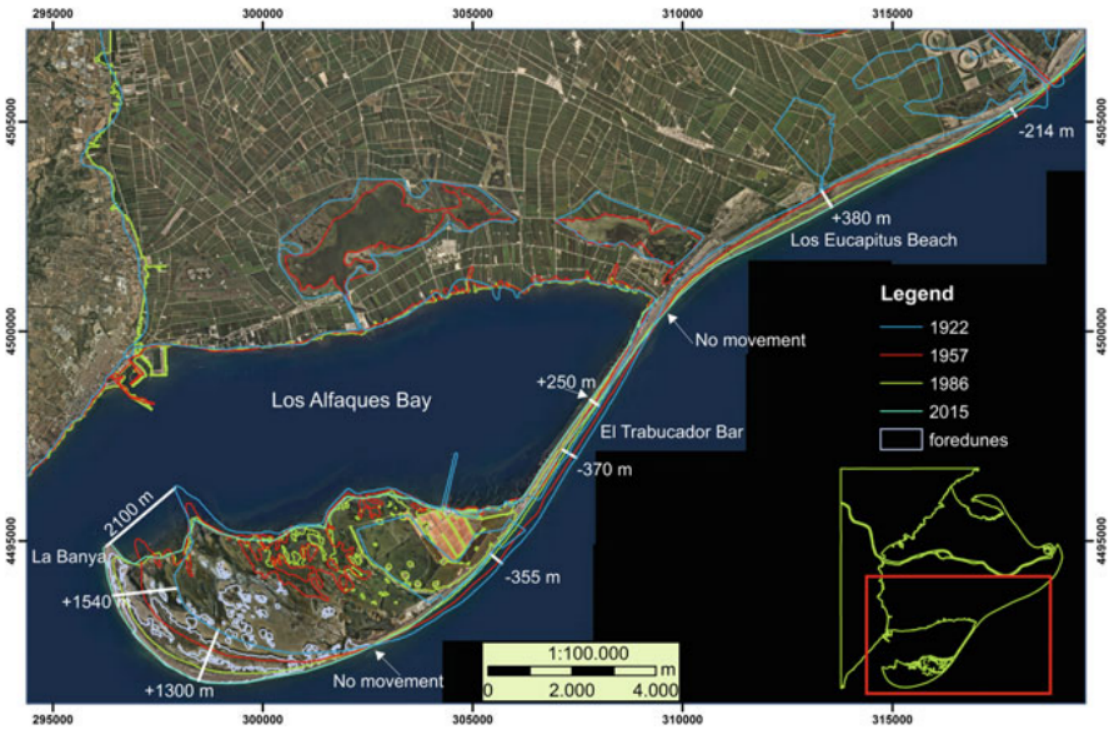
Coletta et al., 2021	Causal Loop Diagrams for supporting Nature Based Solutions participatory design and performance assessment
Giordano et al., 2020	Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis
Martín et al., 2021	Assessing the long-term effectiveness of Nature-Based Solutions under different climate change scenarios
Pagano et al., 2019	Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: A participatory System Dynamics Model for benefits and co-benefits evaluation
Castro, 2022	Systems-thinking for environmental policy coherence: Stakeholder knowledge, fuzzy logic, and causal reasoning
Kotir, 2020	Managing and Sustaining the Coupled Water-Land-Food Systems in the Context of Global Change: How Qualitative System Dynamic Modelling Can Assist in Understanding and Design
Martín et al., 2020	Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals
Almenar et al., 2023	Modelling the net environmental and economic impacts of urban nature-based solutions by combining ecosystem services, system dynamics and life cycle thinking: An application to urban forests

Appendix B: Data and informative maps of the Ebro Delta

Figure B.1: The Ebro Delta Natural Park - Spain, Sentinel-2, 19 July 2021 (European Union, 2021)



(a) Evolution of El Fangar spit



(b) Evolution of Los Alfaques spit, El Trabucador bar and Los Eucaliptus Beach

Figure B.2: Coastline evolution of the Northern and Southern spit (Rodríguez-Santalla & Somoza, 2018)

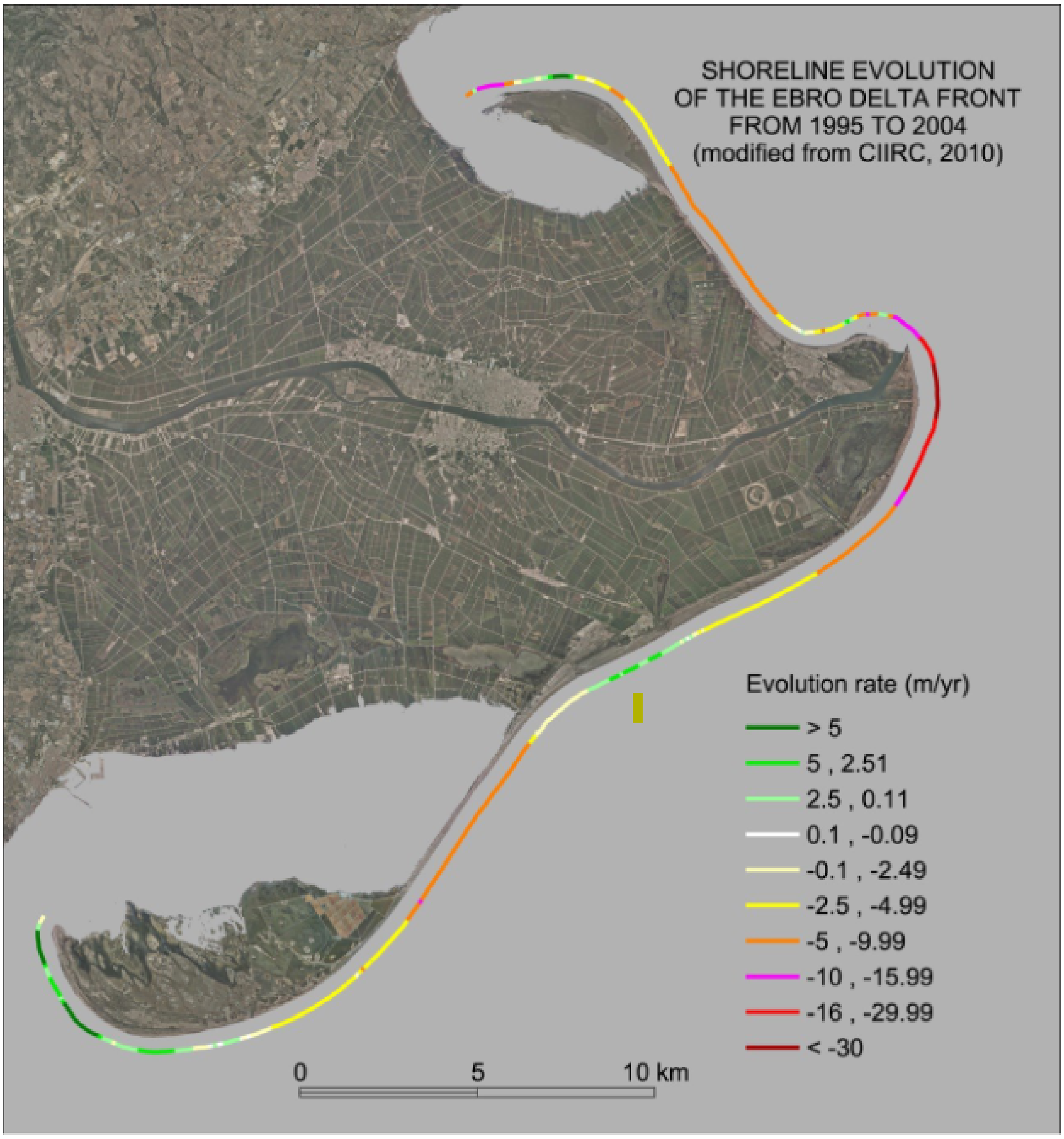


Figure B.3: Distribution of stretches of erosion and accretion along the delta coastline (Rodriguez et al., 2018). In more recent years the distribution has slightly shifted towards more accretion over the entire line with the exception of the mouth

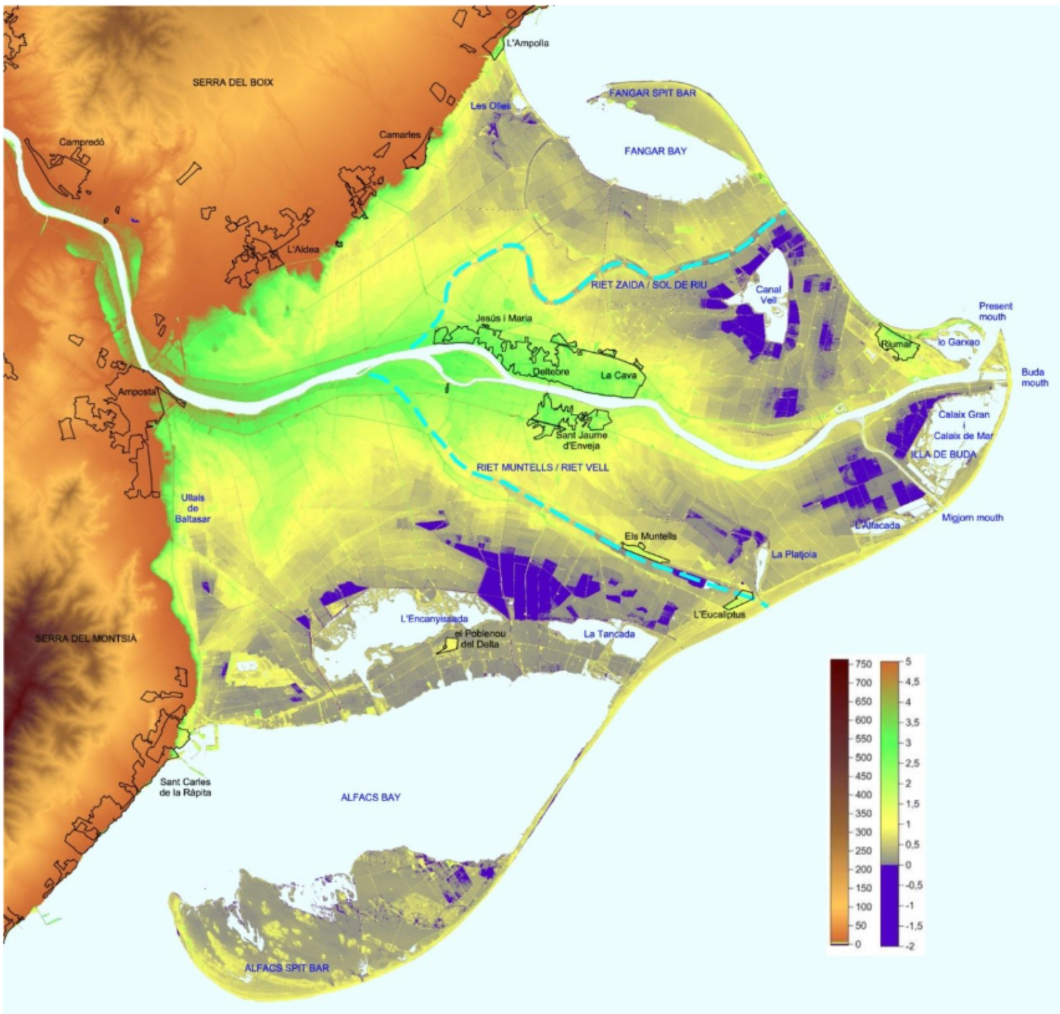


Figure B.4: Elevation map showing the distribution of the main wetlands, urban settlements, ancient river channels (indicated by dotted light blue lines), and other significant geomorphological features (Rodriguez et al., 2018)

RSLR (m)	Area inundated (ha)	
	Open canals	Closed canals
0.10	470	470
0.20	1780	670
0.30	2770	1010
0.40	4420	1550
0.50	5620	2220
0.60	6530	2780
0.70	7270	3190
0.80	7980	3570
0.90	8590	7350

Table B.1: Area inundated under different scenarios of Relative Sea Level Rise (RSLR), either without or with flood transporting irrigation channels closed (CEDEX, 2021).

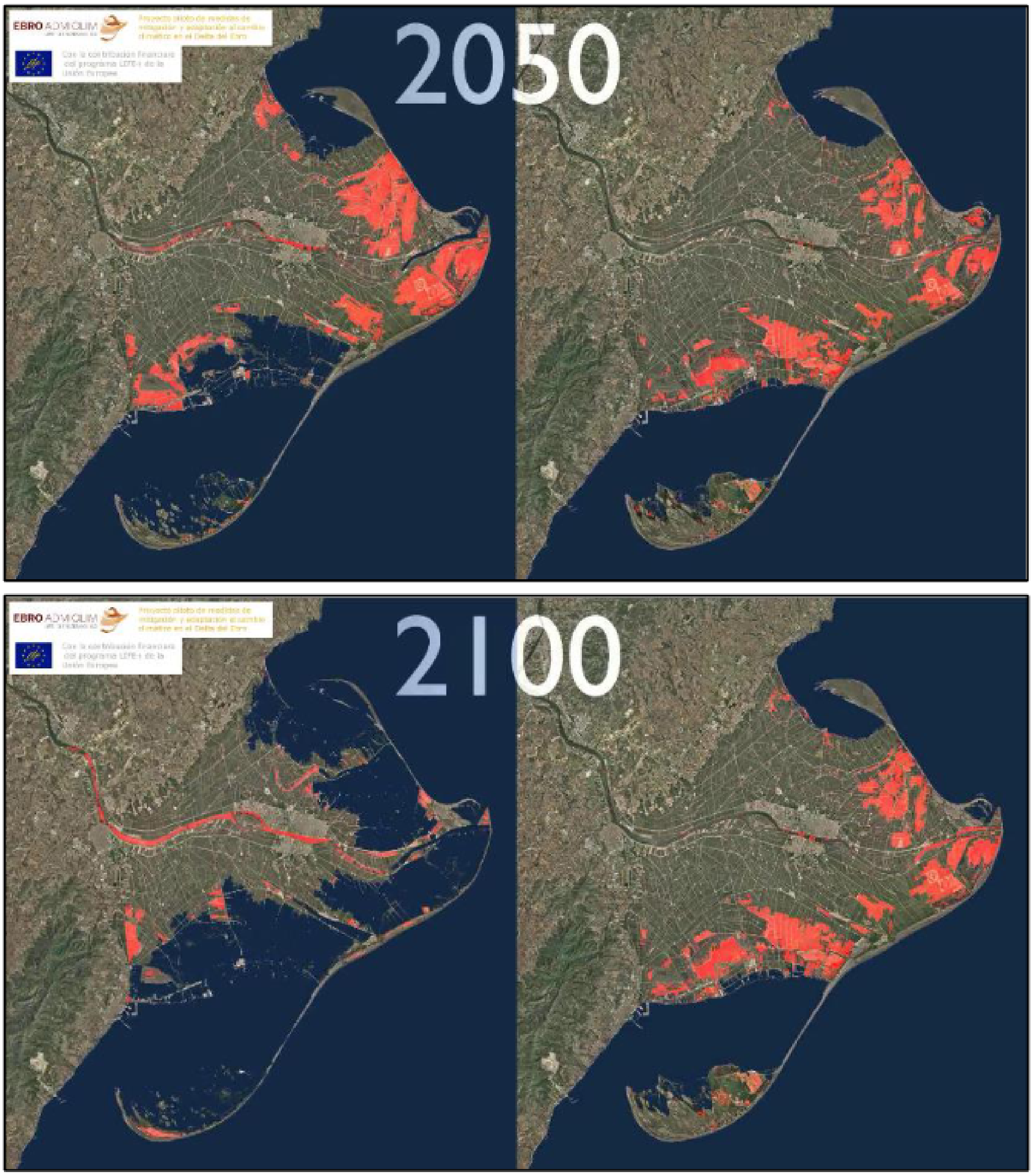


Figure B.5: Flood simulations in the Ebro Delta depict two scenarios: on the left, the evolution with minimal sediment deposition, and on the right, the evolution with an anticipated sediment deposit of approximately 2 million tonnes per year (Officina Catalana del canvi climàtic, 2018). The red areas indicate regions that are currently below sea level due to subsidence but remain unflooded as they are not yet connected to the sea. The sea level rise conforms to the IPCC's most moderate scenario, averaging around 6 mm per year.

Changes in river discharge and sediment transport

Discharge
Peak floods could reach 20,000 m^3/s, while in the summer it was typical to see minimum flows of around 50 m^3/s (Rodríguez-Santalla & Somoza, 2018). Under natural conditions, the river would contribute around 18,000 Hm^3/year (600 m^3/s) at its mouth, but recent decades see only half of that. The 187 dams impound 60% of mean annual runoff and store 7,600 Hm.

Sediment
The pre-dam fluvial sediment flux and bed-load flux are roughly estimated around 600 kg s−1 (20 Mt yr−1) and 71 kg s−1 (2.2 Mt yr−1) respectively (Nienhuis et al., 2017). Bedload transporting river flows (> 900 m^3/s) were greatly reduced after dam construction, and moreover, reservoirs trap 90% of the upstream suspended sediment load and 100% of the upstream bedload. Consequently, modern loads at 50 km upstream of the delta are estimated at about 28 kg s−1 (0.9 Mt yr−1), of which 40% is transported as bedload. The mouth sees 1.6 kg s−1 (0.05 Mt yr−1).

Appendix C: Background ecosystem services

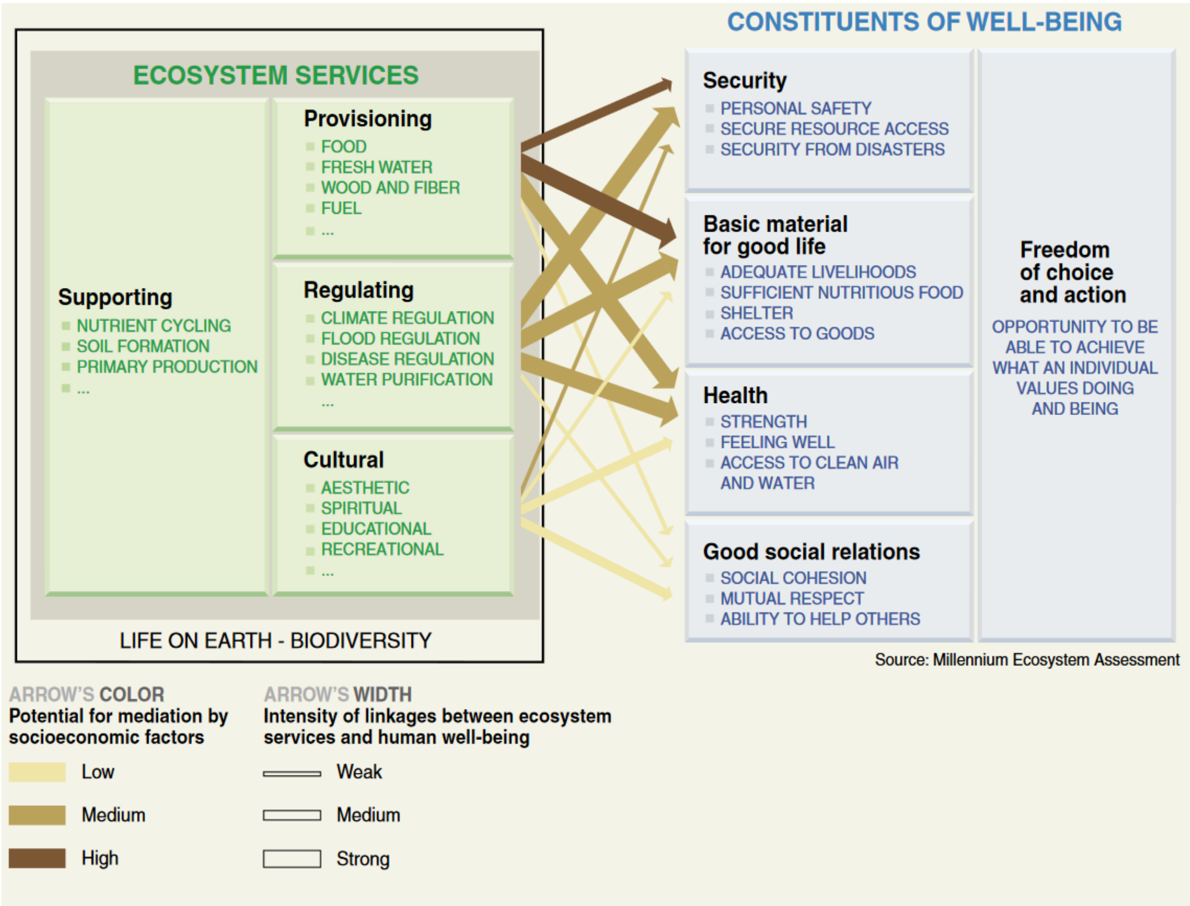
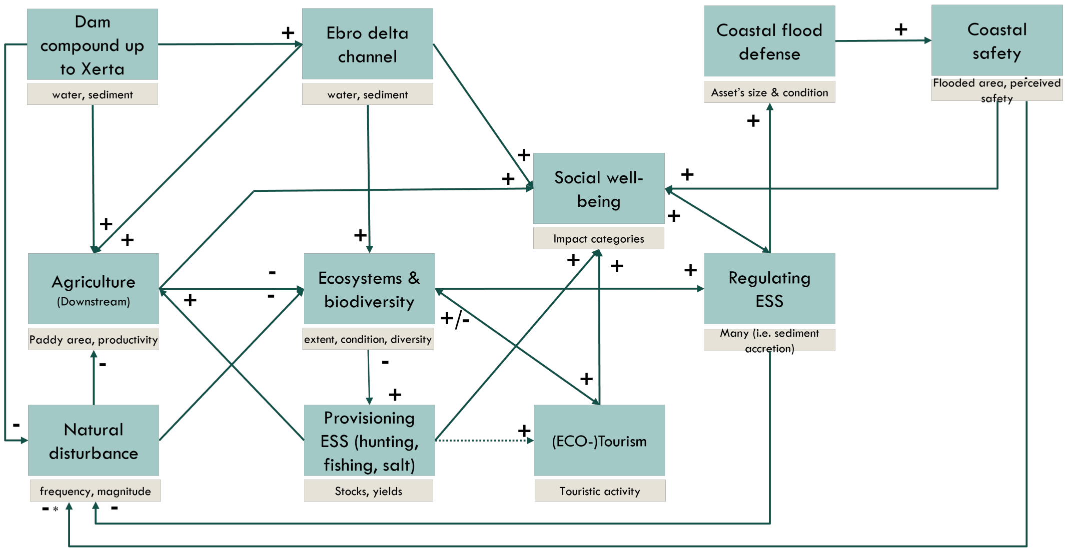
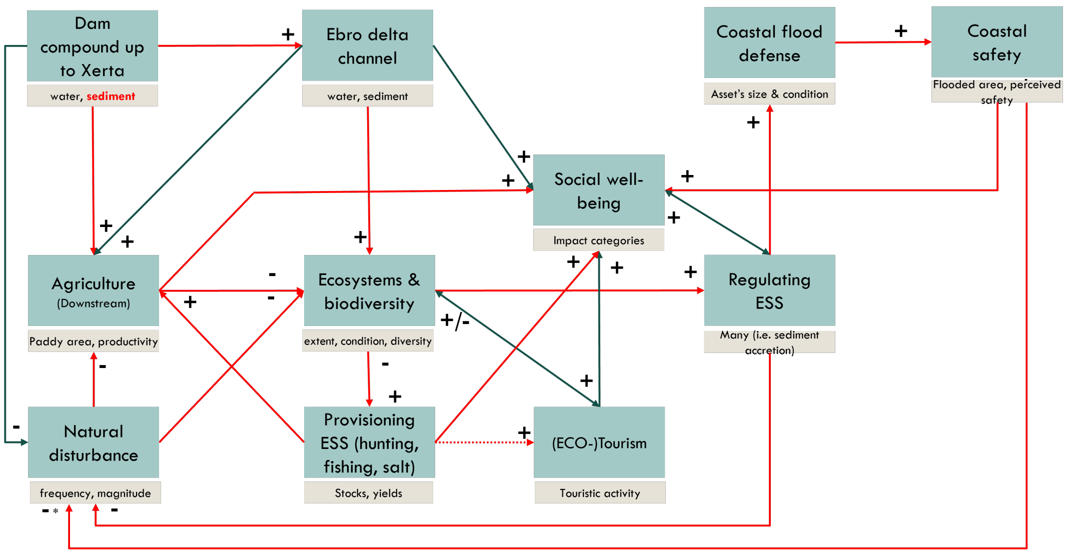


Figure C.1: For an extensive explanation, see (MA, 2005)

Appendix D: ICE-Ebro extended



(a) The brown boxes below the subsystems depict the most important variables within that subsystem. I.e. the Ebro river carries mainly a discharge and a related transported volume of sediment.



(b) Lets say 100% of sediment is retained in the dam compound, than this retained sediment does not arrive downstream in the Ebro delta channel. No fertilizing or delta plain accretion benefits for agriculture are attained. Moreover, the sediment does not contribute to (endemic) habitats condition, further negatively influencing all ESS flows. Primarily, respective regulative ESS are halted, meaning the counter to erosion is too as sediment is not replenished. Subsequently, coastal safety is reduced, meaning that the impact of natural disturbances increases (i.e. more vulnerable to hazards). This in turn negatively influences agriculture, social well-being (via safety loss primarily), and ecosystems & biodiversity further. Additionally, the perceived safety drops meaning a direct negative influence on social well-being is found as well.

Figure D.1: Detailed internal relations of the Ebro-ICE-model. D.1b depicts the far-reaching influence that the elimination of sediment has on the system, as an example.

Appendix E: Sediment transport components

Fluvial sediment transport can be broken down into several components, which will be discussed here. Thorne et al. (2000), San Diego State University (2019) and Wickert (n.d.) have been consulted to write this section.

Total sediment load

The total mass of *solid* sediment particles transported by the stream (thus not including dissolved particles in this definition). It can be categorized by source or transport mechanism, as shown in Figure E.1 and E.3.

Bed load

Component of the total sediment load consisting of particles that move in frequent, successive contact with the bed. Transport occurs at or near the bed, with movement happening through rolling, sliding, or saltation (hopping motion).

Suspended load

Component of the total sediment load consisting of sediment particles that move continuously in suspension within the water column, driven by the action of turbulence. Particles transported as suspended load are finer than those in the bed load.

Dissolved load

The dissolved load consists of soluble materials, such as ions and minerals, that are completely dissolved in the water. Dissolved load originates from chemical weathering of rocks, soil, and other materials, as well as from human activities such as agriculture and industrial processes. Deposition only occurs if there is a change in the chemical composition of the water (e.g., evaporation, chemical reactions). As the total sediment load typically includes only the solid particles transported by a stream or river, the dissolved load is often not included.

Bed material load

Portion of the total sediment load that is composed of grain sizes found in significant quantities in the stream bed. The bed material includes the bed load plus the portion of the suspended load made up of particles of a size that are found in substantial amounts in the bed. Bed material load represents the coarser fraction of the sediment load, which may have originated from the channel bed and can be subject to deposition under certain conditions.

Wash load

The finer fraction of the total sediment load, representing all particles that have not originated from the channel bed. Essentially, the wash load is a subset of the suspended load, representing particles largely unaffected by the flow hydraulics. Thus, the wash load will not deposit even under very low or no flow.

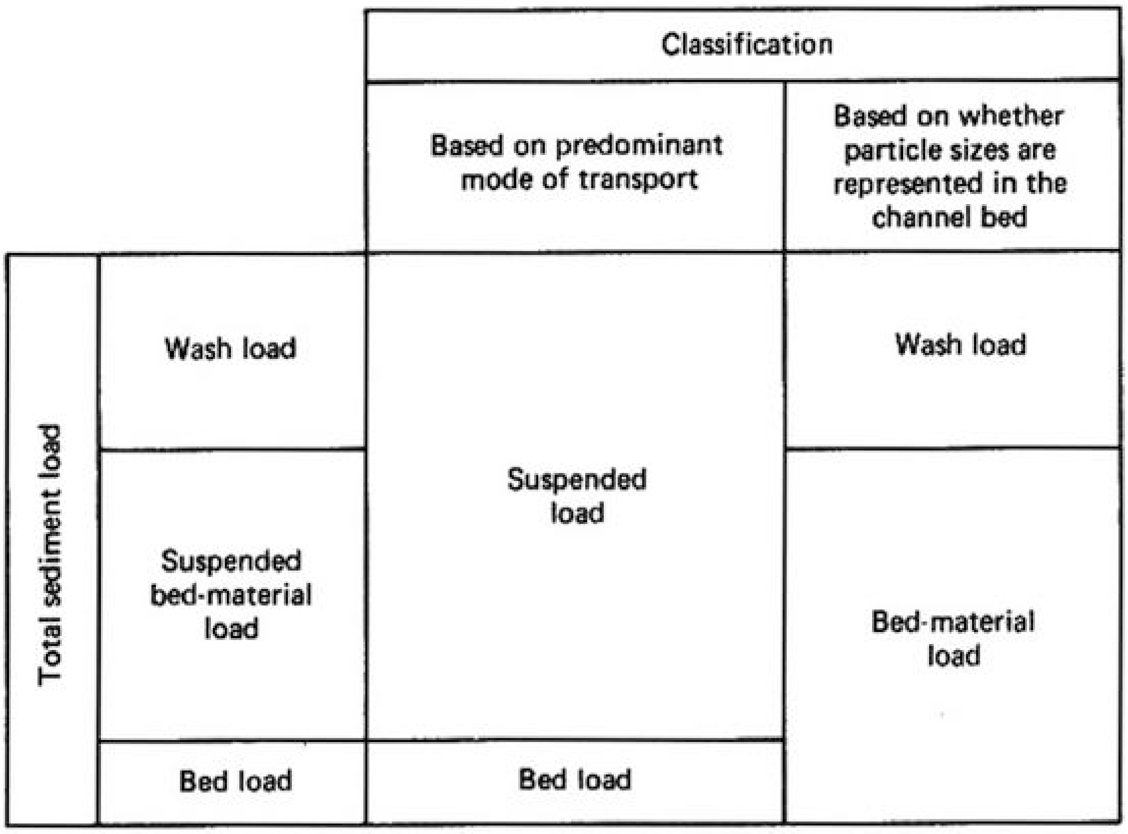


Figure E.1: Classifications of fluvial sediment load (San Diego State University, 2019)

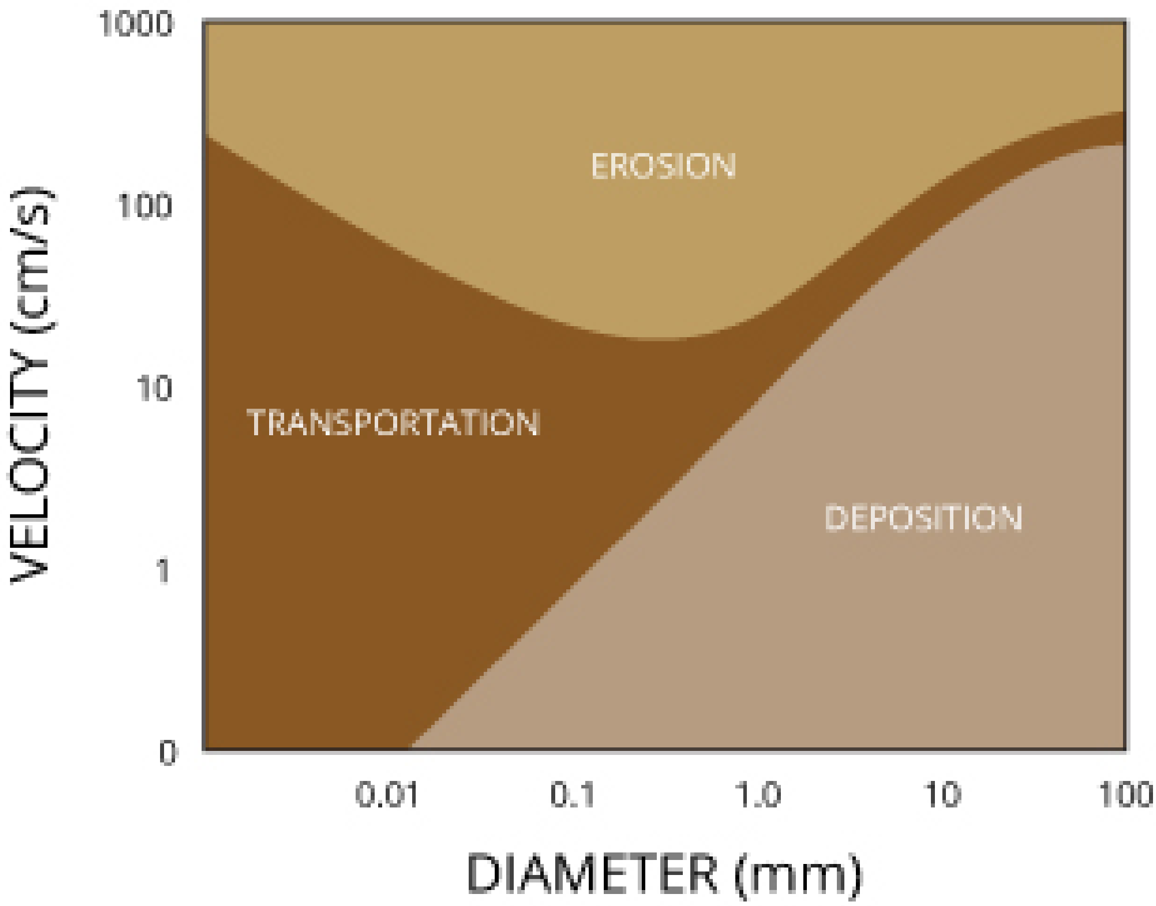
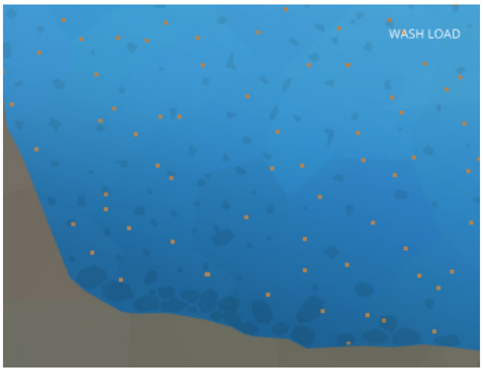
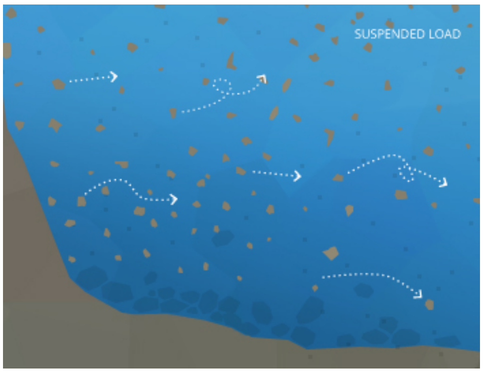


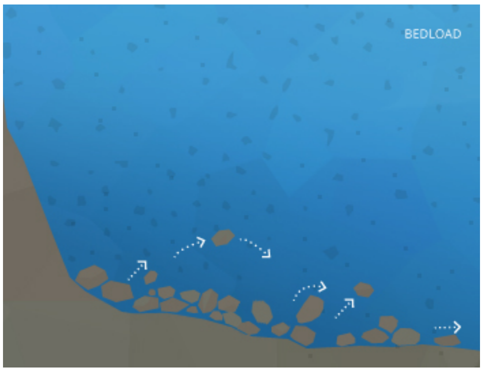
Figure E.2: Rough relationship between transported sediment particles and flow rate (Fondriest Environmental, 2014). Transport is possible after the motion is initiated (i.e. erosion)



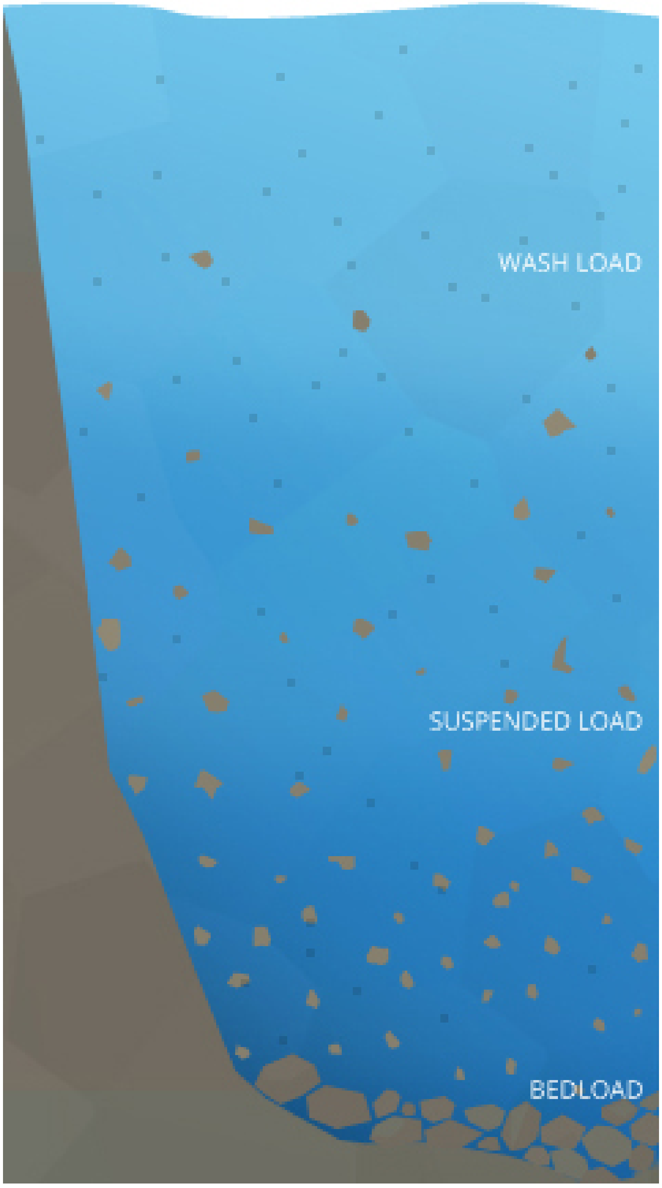
(a) Wash load



(b) Suspended load



(c) Bed load



(d) Total sediment load

Figure E.3: Components of total sediment load (Fondriest Environmental, 2014)

Appendix F: Natural flood defence effectiveness

Effectiveness of natural flood defences

Coastal natural flood defences maintain safety of the hinterland in three ways: 1) They withstand wave impacts, 2) they partially reflect wave energy, and 3) they dissipate wave energy through friction, turbulence, and erosion primarily (Grases et al., 2020). They are however significantly more vulnerable to stationary water-level increases, meaning RSLR is the dominant long-term threat, see also section 5.4.

The effectiveness of natural flood defences in providing flood protection relies on various factors such as dune height distribution, beach width and condition, vegetation density, the swash-zone profile shape, and more, but also the characteristics of storms (such as intensity and duration) (Barbier et al., 2011; Toimil et al., 2023). As such, the shoreline response to coastal dynamics significantly affects the protection against subsequent coastal flooding. For this reason, it is imperative to couple flooding and erosion over time to assess beach protection benefits, as argued for by Toimil et al. Beaches and dunes not only absorb and distribute wave energy, but also demonstrate resilience by recovering from erosion induced by storms and SLR during calm periods. The amount (and profile) of sand volume retained in the system affects the ability to replenish eroded areas and maintain dune integrity; this is one of the reasons why sediment-trapping vegetation provides a crucial role in natural flood defences, and why beach nourishment is an important coastal protection measure for many regions (Costa et al., 2023; de Schipper et al., 2021; Toimil et al., 2023). See Kindeberg et al. (2023) for an extensive discussion on the interaction between beach nourishment and ecology within the NbS lens. In the upcoming years, erosion from storms combined with chronic coastline retreat driven by SLR will continue to diminish the width of the coastal landscape (Toimil et al., 2023).

Dissipating effectiveness of vegetated coastal habitats

Vegetation provides multiple benefits to the natural flood defence. Here we discuss only main effects for dunes and wetlands (aggregating and omitting other types like seagrass).
Coastal wetlands are very effective as a buffer against storm impacts and erosive processes (Barbier et al., 2011; Ibáñez & Caiola, 2021b; Möller et al., 2014). Möller et al. (2014) found that (tidal) salt marshes effectively dissipate even extreme storm waves, while maintaining resilience, although these were tidal marshes. Through vegetation (root) structures, sediment trapping efficiency is increased (Barbier et al., 2011). Moreover, wetlands may modulate peak flows by storing water (slowly releasing it over time) (Ferreira et al., 2023). Of course, wetlands provide many other ESS like water purification, water balance modulation, recreation, food provisioning, and others.

Vegetation offers additional benefits to dunes: it dissipates wave energy more effectively than bare soil, increases the dune's mechanical resistance, and helps dunes recover sand by trapping wind-driven sediments with its plant structure (Barbier et al., 2011; Costa et al., 2023).

Appendix G: Habitat condition change

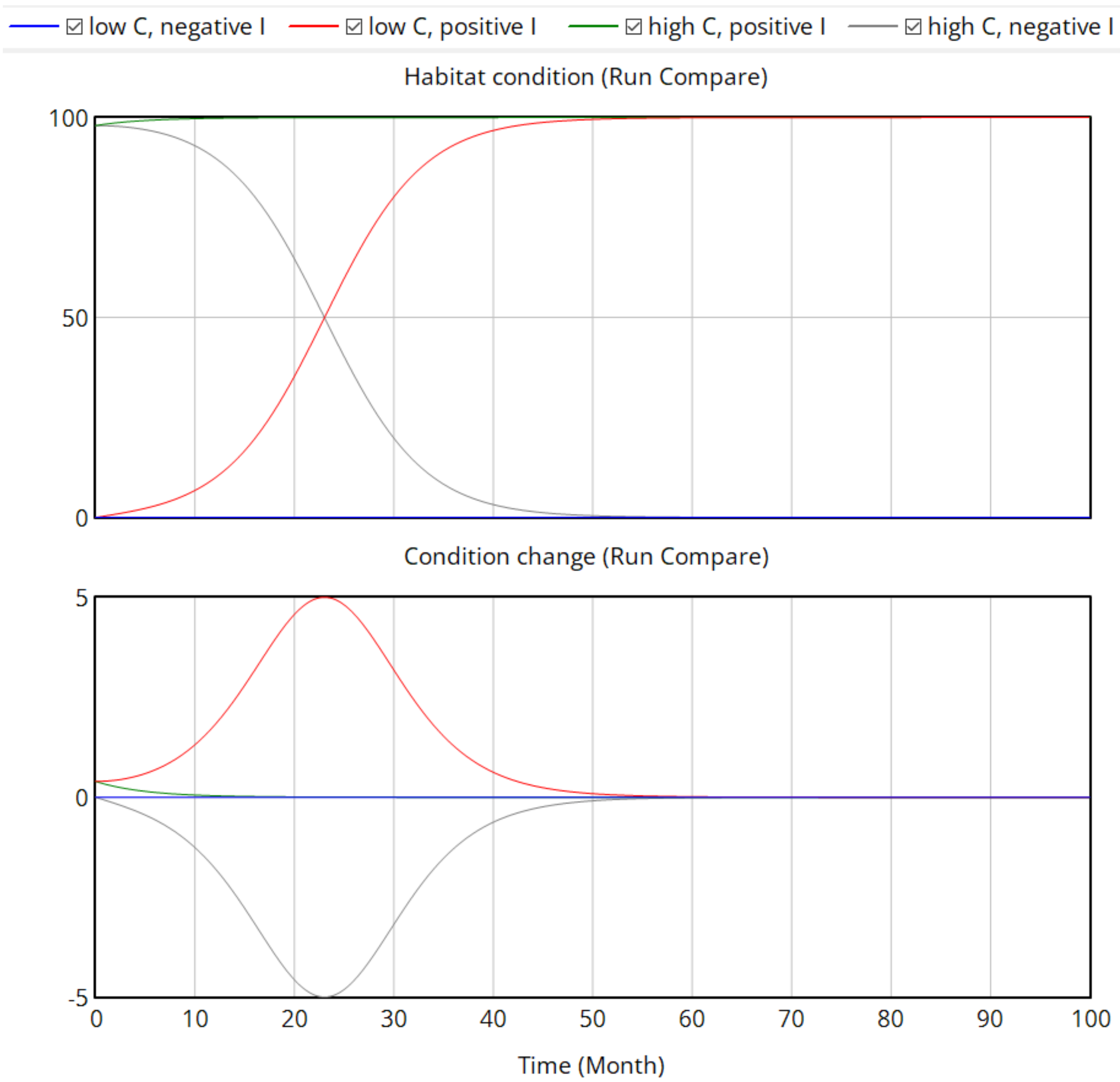
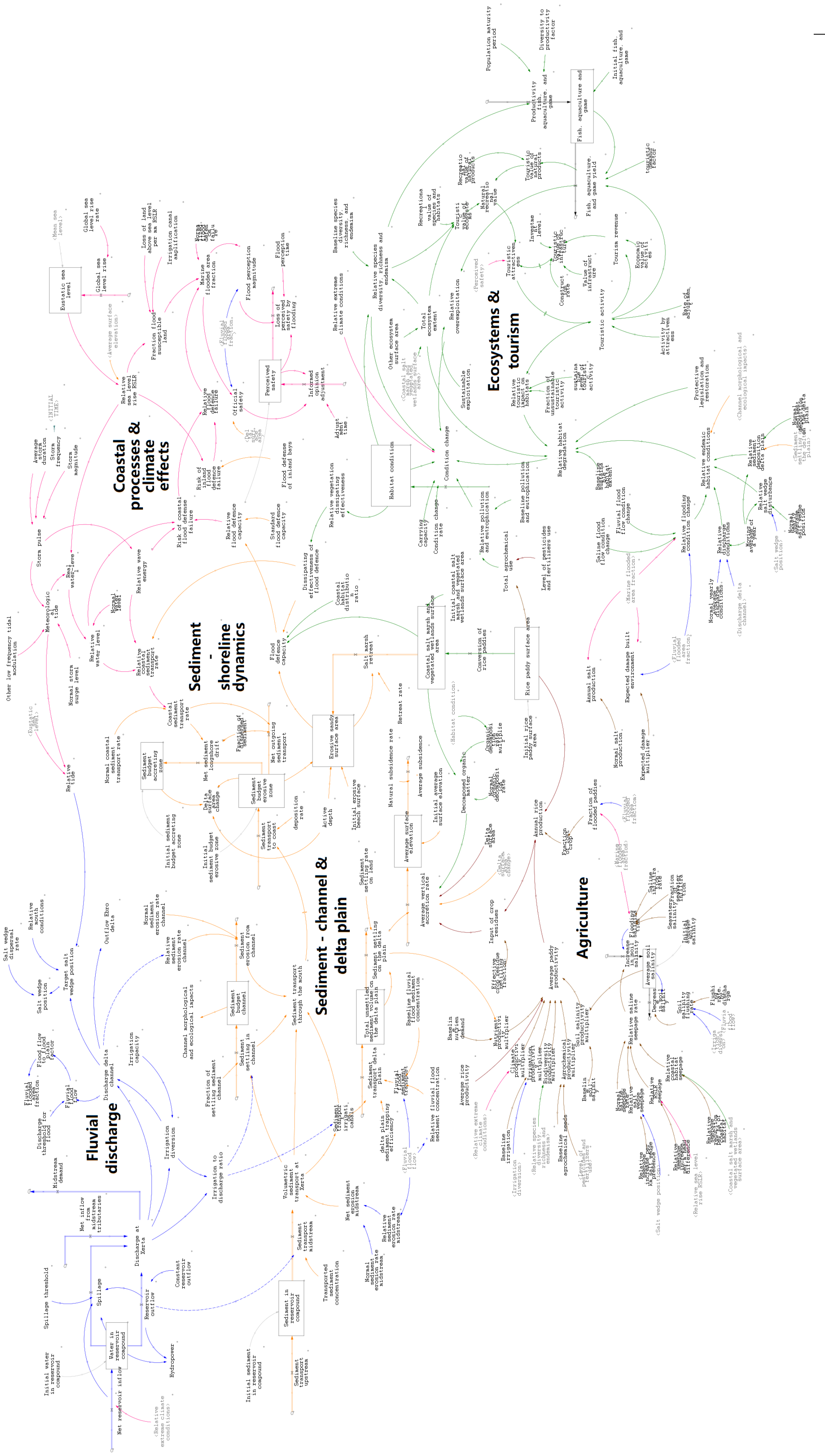


Figure G.1: Scenarios for habitat condition (C) and change against *constant* impacts (I). Habitat condition is scaled from 0 to 100 (carrying capacity = 100). The restoration or degradation process of an ecosystem can be represented by an S-shaped curve (the logistic curve). The upper and lower asymptote represent saturation and depletion respectfully. I.e. if a habitat with maximum condition (i.e. saturated conditions) suffers a constant disturbance, initially, there is some resilience against change. As populations begin to suffer damage, feedback between different components begins to accelerate condition loss. when habitat condition is close to zero, it implies severe degradation, and further negative impacts might not cause a rapid decrease since there's not much left to degrade. In contrast, when a depleted ecosystem is allowed to restore through a constant positive impact, initially, it takes a while to build life-supporting capacity. As recovery progresses, productivity gradually rises until it peaks. Past this stage, the ecosystem may reach a saturation point where productivity starts declining due to resource constraints.

Appendix H: Model

See next page.


Coastal processes & climate effects
Sediment - shoreline dynamics
Ecosystems & tourism
Sediment - channel & delta plain
Agriculture
Fluvial discharge

Appendix I: The model equations

The tables with model equations per submodel are given on the subsequent pages. These are the fluvial discharge, Sediment - channel & delta plain, Sediment - shoreline dynamics, Coastal processes & climate effects, Agriculture, and finally Ecosystems & biodiversity submodel.

Explanations are given if an equation demands more context. Furthermore, assumptions are stated *if* they have not been disclosed in the main text. We denote the input of data with an α, as our formalisation has not included full data-specification (we have however specified with regard to data availability).

The continuous table functions or multiplier functions are classified (type) as increasing or decreasing (CTF_{inc} and CTF_{dec} respectfully). Although we have delineated the multiplier equations in 6.4.1, the formalized Vensim system dynamics model has not specified the equations in full as we have not parameterized the model. Thus, the three multiplier parameters A, B & g have neither been specified for this research. In that regard, the respective equations below only give the multiplier input.

Finally, we expect there to be some model errors in the specification: as we have not specified the multiplier functions, many unit errors are still unresolved. Furthermore, these cloud other potential model errors. Without running, equations have not been tested for expected or extreme behaviour.

Fluvial discharge					
Name	Type	unit	Equation	Explanation	Assumptions
Water in reservoir compound	Stock	Hm3	Net reservoir inflow-Reservoir outflow-Spillage Initial value: Initial water in reservoir compound		
Initial water in reservoir compound	Const	Hm3	α		
Net reservoir inflow	Flow	Hm3/Month	α * Extreme climate conditions	Primarily; Inflow + precipitation + evaporation. Note that these are all affected by climate change.	Evaporation is affected by the surface area of the reservoir (and other factors) in reality, which are not taken into account
Reservoir outflow	Flow	Hm3/Month	Constant reservoir outflow		
Spillage	FLow	Hm3/Month	IF THEN ELSE(Water in reservoir compound + (Net reservoir inflow - Reservoir outflow)*Month > Spillage threshold, Net reservoir inflow - Reservoir outflow ,0)		Assumed that any discharge exceeding the threshold is spilled linearly.
Constant reservoir outflow	Aux	Hm3/Month	α	Following dam operation schedule/plan	
Discharge at Xerta	Aux	Hm3/Month	Reservoir outflow + Spillage - Midstream demand - Net inflow from midstream tributaries		
Net inflow from midstream tributaries	Flow	Hm3/Month	α	The combined discharge from all tributaries between the dam compound and Xerta	
Midstream demand	Flow	Hm3/Month	α	The combined demand from the midstream section	
Spillage threshold	Const	Hm3	α	Threshold of dam compound for spillover	
Hydropower	Aux	Watt	No specified equation.	Included for comprehensiveness. Equation would follow: P = m x g x Hnet x η m = flow rate in litres per second η = product of all component efficiencies ≈ 0.9 g = 9.81 Hnet = net head (calculated with volumetric profile of reservoir)	
Discharge delta channel	Aux	Hm3/Month	Discharge at Xerta - Irrigation diversion		
Irrigation diversion	Aux	Hm3/Month	IF THEN ELSE(Discharge Ebro at Xerta < α , β, Irrigation capacity)	Irrigation channels start at Xerta. A servere drought (α) will lead to temporary irrigation diversion cuts (β) (e.g. 2023 saw a 50% reduction)	
Irrigation to Discharge ratio	Aux	dmnl	Irrigation diversion/Discharge Ebro at Xerta		
Irrigation capacity	Const	Hm3/Month	α	Max capacity of the irrigation canals, which is always used except during crisis.	
Outflow Ebro delta	Aux	Hm3/Month	Discharge delta channel	Water flowing out of the mouth of the Ebro delta, into the sea.	Assumed to match the discharge through the channel (no losses or gains), with precipitation and evaporation considered to be zero
Fluvial flood flow	Aux	Hm3/Month	MAX(0,Discharge delta channel - Discharge threshold for flood)	If discharge of channel exceeds the capacity (accounting for the profile), a fluvial flood will occur, inundating a certain fraction of land	Assumed that any discharge exceeding the threshold creates a linear flood of respective magnitude.
Discharge threshold for flood	Const	Hm3/Month	α	channel discharge capacity of bottleneck (i.e. minimum of maximum capacity of Ebro channel)	
Flood flow to flood plain factor	CTF_inc	Dmnl	Fluvial flood flow		
Fluvial flooded area fraction	Aux	Dmnl	Flood flow to flood plain factor	Calculates the flooded surface area with respect to fluvial flood flow	For simplicity, only fluvial flood flow used for calculation, e.g.surface area level is not taken into account.
Salt wedge position	Aux	km	DELAY1(Target salt wedge position, Salt wedge dispersal rate)	Real salt wedge position, which pursues the theoretical position but is delayed	
Target salt wedge position	Aux	km	IF THEN ELSE(Discharge Ebro delta channel * (1/2.628) >400, Discharge Ebro delta channel * (1/2.628), Discharge Ebro delta channel * (1/2.628) * Relative water level * Relative sill height) ([(0,0)-(10,10)],(0,32),(90,32),(100,18),(300,18),(350,0),(1000,0))	(1/2.628) = hm3/month to m3/s. The theorethical position of the salt wedge based on input variables.	Reality is slightly more dynamic and uncertain
Salt wedge dispersal rate	Const	Month	α	Rate of pursuit	
Relative sill height	CTF_inc	dmnl		A deep mouth (with low sill) is unfavorable for salt wedge position, allowing more saline water intrusion, and vice versa.	Reality is slightly more dynamic and uncertain
Relative tide	CTF_dec	dmnl	Meteorological tide + Eustatic sea level	High tide advances the salt wedge through a head difference. RSLR is not applicable as effects of subsidence do not count for the river surface level.	

Sediment – Channel & delta plain					
Name	**Type**	**unit**	**Equation**	**Explanation**	**Assumptions**
Sediment in reservoir compound	Stock	m*m*m	Sediment transport upstream - Sediment transport midstream Initial value = Initial sediment in reservoir compound	Sediment transport from upstream >> Sediment transport downstream (meaning there are no extreme behaviour difficulties)	Loss of hydropower capacity due to siltation not included
Sediment transport upstream	Flow	m*m*m/Month	α		
Sediment transport midstream	Flow	m*m*m/Month	Reservoir outflow * Transported sediment concentration		
Transported sediment concentration	Const	m*m*m/Hm3	α	Sediment in water (not compounded by the dams)	Reality is not linear. Dependent on discharge rate, particle sizes, bed profile, etc.
Volumetric sediment transport at Xerta	Aux	m*m*m/Month	Sediment transport midstream + Net sediment erosion midstream		
Normal sediment erosion rate midstream	Aux	m*m*m/Month	α		
Relative sediment erosion rate midstream	CTF_inc	Dmnl	Fluvial flood flow		
Net sediment erosion midstream	Aux	m*m*m/Month	Normal sediment erosion rate midstream * Relative sediment erosion rate midstream	Channel erosion (e.g. scour) - Channel sedimentation. Finally, under natural conditions fluvial-dominated deltas always have river sediment inputs in excess of what is deposited in the delta plain and this sediment is deposited on the delta front, especially during large flood events that carry a significant amount of the annual sediment load	Aggregates main channel and tributaries. α is assumed constant, with a flood flow linearly increasing the erosion. Not constant and not linear in reality.
Initial sediment in reservoir compound	Const	m*m*m	α		
Sediment transport through the mouth	Aux	m*m*m/Month	Volumetric sediment transport at Xerta - Sediment settling in channel - Sediment transport farmland + Sediment erosion from channel		
Sediment transport irrigation canals	Aux	m*m*m/Month	Volumetric sediment transport at Xerta * Irrigation to discharge ratio		Assumed is that sediment concentration in irrigation canals is equal to sediment concentration in delta channel.
Sediment transport delta plain	Flow	m*m*m/Month	Sediment transport irrigation canals + delta plain sediment trapping efficiency * Fluvial flood sediment transport	In case of a flood, not all sediment is trapped.	Assumed that sediment from irrigation canals fully settles, whereas sediment from a flood does not settle in full.
Total unsettled sediment volume on the delta plain	Stock	m*m*m	0; Sediment transport farmland - Sediment settling on the delta plain	Sediment volume suspended into water on farmland, has not settled on surface yet. No initial unsettled volume (0)	It is assumed 100% is deposited. Farmland and habitats are aggregated, while irrigation only inundates rice paddies.
Sediment settling on the delta plain	Flow	m*m*m/Month	Total unsettled sediment volume on the delta plain/Sediment settling rate on land		
Sediment settling rate on land	Const	Month	α		Assumed constant
Delta plain sediment trapping efficiency	Const	dmnl	α	Not all sediment in flood flow will settle. More vegetation increases the sediment trapping efficiency, however, this effect has been left out due to model scope.	Assumed constant. Reality is not linear, dependent on flood dynamics, flooded surface profile, sediment characteristics, etc
Baseline fluvial flood sediment concentration	Const	m*m*m/Hm3	α		
Relative fluvial flood sediment concentration	CTF_inc	dmnl	Fluvial flood flow	The higher the flood, the more sediment	Complicated realitionship depending on many variables
Fluvial flood sediment transport	Aux	m*m*m/Month	Baseline fluvial flood sediment concentration * Relative fluvial flood sediment concentration * Fluvial flood flow		
Average vertical accretion rate	Flow	m/Month	(Sediment settling on the delta plain + input of crop residues + Decomposed organic matter) / (Delta surface area - Delta surface area change)	Average of all delta area (homogeneous)	Aggregation of different components onto one surface area
Average surface elevation	Stock	m	Average vertical accretion rate-Average subsidence Initial value = Initial average surface elevation		
Initial average surface elevation	Const	m	α		
Average subsidence	Flow	m/Month	Natural subsidence rate		
Natural subsidence rate	Const	m/Month	α	Artificial subsidence is null	Assumed constant
Sediment settling in channel	Flow	m*m*m/ Month	(1-Irrigation to discharge ratio) * Volumetric sediment transport at Xerta * Fraction of settling sediment channel	(In) A fraction settles in relation to the discharge rate. As discharge is >> 0, most sediment does not settle and remains suspended.	
Sediment budget channel	Stock	m*m*m	Sediment settling in channel - Sediment erosion from channel	(Sn)	Complicated realitionship depending on many variables. Transport capacity is not included.
Sediment erosion from channel	Flow	m*m*m/ Month	Relative sediment erosion rate channel * Normal sediment erosion rate channel	(On) (often called scour)	
Relative sediment erosion rate channel	CTF_inc	dmnl	Discharge delta channel	If very big, larger erosion than normal	
Normal sediment erosion rate channel	Aux	m*m*m/ Month	α	about 30 mm a year	
Channel morphological and ecological impacts	CTF_dec	dmnl	Sediment budget channel		We assume more sediment leads to better conditions as currently the channel is sediment starved. This relationship will be more similar to a normal curve in reality
Fraction of settling sediment channel	Const	dmnl	α		Assumed constant

Sediment – Shoreline dynamics					
Name	Type	unit	Equation	Explanation	Assumptions
Sediment budget erosive zone	Stock	m*m*m	Sediment transport to coast-Net outgoing sediment transport-Net sediment longshore drift		
Sediment transport to coast	Flow	m*m*m/Month	DELAY1(Sediment transport through the mouth, deposition rate)		
Net outgoing sediment transport	Flow	m*m*m/Month	Fraction of dispersed sediment * Coastal sediment transport rate	Sediment sink out of system boundary	
Net sediment longshore drift	Flow	m*m*m/Month	(1- Fraction of dispersed sediment) * Coastal sediment transport rate		Aggregation of all sediment transported from erosive zone to accreting zone
Deposition rate	Const	Month	α		Assumed constant
Fraction of dispersed sediment	Const	Month	α		Assumed constant
Initial sediment budget erosive zone	Const	m*m*m	α	Set to the sediment deficit respective to the time at the start of the model	
Normal coastal sediment transport rate	Const	m*m*m/Month	α		Assumed constant
Sediment budget accreting zone	Stock	m*m*m	Net sediment longshore drift Initial value: Initial sediment budget accreting zone		
Initial sediment budget accreting zone	Const	m*m*m	α	Set to the sediment in the accreting zone respective to the time at the start of the model	
Delta surface area change	Aux	m*m	(Sediment budget accreting zone - Sediment budget erosive zone) / Active depth	Set to the surface area loss respective to the time at the start of the model	
Active depth	Const	m	α		
Erosive sandy surface area	Stock	m*m	Sediment budget erosive zone/Active depth + Salt marsh retreat		
Salt marsh retreat	Flow	m*m/Month	IF THEN ELSE(Erosive sandy surface area<0.1, Erosive sandy surface area/Retreat rate, 0)	If sandy surface retreats, salt marsh degrades and becomes sandy surface.	Assumed linear relationship, and to kick in at threshold
Retreat rate	Const	Month	α		
Flood defence surface area	Aux	m*m	Coastal salt marsh and vegetated wetlands surface area + Erosive sandy surface area		
Dissipating effectiveness of flood defense	Aux	dmnl	1 + (MAX(0, (Coastal salt marsh and vegetated wetlands surface area/Flood defense surface area) * Natural flood defense effectiveness * 0.5)	Multiplication factor for flood defence. 1 = no additional effectiveness, 1.5 = maximum additional effectiveness.	Complicated realitionship depending on many variables.
Flood defence capacity	Aux	m*m	Flood defense surface area * Dissipating effectiveness of flood defense		
Relative coastal flood defence capacity	Aux	dmnl	Flood defence capacity/Standard flood defense capacity		
Standard flood defence capacity	Const	m*m	α		
Relative inland flood defence capacity	Aux	m	α	No hydrodynamics, so defence capacity is given in relation to crest height.	Aggregation of failure mechanisms into overtopping

APPENDIX I. THE MODEL EQUATIONS

Coastal processes & climate effects					
Name	Type	unit	Equation	Explanation	Assumptions
Risk of coastal flood defence failure	Aux	dmnl	Relative water level * Relative wave energy - Relative coastal flood defense capacity	If risk > 0 there is a flood. The higher risk, the bigger the flood. Can go negative with higher coastal safety	
Risk of inland flood defence failure	Aux	dmnl	Relative sea level rise RSLR - Relative inland flood defence capacity	If risk > 0 there is a flood. The higher risk, the bigger the flood. Can go negative with higher coastal safety	
Flood defence failure	Aux	dmnl	MAX(0, Risk of coastal flood defense failure + Risk of inland flood defence failure)	If risk > 0 there is a flood. The higher risk, the bigger the flood. Can't go negative. Either a there is a flood of a certain magnitude, or there isn't .	assumed that double failure (coastal & inland) linearly increases magnitude respective to components
Relative wave energy	CTF_inc	dmnl	Storm pulse		
Relative water level	CTF_inc	dmnl	Real water-level		
Normal water level	Const	m	α		
Relative coastal sediment transport rate	Aux	dmnl	Relative water level * Relative wave energy - Dissipating effectiveness of flood defense	Flood defence can dissipate wave energy	
Real water-level	Aux	m	Relative sea level rise RSLR + Meteorological tide		
Meteorological tide	Aux	m	Storm pulse * Normal storm surge level + Other low frequency tidal modulation		
Relative sea level rise RSLR	Aux	m	Eustatic sea level - Average surface elevation		
Other low frequency tidal modulation	Aux	m	α	Respective to weather and tidal dynamics	
Normal storm surge level	Const	m	α	Average of a moderate storm	
Storm pulse	Aux	m	PULSE(Storm frequency, Average storm duration) * Storm magnitude		Storm is assumed to be of a constrant strength and duration
Average storm duration	Const	Month	α		Assumed constant
Storm frequency	Aux	dmnl	α	time series of storms	
Storm magnitude	Aux	m	α	Expressed in surge level	
Eustatic sea level	Stock	m	Global sea level rise intitial value: Mean sea level		
Global sea level rise	Flow	m/Month	Global sea level rise rate		
Global sea level rise rate	Aux	m/Month	α	Respective to climate scenarios	
Fraction of flood susceptable land	Aux	Dmnl	Relative sea level rise RSLR * Loss of land above sea level per mm RSLR * Irrigation canal amplification	land susceptible to inundation. Irrigation canals amplify the flood propagation, and thereby the flooded area	Assumed to be linearly related to RSLR (Surface area level below sea level has a high inundation rate), and linearly amplified by canals
Loss of land above sea level per mm RSLR	Aux	1/m	α	Land that subsides below sea level	
irrigation canal amplification	Aux	Dmnl	α		
Normalized flood defence failure	Const	Dmnl	α	variable that normalizes the flood defence failure	
Marine flooded area fraction	Aux	m*m	(min(1.25, Relative flood defence failure/Normalized flood defence failure)) * Fraction flood susceptible land	Depending of flood magnitude, either less, equal, or more than the flood susceptible land floods.	
Official safety	CTF_dec	Dmnl	(Marine flooded area fraction + Fluvial flooded area fraction)	Both a fluvial and saline flood flow reduce safety. A decreasing multiplier is used, where 100% flooded is 0% safety	Assumed aggregation of risk of fluvial and saline flood flow. The same area cannot be inundated twice, but could be inundated with a higher water level.
Perceived safety	Stock	Dmnl	Informed opinion adjustment-Loss of perceived safety by flooding Initial value: Relative flood defense capacity		
Informed opinion adjustment	FLow	1/Month	(Official safety - Perceived safety) / Adjustment time	Opinions adjust slowly	
Adjustment time	Const	Month	α		Assumed constant
Loss of perceived safety by flooding	Flow		(Perceived safety * Flood perception magnitude) / Flood perception time	Perceived safety deteriorates rapidly in case of flood	
Flood perception time	Const	Month	α		Assumed constant
Flood perception magnitude	CTF_inc	Dmnl	Marine flooded area fraction + Fluvial flood flow		

APPENDIX I. THE MODEL EQUATIONS

Agriculture					
Name	Type	unit	Equation	Explanation	Assumptions
Annual rice production	Aux	mT/Month	(1-Fraction of lost crop)(Rice paddy surface area*Average paddy productivity)	No delays or crop cycles included. The variable is in that sense more of a theorethical rice productivity output at time t.	
Rice paddy surface area	stock	m*m	- Conversion of rice paddies Initial value: Initial rice paddy surface area		
Initial rice paddy surface area	Aux	m*m	Initial rice paddy surface area		
Level of pesticides and fertilizers use	Aux	(L/(m*m))/Month	α	Amount of chemicals used per hectare per month	
Total agrochemical use	Aux	L/Month	Level of pesticides and fertilizers use * Rice paddy surface area		Assumed that all chemicals are equaly harmfull
Average soil salinity	Stock	dS/m	Increase in soil salinity-Decrease in soil salinity		
Increase in soil salinity	Flow	dS/m/Month	Relative saline seepage rate + Flooding salinization	soil salinity can increase through saline seepage or saline flooding.	A flood is assumed to linearly increase soil salinity over time
Flooding salinization	aux	dS/m/Month	(Seawater salinity * Fraction of seawater infiltration * Marine flooded area fraction) / Saline infiltration rate		
Decrease in soil salinity	Flow	dS/m/Month	Average soil salinity/Soil salinity flushing rate	soil salinity mainly decreases through freshwater flushes	
Initial average soil salinity	Const	dS/m	α		
Saline infiltration rate	Const	Month	α		Assumed constant
Seawater salinity	Const	dS/m	α		Assumed constant
Fraction of seawater infiltration	Aux	Dmnl	α		
Relative saline seepage rate	Aux	dS/m/Month	Normal saline seepage rate * Salt wedge seepage multiplier * RSLR seepage multiplier * Coastal habitat seepage multiplier		Complicated realitionship depending on many variables. No distance component included
Normal saline seepage rate	Const	dS/m/Month	α		
Relative salt wedge seepage	CTF_inc	Dmnl	Salt wedge position/Baseline salt wedge seepage	Salt wedge advancement increases saline seepage	
Baseline salt wedge seepage	Const	1/km	α		
Relative RSLR seepage	CTF_inc	Dmnl	Relative sea level rise RSLR/ Baseline head difference seepage	higher head difference increases saltwater intrusion	
Baseline head difference seepage	Const	1/m	α		
Relative coastal habitat seepage	CTF_dec	Dmnl	Coastal salt marsh and vegetated wetlands surface area/Baseline wetland seepage reduction	filtering effect of coastal salt marshes reduces saline seepage	
Baseline wetland seepage reduction	Const	1/m*m	α		
Soil salinity flushing rate	Aux	Month	(Fluvial flood flow + irrigation diversion) * Flushing rate by discharge	fresh water flows flush salt from the system effectively.	
Flushing rate by discharge	Const	1/Hm3	α		Assumed linear
Soil salinity productivity multiplier	CTF_dec	Dmnl	Average soil salinity / Baseline soil salinity		
Baseline soil salinity	Const	dS/m	α		
Average paddy productivity	Aux	mT/(m*m)/Month	Average rice productivity * Soil salinity productivity multiplier * Climate productivity multiplier * Irrigation productivity multiplier * Biodiversity productivity multiplier * Agrochemical productivity multiplier * Nutrient productivity multiplier	Average rice crop productivity * fraction of flooded paddies * productivity multipliers. The formula does not capture delayed effects	Assumed linear and instant relationship between productivity multipliers. Assumed instant productivity loss from flooded paddies. (reality would see loss of productivity for an entire year, as crop is lost)
Fraction of lost crop	Aux	Dmnl	IF THEN ELSE(Fraction of flooded paddies>0, Fraction of flooded paddies, 0)	No crop cylce timing and delays included, i.e. the variable computes instant loss of crop production for the duration of the flooding, and instant regained productivity after	Assumed 100% loss of crops on inundated land, no matter the magnitude and duration of the flooding event.
Fraction of flooded paddies	Aux	Dmnl	Marine flooded area fraction + Fluvial flooded area fraction / Rice paddy surface area		Assumed linear relation between fraction of total flooded surface and flooded paddies (= equal distribution)
Average rice productivity	Const	mT/m*m/Month	α		
Climate productivity multiplier	CTF_dec	Dmnl	Extreme climate conditions	extreme weather conditions disturb rice production. Already given in a *relative* value.	
Irrigation productivity multiplier	CTF_inc	Dmnl	Irrigation diversion/Baseline irrigation		
Baseline irrigation	Const	Hm3/Month	α		
Biodiversity productivity multiplier	CTF_inc	Dmnl	Species diversity, richness and endemism	higher biodiversity leads to higher regulating ESS (e.g. natural pest control) and pollination	
Agrochemical productivity increase	CTF_inc	Dmnl	Level of of pesticides and fertilizers use / Baseline agrochemical needs	Higher usage is higher yield	
Baseline agrochemical needs	Const	L/Month	α		
Nutrient productivity multiplier	CTF_inc	Dmnl	Sediment settling on the delta plain / Baseline nutrient demand	Higher volumes of sediment equals higher volumes of nutrients.	
Baseline nutrient demand	Const	m*m*m/Month	α	Given in sediment volume	
Input of crop residues	Aux	m*m*m/Month	Annual rice production * Effective crop residue retilling fraction * Residue weight to normalized volume		Linearly dependend on yield. Is directly given as height (assumed equal distribution on farmland)
Effective crop residue retilling fraction	Aux	dmnl	1	Aggregation of what % of residue is ploughed back into soil, and of the % of crop residue to crop product, and how this relates to vertical accretion	Assumed 100% (law is followed perfectly)
Residue weight to normalized volume	Const	m*m*m/Mt	α	Relates weight (mT) to correct volume leading to a certain accretion rate when divided by delta surface area	Assumed constant fraction of crop to crop residue
delta surface area	Const	m*m	α		To compute average deltaic accretion rate, total surface area is used (aggregating different suface types; nature, farmland, also including urban surface area)
Annual salt production	Aux	mT/Month	Normal salt production * Marine flooded area fraction		Assumed linear relationship with magnitude of flood
Expected damage multiplier	Const	Euro/Month	α		Assumed constant for simplicity
Expected damage built environment	Aux	Euro/Month	(Fluvial flood flow + Marine flooded area fraction) * Expected damage multiplier		Heavy simplification, assumed to be only related to flooding, and linear effect

APPENDIX I. THE MODEL EQUATIONS

Ecosystems & Tourism					
Name	Type	unit	Equation	Explanation	Assumptions
Coastal salt marsh and vegetated wetlands surface area	Stock	m*m	Conversion of rice paddies-Salt marsh retreat Initial value: Initial coastal salt marsh and vegetated wetlands surface area		
Initial coastal salt marsh and vegetated wetlands surface area	Const	m*m	α		
Conversion of rice paddies	Flow	m*m	α	This would be a measure. No conversion rate included as of now	
Decomposed organic matter	Aux	m/Month	Normal organic decomposition rate * Organic decomposition rate multiplier * Coastal salt marsh and vegetated wetlands surface area		Is directly given as height (assumed equal distribution on land)
Normal organic decomposition rate	Const	m/(m*m)/Month	α		Assumed constant
Organic decomposition rate multiplier	CTF_inc	Dmnl	Habitat condition		Assumed that a better condition will lead to higher organic growth
Habitat condition	Stock	Dmnl	Habitat condition Initial value: 0.5	Can only change in response to drivers (no tipping points or other behaviour included)	
Total ecosystem extent	Aux	m*m	Coastal salt marsh and vegetated wetlands surface area + Other ecosystem surface area		
Relative species diverstiy, richness, and endemism	CTF_inc	Dmnl	(Habitat condition * Total ecosystem extent) / "Baseline species diversity, richness, and endemism"		
Condition change	Flow	Dmnl	1/Condition change rate * (Habitat condition) * (1 - Habitat condition/Carrying capacity) * (Relative pollution and eutrophication * "Relative species diversity, richness and endemism" * Relative habitat degradation * Relative overexploitation * Relative extreme climate conditions)		
Condition change rate	Const	Month	α		Assumed constant
Relative pollution and eutrophication	CTF_dec	Dmnl	Total agrochemical use / Baseline pollution and eutrophication		
Baseline pollution and eutrophication	Const	L/Month	α		
Other ecosystem surface area	Aux	m*m	α		
Baseline species diversity, richness, and endemism	Const	m*m	α		Difficult to define a baseline
Relative overexploitation	CTF_dec	Dmnl	Fish, aquaculture, and game yield / Sustainable exploitation		
Sustainable exploitation	Const	mT/Month	α	Static, does not change in response to stock size	Assumption of static sustainable exploitation level (while it depends on a multitude of factors, and on what is defined by sustainable)
Relative habitat degradation	Aux	Dmnl	(Total ecosystem extent/Baseline sustainable habitat extent) * Relative touristic impact on habitats * Relative endemic habitat conditions * Protective legislation and restoration	Captures connectivity and changes in land use	
Baseline sustainable habitat extent	Const	m*m	α		Difficult to define a baseline, and different perspectives on what is defined by sustainable
Protective legislation and restoration	CTF_inc	Dmnl	*no equation given*	Not expanded upon, given for comprehensiveness	
Relative endemic conditions	Aux	Dmnl	Channel morphological and ecological impacts * Relative flooding condition change * Relative discharge conditions * Relative salt wedge disturbance *Relative sediment deposition delta plain		
Relative flooding condition change	Aux	Dmnl	Fluvial flooded area fraction * Fluvial flood condition change + Marine flooded area fraction * Marine flood condition change		Assumed linear relationship. Reality is highly complex and bipolar over time, space, and context
Marine flood condition change	Const	Dmnl	α		Assumed constant
Fluvial flood condition change	Const	Dmnl	α		Assumed constant
Relative discharge conditions	CTF_inc	Dmnl	SMOOTH(Discharge delta channel, Moving average of a year) / Normal yearly average discharge conditions	Computed on yearly moving average	
Relative salt wedge disturbance	CTF_dec	Dmnl	SMOOTH(Salt wedge position, Moving average of a year) / Normal yearly average salt wedge position	Computed on yearly moving average	
Relative sediment deposition delta plain	CTF_inc	Dmnl	SMOOTH(Sediment settling on the delta plain, Moving average of a year) / Normal sediment deposition on the delta plain	Computed on yearly moving average	
Moving average of a year	Aux	Month	12		
Normal yearly average discharge conditions	Const	Hm3/Month	α		
Normal yearly average salt wedge position	Const	km	α		
Normal sediment deposition on the delta plain	Const	m*m*m/Month	α		

Ecosystems & Tourism					
Name	Type	unit	Equation	Explanation	Assumptions
Fish, aquaculture, and game	Stock	mT	Productivity fish, aquaculture, and game-"Fish, aquaculture, and game yield" Initial value: Initial fish, aquaculture, and game	No (interactions with) external populations included. Can only decrease through humans (i.e. no aging/disease mechanics)	
Fish, aquaculture, and game yield	Flow	mT/Month	Fish, aquaculture and game / (Touristic activity * touristic demand factor)		
Productivity Fish, aquaculture, and game	Flow	mT/Month	Relative species diversity, richness and endemism*Diversity to productivity factor * (1/Population maturity period)	Biodiversity can only increase productivity, but we have not modelled a negative productivity, meaning the stock at time ti is insensitive to biodiversity loss. Aggregation of aquaculture and natural stocks for simplicity.	Only biodiversity captures the link between natural degradation and the populations (and only through productivity change)
Diversity to productivity factor	Const	mT	α		
Initial fish, aquaculture and game	Const	mT	α		
Population maturity factor	Const	Month	α		
Touristic demand factor	Aux	1/Tourists	α		α
Touristic activity	Aux	Tourists/Month	DELAY1((Touristic attractiveness*Activity by attractiveness), Rate of adjustment)	In this model only related to attractivity	
Activity by attractiveness	Const	Tourists/Value	α		Assumed constant
Rate of adjustment	Const	Month	α		
Touristic attractiveness	Aux	Value	(Touristic value of infrastructure + Natural recreational value) * Perceived safety	Only infrastructure and natural recreational value included	
Relative touristic impact on habitats	Aux	Dmnl	Touristic activity*Fraction of unsustainable touristic activity / sustainable level of touristic activity		
Fraction of unsustainable touristic activity	Aux	Dmnl	α		
Sustainable level of touristic activity	Aux	Tourists/Month	α		Assumed to be computable. Inherently complex in reality. Also depends on perspective of what is defined by sustainable.
Touristic value of infrastructure	Aux	Value	DELAY3((Tourism revenue * Investment level * Value of infrastructure),Construction rate)		
Construction rate	Const	Month	α		
Value of infrastructure	Const	Value/Euro	α		Assumed constant
Investment level	Aux	Month*Month	α		
Tourism revenue	Aux	Euro/Month	Economic value of activities * Touristic activity		
Economic value of activities	Const	Euro/Tourists	α		Assumed constant
Natural recreational value	Aux	Value	Touristic value of natural products + Touristic value of ecosystems		
Touristic value of natural products	Aux	Value	Fish, aquaculture, and game yield * Recreational value of natural products		
Touristic value of ecosystems	Aux	Value	Total ecosystem extent * "Relative species diversity, richness and endemism" * Recreational value of species and habitats		
Recreational value of natural products	Const	(Value*Month)/mT	α		Assumed constant
Recreational value of species and habitats	Const	Value/m*m	α		Assumed constant