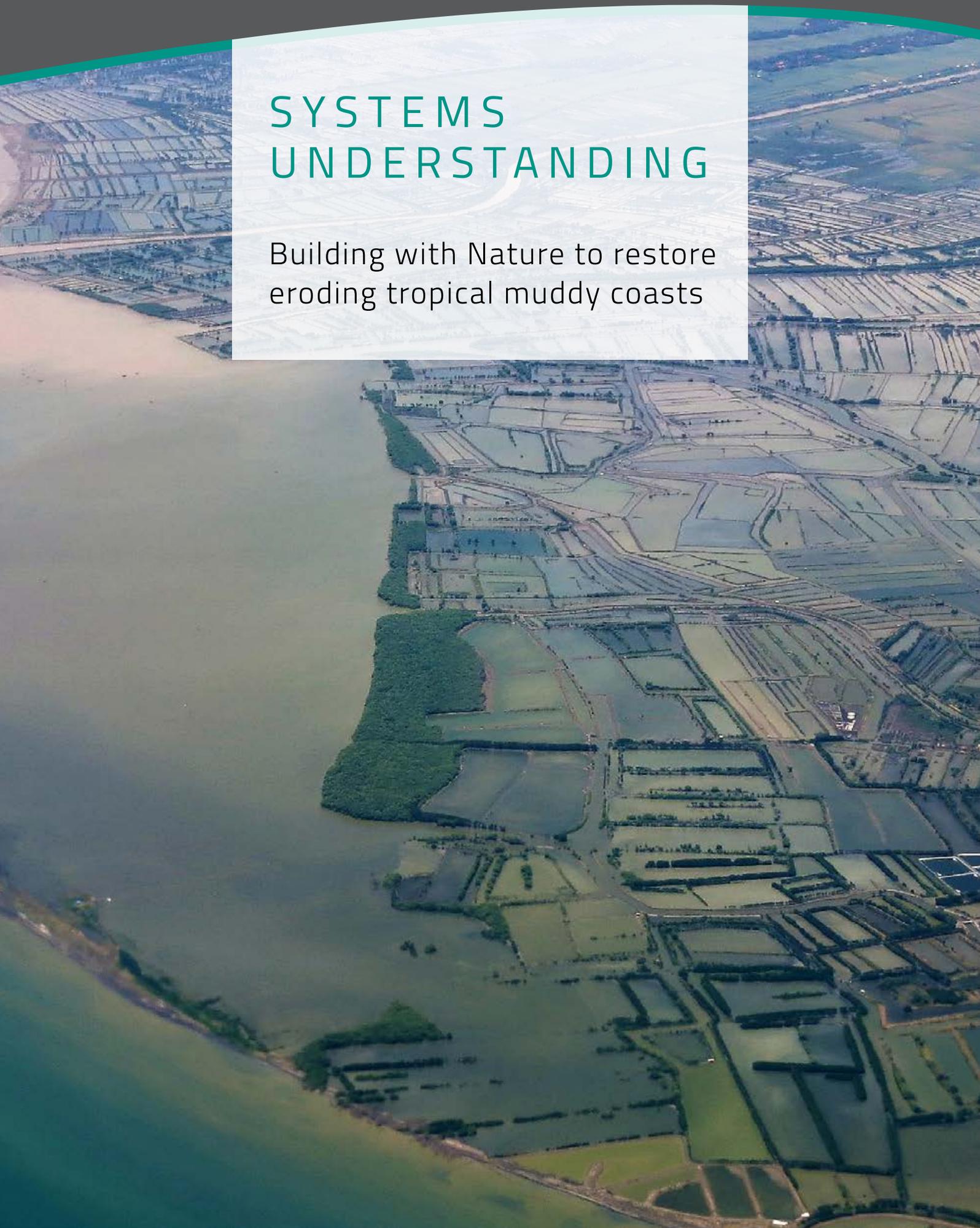# SYSTEMS UNDERSTANDING

Building with Nature to restore
eroding tropical muddy coasts

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TECHNICAL GUIDELINES SERIES

This guideline on Natural System Analysis is part of a series of Technical Guidelines on technical and socio-economic Building with Nature measures that, in combination, help to restore eroding tropical muddy coasts. These guidelines are based on insights and lessons learnt during the implementation of a district scale pilot in Central Java as part of the Building with Nature Indonesia programme. By sharing our lessons learnt in these practical guidelines, we aim to enable replication by government agencies, the water and aquaculture sector and NGOs. Building with Nature measures need to be part of integrated coastal zone management and require a thorough problem understanding and system analysis. Stakeholders interested in replicating our approach bear full responsibility for the success and sustainability of the approach.

AVAILABLE GUIDELINES
#1   Building With Nature Approach
#2   Systems Understanding
#3   Permeable Structures
#4   Associated Mangrove Aquaculture Farms
#5   Sustainable Aquaculture Through Coastal Field Schools

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

BACKGROUND

Two thirds of the world's population live in coastal regions, with higher population density around estuaries and deltas. These areas are highly productive and offer excellent opportunities for agriculture, aquaculture and fisheries. Still, pressure on delta and river ecosystems is expected to increase as population growth and economic development intensify urbanisation and the demand for infrastructure. A major challenge is realising economic development, urgently needed to reduce poverty and achieve a more equitable income distribution, without overexploiting natural resources. Planning infrastructure development, with the health of the natural system in mind from the start, can constitute part of the answer.

WHAT IS A NATURAL SYSTEM?

In coastal zone, river and water resource management the system comprises three interacting subsystems: the natural system, the socio-economic system and the institutional system. Understanding these three systems is vital in the design of good management strategies. In the present guideline, we only focus on the natural system and provide details about deltas and coastal systems. The features of natural systems are the result of an intricate interplay between the underlying geology, hydrodynamics, morphological processes and ecology. These processes continuously reshape the coast on distinct spatial and temporal scales, resulting in a wide range of coastal typologies. Coastal ecosystems not only play an important role for biodiversity and the natural world, but also deliver benefits for humans. This dependency of humans on the input from ecosystems needs to be explicitly incorporated into any project, alongside the biophysical processes acting on larger scales in time and space.

WHY NATURAL SYSTEM ANALYSIS?

System analysis is key to understanding the environment in which infrastructural developments are planned. In addition, knowledge of the natural system is required for the analysis of hazards that threaten people, assets and economic development, e.g. landslides, floods or erosion. A deep understanding aids in analysing the risks and opportunities and can ultimately determine the success of interventions. System analysis should therefore be based on a combination of theoretical understanding of natural systems and thorough insight into site-specific processes.

HOW TO PERFORM A NATURAL SYSTEM ANALYSIS?

To assess the natural system and human influences, a site visit is ideal. However, in preparation for a site visit, exploring global data sources to obtain a broad perspective is required. Information about the natural system and human influences can be learned not only from the initial field visit, but also from the local community. Moreover, as part of project development, and if resources and capacity are available, monitoring can be built in to obtain necessary data. Knowledge of the present is the key to planning for the future. Once the dynamics in a natural system are understood, numerical modelling can aid in predicting the potential response of the system under future scenarios.

FROM SYSTEM ANALYSIS TO PROJECT IMPLEMENTATION

Analysing the development of the natural system over time and investigating the likelihood of natural hazard occurrence, leads to the development of sustainable and climate resilient intervention strategies. If the system and risk analyses conclude that active intervention is necessary and feasible, different intervention strategies can be compared. These can be non-structural, such as proactive spatial planning, early warning systems and evacuation plans, or structural. Structural interventions are divided into 'hard' and 'soft' solutions. Hard solutions are solid structures such as seawalls, breakwaters and dams, while soft or ecosystem-based solutions encompass the wide array of nature-based solutions including mangroves, coral reefs, seagrass meadows and coral reefs. Regarding coastal safety, ecosystems offer ecosystem services, such as wave attenuation, sediment capture and shoreline stabilisation. Integrating these natural processes into hydraulic and marine infrastructure design is what we call Building with Nature.

To deliver an optimal mix of interventions, setting objectives and translating these into measurable targets is vital. Building with Nature designs are relatively new compared to more traditional interventions, hence monitoring performance and development is essential. It is advised to monitor and adapt if interventions do not meet the set objectives. During project development, monitoring and adaptive management, users will likely improve natural system understanding, which can be directly applied to adapted interventions and into knowledge for future projects. This guideline advises how high-technology system understanding can ensure a smart use of low-technology, or nature-based interventions. It provides a starting point for a basic system analysis, while also advocating for a paradigm shift in the engineering discipline and within society, aiming to transform the way we interact and build with natural systems in mind.

1 INTRODUCTION

1.1. GLOBAL TRENDS

Increasing population in coastal zones has led to an increased demand for space and developments that hinder the natural fluxes of sediment, water and nutrients in the coastal zone. Combined with sea level rise caused by climate change, this results in more frequent flooding and coastal erosion. Consequently, the need for proper coastal zone management, including both preventive and restorative interventions, is larger than ever. Traditional engineering interventions to address these problems are often considered first. However, there is an increasing need for self-sustaining strategies that integrate the natural system and the socio-economic system as intrinsic parts of the coastal protection scheme over longer periods of time. This implies that natural processes can be used to mitigate risk, for example by allowing currents and waves to reinforce the coastline with sediment, or by restoring ecosystems so that they provide protection against storms. Additionally, there is a growing perception that management interventions that integrate natural systems and provision of ecosystem services can be cost-effective and have the potential to offer a range of co-benefits to society, namely food security, livelihood development, carbon storage and biodiversity conservation. Extreme weather events, sea level rise and resulting coastal squeeze, where intertidal ecosystems are squeezed between rising sea levels and the build environment, put extra stress on already threatened coastal ecosystems. This jeopardises essential ecosystem services, such as coastal protection and fisheries, and may lead to a rapid decline in economic sectors important for rural coastal communities, and to an increased expenditure for maintaining coastal infrastructure.

Nature-based solutions such as Building with Nature are increasingly popular across the world. More and more projects aim to include natural functions in infrastructure development in a better way. One of the reasons may be that traditional coastal engineering is challenged by growing population and increasing threats from climate change. Many countries are approaching the limits of what is feasible, because building infrastructure to protect large stretches of low-lying coastal areas incurs high construction and maintenance costs. Sea level rise and increasing rainfall necessitate continuous retrofitting, and often governments spend resources on building in one area, while, in another area, the infrastructure collapses. For development of long-term sustainable and resilient infrastructure, development of Building with Nature projects alone is not enough. A paradigm shift is needed towards *developing infrastructure that respects the natural flows of water, sediment and species with the aim to safeguard the health and functioning of ecosystems*. This implies that the natural system constitutes an intricate part of the design of infrastructure, and that natural system understanding is essential for Building with Nature projects. This guideline presents a basic method of incorporating natural science into system analysis. *Although Building with Nature interventions are sometimes considered low-technology with respect to physical construction, system understanding needs high-technology knowledge.*

Figure 1: Failed seawall (Demak, Indonesia) © Bregje van Wesenbeeck

1.2. NATURE INCLUSIVE INFRASTRUCTURE DEVELOPMENT

Inclusion of natural processes and functions is key for long-term sustainable coastline management. However, including natural processes and ecosystem health in our standard coastal management toolkit requires a paradigm shift. Frequently, integration of water flows, sediment transport, nutrient cycling and wildlife populations fail to be considered in detail in infrastructure projects (van Wesenbeeck et al., 2019). This results in suboptimal infrastructure design with unexpected problems emerging after construction. For example, roads that cut across main hydrological flows may amplify flooding and have a shorter lifetime. Infrastructural needs are immense in fast growing countries, but infrastructure that fails because of suboptimal design wastes both resources and time. Consideration of water flows, sediments and the health of existing ecosystems at the design stage, can result in benefits for nature and better infrastructure resilience. Several programmes across the globe, such as Building with Nature (BwN, EcoShape)[1], living shorelines (NOOA)[2], Working with Nature (WwN, PIANC)[3] and Engineering With Nature (EWN, USACE)[4], actively strive to implement pilot projects and increase the knowledge base for interventions that combine nature and civil engineering. They refer to their philosophy and project with terms like Building with Nature, Working with Nature, Engineering with Nature, Green Infrastructure and Nature-Based Solutions. Throughout this guide, we use the term Building with Nature, as this guidance was based on a Building with Nature project in northern Java that was implemented in the framework of the EcoShape Building with Nature network.

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[1] https://www.ecoshape.org/en/

[2] https://www.fisheries.noaa.gov/insight/understanding-living-shorelines

[3] https://www.pianc.org/working-with-nature

[4] https://ewn.el.erdc.dren.mil/

1.3. AIM OF THIS GUIDANCE

A central element of the Building with Nature approach is the essential role that the natural system plays in the design. To truly make use of ecosystem services and to conserve or restore natural processes and functions, the natural system needs to be well understood, both in a qualitative and in a quantitative sense. Therefore, nature-inclusive design is neither simple nor straightforward and very little guidance is yet available. Here, we give an overview of the main elements of natural system analysis that will help optimising infrastructure investments for nature, economy and people.

This guidance targets not only officials at governmental infrastructure departments that allocate infrastructure investments, but also implementation agencies, engineers and NGOs who assess feasibility of green and grey infrastructure and finalise this into design and implementation. The current guideline focuses on coastal areas and facilitates inclusion of nature by providing a basic understanding of the different natural system components and how these can be assessed. The geological, hydrological and ecological processes that shape coastal systems are explained, along with how these can be assessed through a variety of methods. The method for completing the system analysis needed for project or investment development processes is usually agency-specific. Hence, this guideline focuses on the steps to perform a qualitative analysis of the natural system, at an overview level. For the next step, i.e. the quantitative understanding, involvement of experts is required.

BOX 1: HOW WILL THIS GUIDELINE BENEFIT YOU?

1. Through reducing risks of project failure and increasing the lifetime of coastal infrastructure;
2. By efficiently using scarce resources, such as funds, time and building materials;
3. Providing a basic understanding of what to ask for when commissioning a system analysis;
4. Judging basic system understanding studies and their quality and relevance.

1.4. READING GUIDE

This guidance was developed as a part of the Building with Nature project in Demak, Java (Indonesia). This project aims to rehabilitate an eroding coastline by restoring mangrove habitat and enhancing natural recolonisation. This document provides a guide to better understand the coastal system, to know what processes to consider and what experts and tools can help develop successful infrastructure and coastal zone management projects. Chapter 2 introduces the reader to the reasons for performing natural system analysis. Chapter 3 presents a brief description of the natural system and of the different elements that constitute it. Chapter 4 elaborates on how to perform

a system analysis. How a system analysis contributes to the formation of a Building with Nature project is described in Chapter 5. The chapters in this guide contain case study boxes that illustrate how the theoretical framework can be applied to projects, by describing how this was done in the project in Demak, including the pathway from system analysis to potential interventions (Figure 2).
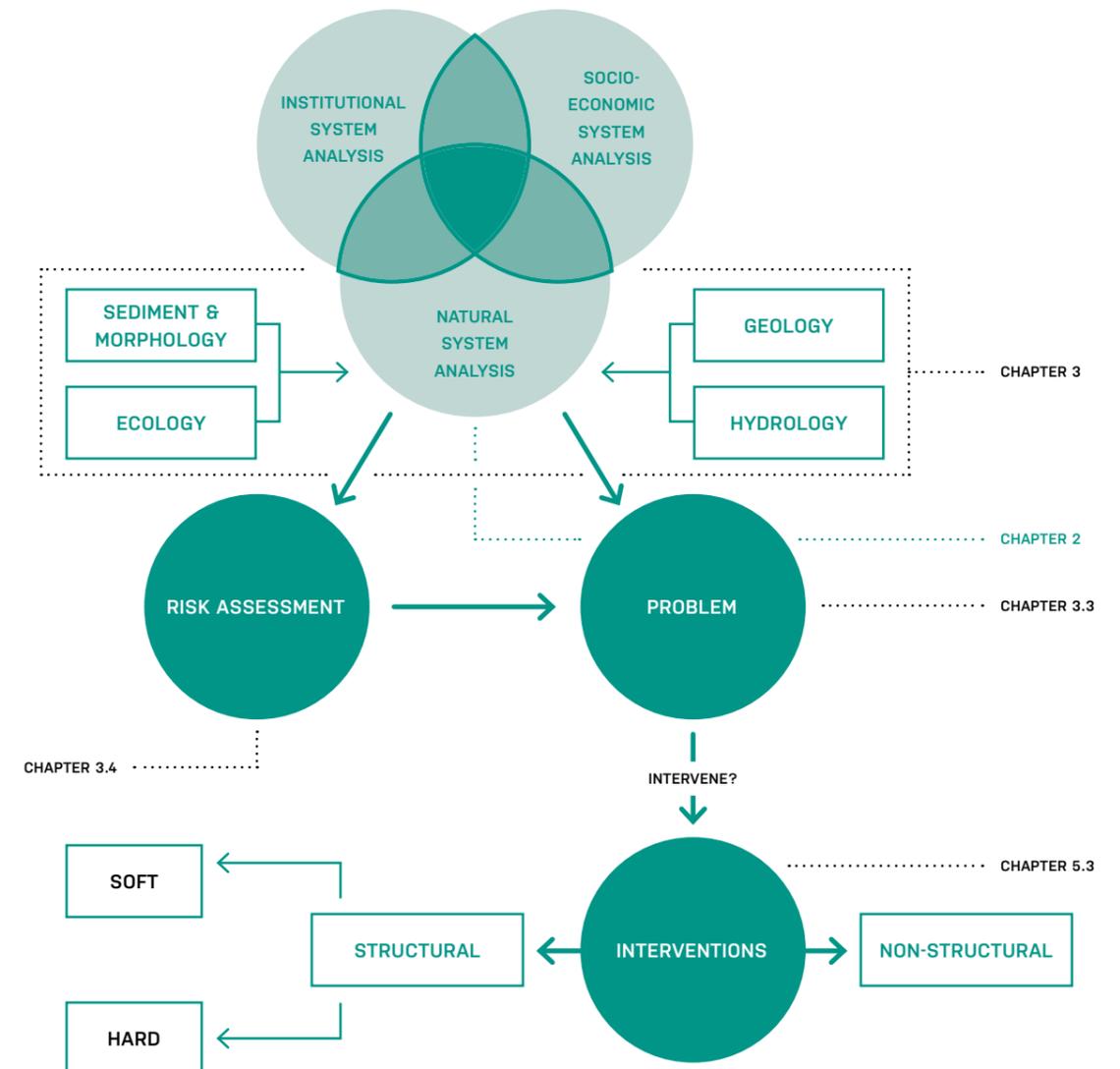
Figure 2: Overview of the different subsystems and of the elements that natural system analysis. Initial definitions of the problem and its causes are followed by system analysis and risk assessment. Interventions that arise should only be implemented if it is feasible within the constraints of the boundary conditions. These boundary conditions for appropriate interventions are again informed by the analysis of the natural, socio-economic and institutional system (i.e. funding resources, legislation, community). Interventions can be non-structural and structural. Structural interventions can be soft or hard. More information on interventions in Chapter 5.

BOX 2: BUILDING WITH NATURE DEMAK: AN INTRODUCTION

Communities in Northern Java are suffering from coastal erosion and flooding, affecting hundreds of kilometres of coastline. In the Demak district in Central Java, entire villages have been swallowed by the sea because of erosion. The district borders the city of Semarang, a coastal city with a port and around 7 million inhabitants. The adjacent Demak province is mainly an agricultural area with paddy fields, fish and shrimp ponds. Both Semarang and areas in Demak suffer from flooding and erosion. At the start of the Building with Nature project, transport routes, the port area and the historic center of Semarang are regularly suffering floods. Land loss caused by coastal erosion in the Demak district contributes to loss of homes and fishponds. Coastal communities in the Demak district are traditional Javanese communities that have lived in the area for many generations. Land ownership in the area is mostly family-based and is passed on between generations. Hence, impacts of losing land are enormous. The government is trying to move people that lose their land further inland, or to relocate them to different islands.

Figure 3: A lady riding a motorbike at a flooded T-junction (Demak, Indonesia) ©Cynthia Boll

2 WHY IS NATURAL SYSTEM ANALYSIS NECESSARY?

2.1. WHAT IS A SYSTEM?

A system is considered a group of interacting or interrelated entities. A system is surrounded by and thus influenced by its environment. In coastal zone, river basin and water resource management, 'the system' is defined as consisting of three subsystems: the natural system, the institutional system and the socio-economic system (Figure 4). These three systems need to be considered together when working on a certain problem and when proposing a management strategy to mitigate a problem. Often, interventions fail because not all systems and their mutual interaction have been thoroughly evaluated. For example, coastal protection infrastructure is often built in areas where communities depend on fishing for their main source of livelihood. In many areas, fishermen need to drag their boats on shore, so that it is not damaged or lost during storms. Infrastructure that prevents them from putting their boats in a safe place may protect their houses against flooding, but at the same time directly jeopardises their main source of income. Therefore, by neglecting the socio-economic system, large infrastructure projects may lead to unintended adverse consequences. Disregarding the institutional system may result in proposing management strategies and interventions that no one is mandated to construct or maintain. This guideline mainly focuses on the natural system and on how to compile a good understanding of it.
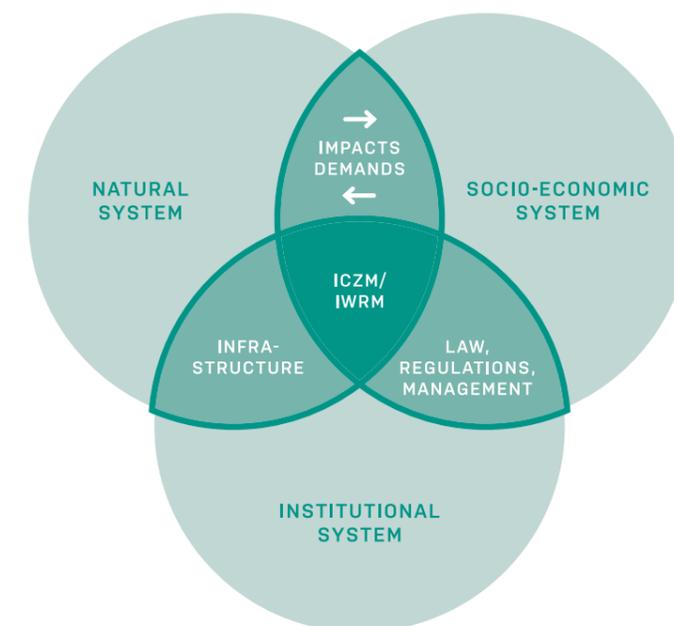

Figure 4: The three systems that need to be considered for Integrated Coastal Zone and Water Resource Management (ICZM/IWRM).

2.2. WHY DO A NATURAL SYSTEM ANALYSIS?

A system analysis is key to understand the environment in which infrastructural developments are planned. It is helpful to think of the system in three layers: the base layer, the network layer and the occupation layer. The base layer constitutes of the water, soil and vegetation and represents the natural system. This layer sets the foundation for the two superseding layers and developments in this layer enfold in a slow pace. To illustrate, infrastructure that belongs to the network layer, such as roads and railways, should respect the characteristics and flows of the base layer. For example, a swampy, peaty or silty environment requires infrastructure that is anchored into deeper more robust soils than the soft substrate above and bridges need to be wide enough to accommodate peak flows of rivers, as otherwise infrastructure becomes very prone to failure. Houses and buildings belong to the third layer, which is called the occupation layer. A natural system analysis exposes all the necessary elements of the base layer in order to make wise decisions on the network and occupation layer and as such limits infrastructure failure and reduces vulnerability of people and assets. A thorough natural system understanding aids in analysing risks and opportunities and can ultimately determine the success of interventions in infrastructure and occupation.

BOX 3: THE IMPORTANCE OF UNDERSTANDING THE NATURAL SYSTEM

Several years ago, the façade of the iconic Jefferson Memorial in Washington, D.C. (USA) was experiencing decay. Harsh chemicals used for cleaning the building were causing corrosion. The building needed to be cleaned often because it was regularly covered in bird droppings. Not only was the cleaning causing damage, it was also expensive. The first solutions proposed were methods to keep the birds away from the building using unsightly spikes or nets. Someone wondered, why are the birds gathering around the building so often? They were drawn to the building to feast on the large number of insects hovering there just before dawn. Why were the insects so attracted to the building? Lights were switched on every morning to display the beautiful monument and the insects were attracted to the lights, an easy breakfast for the birds and a target for their excrement. After discovering that the building needed cleaning because the insects drawn to the lights attracted all the birds – an easy and costless solution was devised. By turning on the lights slightly later when it was already bright, the insects did not come, the birds did not gather around the building anymore and no more expensive and damaging cleaning was necessary.

2.3. System analysis in the context of problem analysis

Coastal engineering projects could be initiated purely from a development perspective, but they often start from a problem perspective, where someone perceives a problem that is brought to the attention of a managing authority or government, which will then decide whether to intervene or not. Problem analysis and system analysis are iterative processes that are closely interlinked. Frequently, problems are caused by the fact that people are living in vulnerable areas. To analyse problems, properly identifying causal relationships, interconnections between boundary conditions and, overall, a holistic approach are crucial. One of the most important elements of problem analysis is distinguishing between causes and effects. Regardless of the problem being addressed, before developing any solutions, it is necessary to step back and ask: What is the root cause of the problem? Why is this problem occurring? Understanding 'why' may also help determine the most appropriate and sustainable solution.

By identifying the root cause of the problem, just like at the Lincoln Memorial (see box 2.1), the task of gathering quantitative information, which helps break the problem down into more manageable tasks, can be started. This knowledge will also aid in disentangling the contribution of natural versus anthropogenic causes to the problem. For example, looking at coastal processes, it is often unclear whether erosion is caused by sea level rise, reduction in sediment transport, a single hurricane or tropical storm, or by the construction of coastal infrastructure, such as long harbour jetties or seawalls that disturb sediment transport along the coast. Usually, it is a complex interaction of causes and effects over a longer timescale, or a new system state that is triggered by a sudden change or event. This understanding of natural processes and their dynamics is the basis for defining proper intervention strategies and pinpointing where in the system to intervene. For all interventions, but specifically for implementation of Building with Nature interventions that purposefully work with the forces of nature, this analysis of the natural system is crucial.

Involvement of different stakeholders in problem analysis is key. What may be identified as a problem by one stakeholder, may simultaneously be regarded as an opportunity by others. Execution of a system analysis is key to any engineering project and will help to determine the cause of a problem and the impact that problem has on different parties and on their dependencies on the natural system. However, especially for Building with Nature projects, an assessment of the natural system is indispensable. The problem, risk and system analyses together will guide towards possible intervention strategies and, ultimately, towards optimised measures that integrate nature and engineering (Figure 2).

2.4. SYSTEM ANALYSIS IN THE CONTEXT OF RISK ASSESSMENT

Risk assessments are often undertaken to elaborate the problem analysis and to identify targets for action. Risk is defined as a combination of hazard, exposure and vulnerability (Sendai 2015) (Figure 5). Hazard is the natural or anthropogenic phenomenon that creates a dangerous situation (or problem). Exposure concerns people and assets that are exposed to that hazard, while vulnerability is related to the characteristics of people and assets that make them susceptible to the damaging effects of hazards. Hence, any risk assessment requires a proper understanding of both natural and socio-economic systems. Understanding what hazards can occur in a certain area, along with their intensity and probability of occurrence, requires a good understanding of natural processes. Examples of hazards that occur frequently in coastal areas are coastal erosion, tidal flooding, storm surges and cyclones. To understand the impact of these hazards, information on the socio-economic system is required, for example whether people and assets are situated in areas that can be impacted by these hazards. Finally, a good understanding of the social system will help to judge whether people are susceptible to the hazard and where the main vulnerabilities are. This is also a factor that can be influenced in a low-regret manner, e.g. preparing people for hazards promptly reduces their vulnerability. Usually, risk is assessed for several predefined scenarios of change, in order to explore how hazard, exposure and vulnerability could develop in the future, for example with climate change.
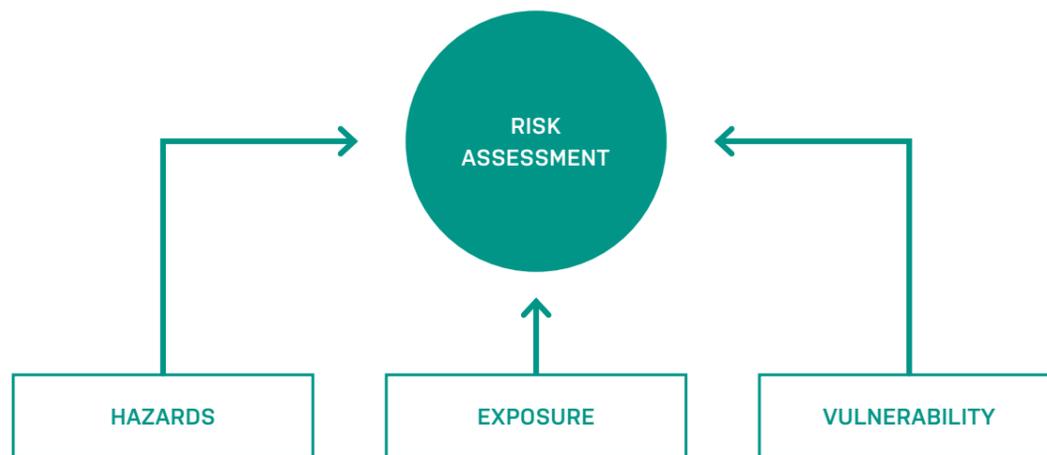
Figure 5: Risk is composed of hazard (e.g. storm surges), exposure and vulnerability.

3 ELEMENTS OF NATURAL SYSTEMS

The natural coastal system is composed of geological, hydrodynamic, morphological and ecological components, all of which need to be considered at different scales in time and space. All these elements should be part of the natural system analysis, even if some elements get more attention than others, depending on the local context and the problem at hand. If applicable, geological processes may also need to be known. For example, the composition of soil layers formed hundreds or millions of years ago, determines the location and the size of aquifers. The course of rivers, the stability of coastlines and the formation of deltas, though all interrelated, often change at different timescales and impacts of these changes may be felt or noticed over longer time periods. An understanding of these processes is required to decide how to modify a system towards a desired objective. The fundamental mechanisms of these components are described briefly in this chapter, along with a discussion of human impact on the natural system. Examples illustrate how system knowledge helped to understand flood problems along the coast of Central Java (Indonesia).

3.1. ROLE OF GEOLOGY

Understanding the geology of an area gives essential information about how a system works on longer timescales, from millennia up to millions of years, and on wider spatial scales of 1000 – 10.000 km. Geology sets the initial state of a system and its properties. This includes the substrate at and below the Earth's surface and its morphology, such as shelf and shoreline configuration. On the largest scale (1000 km – 10.000 km), configuration of the shelf and shoreline is controlled by tectonics. This impacts the physical appearance and behaviour of coastal systems. For example, wide and flat continental shelfs allow for more rapid coastal growth, while steep and narrow shelfs are susceptible to erosion (Masselink, Hughes, & Knight, 2011). In turn, coastline configuration controls hydrodynamic conditions. For example, less energetic conditions will prevail at lee sides of islands. The appearance of the coastline reveals what geological processes are at work (Figure 7).

The type of rocks on the surface controls the recession rate and cliff profile development along eroding rocky coasts. Sediment is formed when rocks disintegrate into smaller particles of clay, silt and sand, which are distributed within the landscape by water, wind or ice. Soils develop upon weathering of rock and sediment, affected further by settlement of vegetation. Soil properties depend on the characteristics of their 'parent material' and determine factors such as soil fertility and thus vegetation and land use, in addition to erodibility or strength. Properties of the subsurface substrate may affect the processes at the surface, especially when we interfere, for example by extracting groundwater from deep wells.
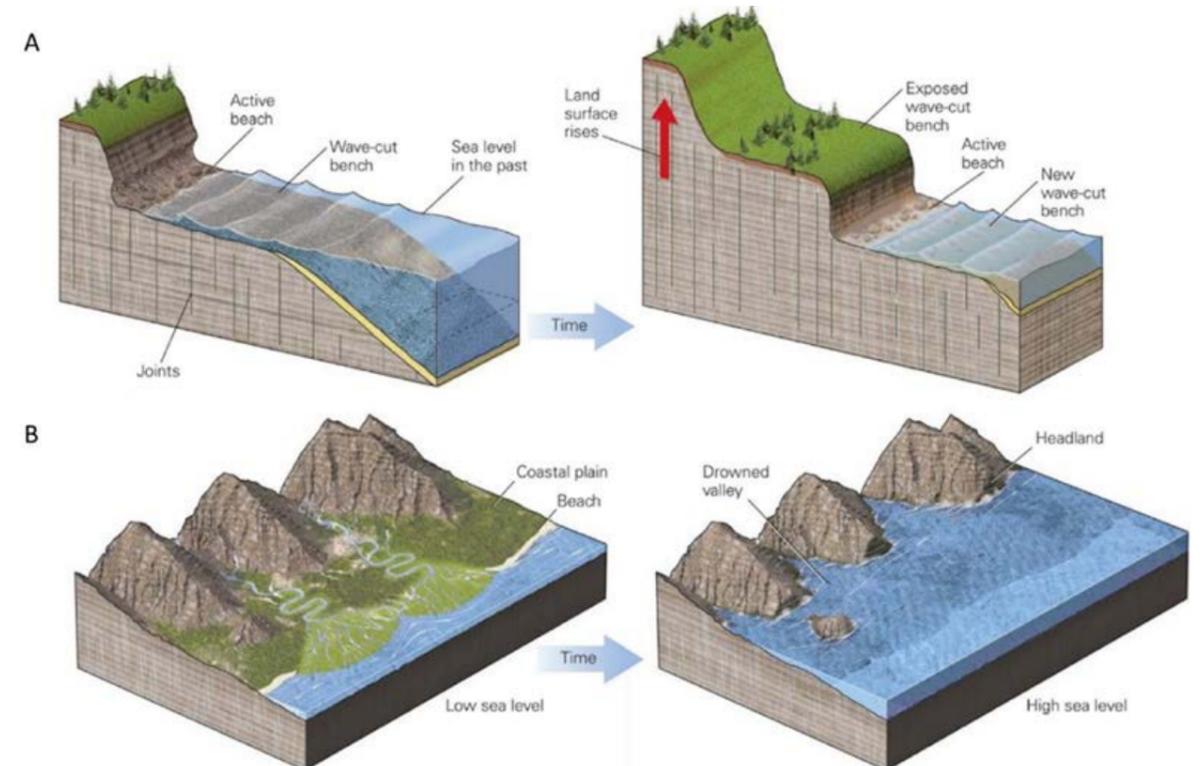
Figure 7: Coastal systems where appearance reflects the active process in geological time. A) Emergent coasts: relative uplift of the continent with respect to the sea. Wave erosion has produced a wave-cut bench along an emergent coast. As the land rises, the bench has become a terrace, and a new wave-cut bench emerges. B) Submergent coasts: relative sea level rise. Prior to sea level rise, coastal plains are present with several delta lobes. As sea level rise progresses, the valleys are drowned and only the elevated geology resembles its former state (Marshak, 2011)

BOX 4: NORTH JAVA COASTLINE GEOLOGY

The north Java coastline of Demak is a relatively young plain composed of riverine and marine sediments and influenced by nearby volcanic activity, originating in the tertiary >2.6 million years ago. (Lloyd, Pim, Watkins, & Suwara, 1985). Sediment from the rivers deposited in coastal marshlands during Holocene or late Pleistocene (~18,000 years ago) now forms the bulk of the sediment. This consists of thick layers of calcareous and shell bearing clay, with thin intercalations of sand, and occasionally gravel or cemented gravel. In addition, the area has been subjected to uplift due to volcano formation, since the beginning of the tertiary (about 66 million years ago) until now. The subduction of the Indian Ocean Crust facilitates the continuous formation and erosion of volcanos (Putranto & Rüde, 2016).

WHAT DOES THIS INFORMATION ADD TO OUR SYSTEM UNDERSTANDING OF THIS COASTAL SYSTEM?

1. The relatively young alluvial plain remains dependent on sediment input from the rivers. These rivers contain a surplus of sediment, because they originate on volcanoes, which are continuously weathering. Deforestation, along with cultivation of the land, has increased sediment run-off from slopes and hence also increased riverine sediment load. In more recent times, however, construction of dams has impeded the influx of sediment, which may lead to erosion of the coastal system.
2. The north coast of Java is composed of clay and sand, with a deep sandy layer containing groundwater, or aquifer. Extracting groundwater from these layers drains the surrounding clay layers, thereby promoting consolidation and in turn subsidence. Fine sediment (mud, clay) is more compressible than sandy layers, making consolidation and subsidence irreversible.

WHAT DOES THIS INFORMATION MEAN FOR POSSIBLE INTERVENTIONS?
Hard infrastructure interventions, such as sea walls and revetments, sink considerably on soft sediment. This could greatly increase construction costs and maintenance costs, as extensive preparatory groundworks may be necessary, and the structures may require regular raising or upgrades.

3.2. ROLE OF HYDRODYNAMICS

Hydrodynamics concern the physics of the motion of water. Hydrodynamic processes, such as tides and waves are the drivers of sediment transport and resulting morphology, which sets the stage for coastal typologies and ecosystems. Three hydrodynamic forces, namely rivers, waves and tides, govern the way sediment is transported and shape coastal features. The shape and characteristics of soft sediment coasts depends

on the relative contribution of these forces to sediment distribution and transport (Doody, 2001; Harris & Heap, 2003). Rivers and subsurface currents provide a continuous influx of freshwater and sediment to the oceans (Masselink and Hughes, 2003). This influx drives water circulation due to the density differences between fresh and salt water (Simpson et al., 1990), which mix and transport the sediment along the coastline. Waves generated by wind also influence the motion of coastal waters, stirring up and transporting the sediment. Waves produce a back-and-forth or oscillatory flow as they propagate towards the coastline at relatively small scale (10m – 100 m) (Holthuijsen, 2007), and may generate currents when they encounter the shoreline (Bosboom and Stive, 2015). Such wave-driven currents can be perpendicular to the coastline (like the undertow) or parallel to the coastline (like the longshore current), and they create coastal features like bars, beaches or spits (see Appendix for more on these typologies). Tides drive sediment transport on a larger scale (100 m – 10 km), as tidal velocities and tidal excursion can be large. Generally, tides have a period of about 12 hours (semi-diurnal) of 24 hours (diurnal), with profound bi-weekly modulations (the spring-neap cycle). In shallow areas, such as bays and estuaries, tides form the typical patterns of channel-shoal systems, which form important ecosystems. Several indicators have been developed to evaluate the relative importance of rivers, waves and tides on sediment transport. For instance, the mean tidal range (i.e. the difference between the highest and the lowest tidal water level) compared to the mean wave height can be used to determine whether coastal processes will be more influenced by tides or waves (Seybold et al., 2007).

3.3. ROLE OF SEDIMENT AND MORPHOLOGY

Sediment and morphology are important components that determine coastal typology (Syvitski et al., 2005). Short term sedimentation processes form mid-term morphology and long-term coastal typology. In general, sediment reaches coastal waters via fluvial (river) and aeolian (wind) pathways and via the sea. Strong winds can pick up sand particles from dunes and deposit them in the sea and vice versa. Sometimes, sediment is mainly transported to the coast via river discharge (Syvitski et al., 2005). However, many coastal sediments stem from erosion of the foreshore, i.e. erosion of the coast itself, or from remote sources. It is important to realise that identification of a sediment source can only be done in relation to the relevant timescale. For instance, all fine sediment in the Guiana coastal waters (South America) stem from the Amazon River. However, many surficial coastal deposits are more than 1000 years old – thus on shorter timescales it is more realistic to relate coastal processes to the redistribution of coastal sediment, and not to its original source. Once a sediment particle enters coastal waters, it either settles or remains in suspension, depending on particle size and hydrodynamic energy. The largest particles settle first as hydrodynamic energy decreases. Smaller particles such as silt and clay are easily kept in suspension by currents and waves and are only deposited in calmer water. Although waves bring sediment into (re) suspension, actual sediment transport occurs by oceanic or tidal currents that bring suspended material along the shore, in-land, to estuaries or lagoons. Sediment leaves the coastal system when it is transported to deeper waters and cannot be picked up by waves again. Basic knowledge of what determines sediment transport and what drives sedimentation processes is needed to understand drivers of sedimentation and erosion processes along coastlines.

BOX 5: NORTH JAVA COASTLINE HYDRODYNAMICS

The region of Demak is influenced by a monsoonal climate, characterised by the North-West (NW) monsoon (December-January), and South-East (SE) monsoon (June-August), and two transition seasons in between (Ervita & Marfai, 2017). Storm seasons characterise the wave climate along the coast of Demak in Northern Java. The North-West monsoon (December-January) generates waves coming from the North-West, and the South-East monsoon generates waves coming from the South-East (Kane et al., 2016). During the NW monsoon the wind blows from the sea and a large input of freshwater reaches the coast through the Wulan river. The largest waves are generated during this season, with wave periods of about 5 s and heights up to 1 m at locations about 500 m offshore (van Domburg, 2018). Although these waves break in deeper water, significant wave energy reaches the shore, inducing erosion. The monsoon winds induce large scale circulations, with an eastward residual current during the NW monsoon, and an opposite westward residual current during the rest of the year. During the SE monsoon, the wind blows from the land, and the wave conditions are considerably milder mostly driven by the local land-sea/sea-land breeze in combination with the small monsoon waves. The local diurnal tidal range varies between 0.4-0.6 m.

WHAT DOES THIS INFORMATION ADD TO OUR SYSTEM UNDERSTANDING OF THIS COASTAL SYSTEM?

1. The Wulan delta is dominated by river influences, while waves and tides become more important further away. The bird-foot shape of the delta indicates river dominance there, and longshore transport of riverine sediment by coastal processes is limited. Further south, coastal mudflats indicate that tides and waves become increasingly important. The presence of sand bars at the river mouth and along the coastline indicates that wave processes noticeably affect coastal features.

2. The relative importance of waves and tides varies over the year. During the SE monsoon, nearshore waves of 0.1 m with a tidal range of 0.4-0.6 m would result in tide-dominated conditions, even if the tidal range is very low. But during the NW monsoon, waves of around 1 m at a tidal range of 0.4-0.6 m become important. This variability of driving forces over the year also has an impact on the coastal dynamics.

3. Information on the tides and monsoon-induced wave height and direction, contributes to understanding sediment transport along the coast over the season. However, longshore transports are small, and locally eroded sediment remains close to its source.

4. The input of freshwater also affects local currents and sediment transport. For instance, high freshwater discharge during the NW monsoon generates a gravitational circulation that keeps the sediment close to the shore (Tonneijck et al., 2015).

5. Subsidence can change the fundamental nature of the tides. Areas that were previously emergent, may suddenly become submerged by the tide, which causes the total intertidal area, and the strength and trajectory of tidal currents to change, and waves to become higher. This will also modify the pathways of sediment and the morphology of the coastline (Bosboom and Stive, 2015).

WHAT DOES THIS INFORMATION MEAN FOR POSSIBLE INTERVENTIONS?
Intervention strategies need to consider prevailing wind directions and wave heights. In addition, fresh water input from rivers and drainage of the land during high rainfall needs to be included in any intervention strategies.

BOX 6: NORTH JAVA COASTLINE SEDIMENT AND MORPHOLOGY

The North Java coastline of Demak is characterised by the Wulan delta, with mud flats and sand bars away from the river. The Wulan delta has a bird-foot shape with sand bars migrating along the delta. The present morphology consists of intertidal mudflats, some of which are sheltered from wave impact by cheniers. Cheniers are lenses of sand atop an otherwise muddy substrate; they can be detached from or attached to the shoreline and may be static or mobile. Cheniers are likely formed by waves and the sorting process between sand and fine particles. Most of the mobile sediment originates from previous coastal erosion events. Land subsidence due to groundwater extraction in the nearby city of Semarang influences the intertidal area. Subsidence rates up to 19 cm/year were observed in the northern part of the city (Abidin et al., 2012).

WHAT DOES THIS INFORMATION ADD TO OUR SYSTEM UNDERSTANDING OF THIS COASTAL SYSTEM?
1) Knowledge on sediment type gives rise to mechanistic understanding on how sediment responds to hydrodynamic forcing. For example, very fine sediment can be stirred by small amplitude waves, has low settling velocities and can therefore be transported seaward by the outgoing tide (Anderson, 1972). Likely this process induces the loss of sediment from the coastal zone to deeper water.
2) As explained above, the cheniers in Demak are likely formed by self-organisation of eroded coastal sediment. They are dynamic and are possibly a temporary phenomenon. Currently, these cheniers protect the coast from further erosion.
3) Sediment sources, composition, transport and quantities determine if a coast is growing and eroding. These parameters also determine if a coast can keep pace with sea level rise and subsidence by accreting sediment

WHAT DOES THIS INFORMATION MEAN FOR POSSIBLE INTERVENTIONS?
Rates of subsidence and sea level rise, in combination with the amount of sediment available and the transport capacity of sediment, also determine what intervention strategies are feasible. For example, mangroves need an intertidal area, while seawalls and levees require regular heightening Preferably, intervention strategies do not reduce sediment availability and sediment transport processes, as this may result in erosion and decreased bed level. Especially with sea level rise and subsidence, sediment input to maintain bed level is essential. Cheniers are important elements for coastal protection. Hence, chenier integrity is important and interventions should preferably not interfere with sediment input towards cheniers. Also, intervention strategies that focus on enhancing chenier formation and on increasing sediment input in the area, have large potential.

3.4. ROLE OF ECOLOGY

When the right environmental conditions are met, ecosystems gain importance in the regulation of sediment transport, by affecting hydrodynamics, trapping sediment, and producing certain morphology. Soft sediment coastlines, characterised by sand, silt or mud, are associated with a wide range of vegetation types and ecosystems, including dunes, intertidal flats, coral and shellfish reefs, sea grass fields and mangrove forests. These coastal ecosystems are of vital importance as nursery habitat for fish, crustaceans and shellfish, which are in turn crucial for local fisheries. In addition, they form important bird habitats and play a large role in coastal protection, nutrient transfer, erosion and pollution control (E. Barbier et al., 2011). There are complex and multiple feedbacks between ecology and the other elements of natural systems: geology, hydrodynamics, sediment transport and morphology. Organisms that are able to transform and alter their surroundings by modifying abiotic processes and thereby creating (or destroying) a habitat are known as ecosystem engineers (Jones, Lawton, & Shachak, 1994). In the light of coastal protection, the primary ecosystem services of coastal ecosystems are shoreline stabilisation, attributable to dissipation of hydrodynamic energy or wave attenuation by roots and sedimentation.

The interaction between hydrological forcing and sediment type is one of the crucial factors in determining coastal vegetation presence and type, along with the prevailing climate. Salt-marsh vegetation is found along sheltered muddy coastlines in temperate zones above mean tidal levels and mangrove vegetation is its equivalent along sheltered coastlines in tropical areas. More exposed coastlines with higher wave impact comprise sandy beaches and dunes with vegetation above mean high tide level, in both tropical and temperate climates. In all these habitats vegetation traps sediment that is transported by wind or currents and thereby increases elevation of the surface, promoting the formation of dunes or of salt marsh, or mangrove soil. An excellent example of how geology and ecology can create a characteristic environment is presented by atolls. Remnants of eroded non-active volcanos offshore provide shallow waters in which reefs can grow. Over time, the volcano continues to erode, while the reef keeps expanding, thereby providing sediment that feeds the atoll in the middle of the reef (McLean & Woodroffe, 1994). The classification of coastal ecosystems in the tropics and their temperate counterparts is presented in Figure 8.

Tropical coasts consist of a mosaic of mangrove forests, seagrass beds and coral reef ecosystems. This tropical 'seascape' is one of the richest repositories of marine biodiversity and provides a number of natural resources and ecosystem services that are vital to human wellbeing, including wave dissipation and erosion control (Moberg & Rönnbäck, 2003). Each ecosystem delivers a range of services (Table 1). For example, along tropical sheltered coastal zones mangroves contribute significantly to coastal stability by attenuating waves and reducing erosion (Gedan et al., 2011). They are also highly valued by local coastal communities for their use as timber and a variety of other products, but are simultaneously threatened, for the same reasons. Sand dunes may also block waves and surges, just as mangroves, but reduction of surges requires mangrove greenbelts of several kilometres wide. Coral reefs function extremely well as natural breakwaters by breaking waves (Ferrario et al., 2014). In addition, ecosystems reduce exposure by providing a buffer zone between people and assets, and the hazard. Healthy ecosystems also reduce vulnerability of communities by providing multiple other services, such as water purification and food production (Table 1).

HABITAT TYPE	ECOSYSTEM SERVICES
Coral Reefs	Breaking of waves, fish habitat, production of sand, creating sheltered conditions for other ecosystems, eco-tourism
Seagrass	Habitat and nursery for fish, clams, sea turtles and dugongs, trapping of silty sediment, carbon storage
Shellfish reefs	Wave energy dissipation, trapping and stabilising sediment, biodiversity enhancement, habitat for other organisms, water quality improvement
Biofilms	Limiting resuspension of sediment to increase visibility of the water column and increasing erosion resistance.
Mangroves	Dampening of waves, trapping and stabilising sediment, carbon storage, nursery for fish and shrimp, provisioning of timber and non-timber forest products such as edible fruits, seeds and honey, eco-tourism
Beaches and dunes	Wave energy dissipation, protection from storm surge, stabilisation of the coastline, eco-tourism
Intertidal flats	Habitat and foraging grounds for migratory birds, shellfish and crab production, wave attenuation

Table 1: Ecosystem services provided by coastal ecosystems, many of which contribute to mitigation of coastal risk.
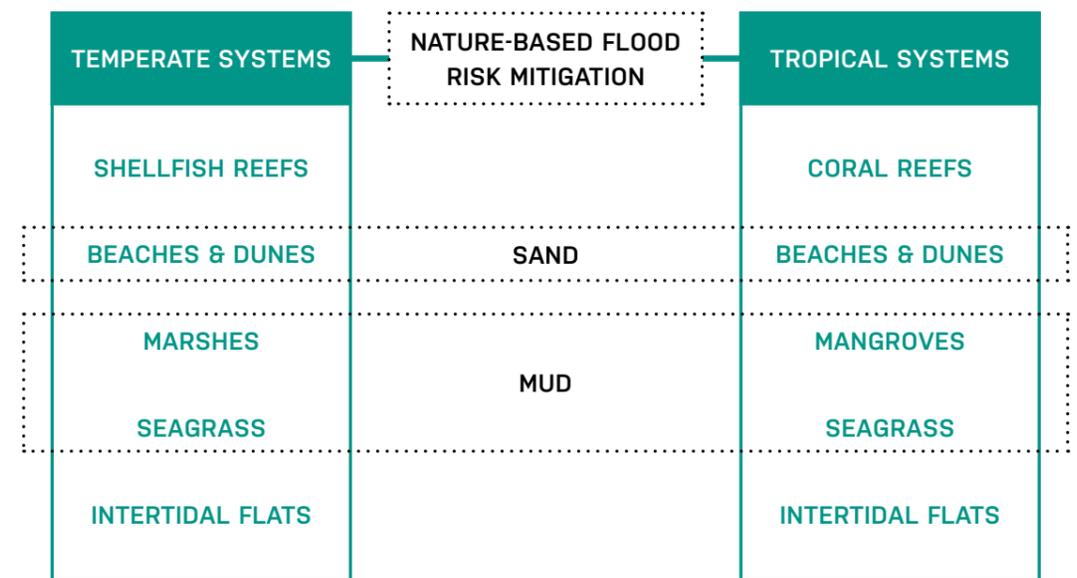

Figure 8: Schematisation of the different ecosystems in the coastal zone in temperate and tropical climates.

BOX 7: MANGROVES AND HAZARD REDUCTION

Along muddy, soft sediment, tropical coast mangroves are one of the most abundant ecosystems. They have a profound influence on the physical environment by influencing nutrient cycling, hydrodynamics and sedimentation. As described above, the right combination of hydrological and sediment conditions needs to exist for mangrove forests to develop and thrive. In a healthy mangrove ecosystem, the ecosystem becomes self-sustaining as the mangroves also play a role in influencing hydrodynamics and sedimentation. Mangroves can effectively attenuate wind and swell waves (for an overview see (Mcivor, Spencer, & Möller, 2012)). Their capacity to reduce wave heights depends on certain characteristics of the mangroves, such as density, diameter and height of the trees. Essentially, the plant characteristics represent the surface area of the vegetation that is met by the wave, as this determines the amount of energy that is transferred from the wave to the trees (Luhar, Infantes, & Nepf, 2017b). This is also influenced by the flexibility of the stems, roots and branches of the trees. In the case of strongly bending vegetation the frontal surface area is reduced, meaning the amount of energy transferred to the vegetation is lower (Bouma et al., 2005; Iris Möller et al., 2014). Furthermore, the reduction depends on hydrodynamic conditions, such as incoming wave height, wave period and water level.

Mangrove communities have demonstrated ability to reduce surge water levels during tropical storms by decreasing current speeds through increased roughness (Mcivor, Spencer, et al., 2012). However, to effectively reduce water levels during these more extreme conditions, extensive mangrove areas of several hundred of metres are needed. Additionally, the specific characteristics of the surge and the local topography are important. For example, surge level reduction by vegetation is more pronounced under fast moving surges (Zhang et al., 2012) and local creeks or fragmented mangrove patches may increase storm impacts locally. Similar evidence is found for tsunamis, where small mangrove stretches were found to increase damage, as trees were uprooted and smashed upon houses by waves. However, extensive mangrove forests may contribute to decreased damage as the trees at the back will trap any uprooted trees from the front. Even though it is important to better quantify any direct protective effects from large greenbelt zones in the future, the indirect effects of these zones, keeping people away from harm, should be acknowledged too.

Through attenuation of hydrodynamic forces, mangroves naturally enhance sedimentation and decrease erosion (Mudd, D'Alpaos, & Morris, 2010). Additionally, mangroves can stabilise soils with their root structure, thereby reducing resuspension of sediments (J. C. Winterwerp, Borst, & de Vries, 2005). They alter soil composition by increasing organic matter content through leaf litter, dead roots, branches and trunks. In more nutrient poor conditions with water logged circumstances, such as within atolls, this can initiate peat formation (Keuskamp, 2014). Although mangroves induce sedimentation on smaller scales, their influence on larger scale coastal dynamics is not completely understood. Mangroves tend to colonise gradual mudflat slopes, which are generally accreting. So, mangrove presence can easily be related to accretion (U Thampanya, Vermaat, Sinsakul, & Panapitukkul, 2006) but this may not necessarily be caused by the mangroves

themselves. Comparing sedimentation in mangrove forests with sedimentation on intertidal flats shows that sedimentation-erosion patterns in dense mangrove forests have less variation than sedimentation on bare intertidal flats within a single year (Balke et al., 2013). Moreover, on larger scales, fully developed mangrove ecosystems could be able to hold soils in place and shape coastal landscapes. Although it seems that, in general, mangroves can trap sediments and create a trend of overall yearly accretion, many mangroves nowadays suffer from anthropogenic influences on sediment fluxes. For example, in many areas upstream damming for hydropower and drinking water has reduced sediment budgets downstream, and canalisation of rivers has often disconnected river from floodplain, thereby diminishing sediment input from the river to the floodplain. In addition, many mangrove areas suffer from rapid subsidence due to extraction of deep groundwater for drinking water and irrigation (Lovelock et al., 2015; B. K. van Wesenbeeck et al., 2015). As a result, while mangroves may be able to accrete enough sediment to counteract moderate sea level rise, they will not be able to keep up with sea level rise aggravated by all these anthropogenic effects (Lovelock et al. 2015).

Figure 9: Mangrove roots dissipating waves. ©Mark Spalding

BOX 8: NORTH JAVA COASTLINE ECOLOGY

Hundreds of years ago, the Wulan delta had unblocked fresh water streams dissecting the delta toward the coast, and no fish ponds. Coastal plains were mainly occupied with mangrove forests and a network of tidal creeks. With intensifying human occupation, mangroves were replaced with rice fields. The last remaining mangroves were mostly removed for shrimp aquaculture half a century ago. Under natural conditions, mangrove forests are frequently inundated by tidal waters. Tidal creeks facilitate drainage and ensure input of water and sediment into the forest. Mangroves also require periods of dry-fall, calm wave conditions and a stable sediment bed (Balke et al., 2011). The current lack of connectivity in Demak, the continuous reworking of the soil for aquaculture practices and the cutting of the mangrove forest have severely impoverished the local ecosystem. Water quality has degraded due to the rapidly expanding population and domestic, agricultural, aquaculture and industrial pollution (Fadlillah, Sunarto, Widyastuti, & Marfai, 2018). Even if mangroves recolonise, they do not contain the full assemblages of mangrove species. Fish populations in the area are small and mainly consist of juveniles and small individuals. The previous large adult fish species and species of reptiles and amphibians have largely disappeared. While mangrove systems are very efficient at fixing carbon, soils in this area have very low organic content. Consequently, newly colonised forests do not come close to older mangrove ecosystems in form or function.

WHAT DOES THIS INFORMATION ADD TO OUR SYSTEM UNDERSTANDING OF THIS COASTAL SYSTEM?
1. The type of ecosystems that are encountered reveal information about other environmental and climate factors. In Demak, the past presence of mangroves indicates that there are large and low-lying coastal plains in the area.
2. The status of the ecosystem reveals any pressures on the natural world. In Demak, mangroves are only found in small patches low in species richness that consist mainly of opportunistic and pioneer mangrove species. This indicates that the forest is not very old and has suffered frequent disturbance.
3. Many unhealthy mangroves are found, and in certain areas, mangroves may collapse because of erosion or winds. This indicates large wind and wave impact from certain directions, and possibly a shortage of sediment (or large relative sea level rise).
4. Salinity levels may also increase above normal and cause some trees to perish, for example where road construction has blocked the water flow through inland channels. Creeks from the seaward side and from the landward side enhance flushing and regulate salinity (Lewis III et al., 2016).

WHAT DOES THIS INFORMATION MEAN FOR POSSIBLE INTERVENTIONS?
As this clearly is a mangrove habitat, intervention strategies that consider mangroves will be entirely feasible. Strategies that use mangroves to reduce wave impact and mitigate coastal erosion, in combination with small earthen levees to stop flooding, could be appropriate. However, poor mangrove conditions also point to several factors that may cause these strategies to fail, as mangroves may not thrive in this area. Identifying abiotic and social factors that hinder mangrove sustainability and health is extremely important.

BOX 9: NORTH JAVA COASTLINE HUMAN IMPACT

In Demak the landscape has largely been shaped by humans. Rivers and streams are embanked and disconnected from the floodplain, hampering sediment deposition in the flood plains. In the Wulan delta this clearly results in a protruding delta, as sediment is deposited further seawards. Upstream land-use practices leading to erosion increased sediment load in rivers, while on the other hand damming may reduce input of sediment downstream. Deforestation of mangrove forests to make place for rice and aquaculture in coastal lowlands results in increased wave impacts upon the coast and in salinity intrusion further inland. Moreover, groundwater extraction for domestic and industrial use, causes gradual subsidence of clayey topsoil. This lowers the low-lying regions of coastal Demak even more, causing regular flooding and ongoing coastal erosion.

WHAT DOES THIS INFORMATION ADD TO THE SYSTEM UNDERSTANDING OF THIS COASTAL SYSTEM?
1. The potential for the Wulan delta to keep pace with relative sea level rise is very much dependent on a positive net sediment balance. To counteract coastal erosion, enough sediment should be available or brought into the system, and
2. wave impact needs to be mitigated.
3. Connection of coastal floodplains to sediment and freshwater from rivers is vital to counterbalance subsidence and sea level rise, but 4) also for sustainable rice and shrimp farming.

WHAT DOES THIS INFORMATION MEAN FOR POSSIBLE INTERVENTIONS?
Interventions should focus on trapping available sediments and increasing the amount of sediment available. Capacity building and community engagement are essential for successful intervention strategies, as actors in the natural system should be aware of the consequences of land use practices and infrastructure construction. Hence, all intervention strategies should include changing unsustainable land use practices while still aiming to increase single household incomes.

Figure 10: Fish processing ©Yus Rusila Noor

Figure 11: Transport of barrells with fish through flooded streets (Demak, Indonesia) ©Cynthia Boll

3.5. HUMAN IMPACTS TO THE NATURAL SYSTEM

Coastal systems across the world are strongly influenced by human modifications and uses of the coastal landscape and of rivers that flow through it. Additionally, many coastal ecosystems are threatened by urbanisation and over-exploitation. For example, coral reefs suffer damage from dynamite fishing and coral bleaching. Climate change leads to increased sea water temperature and acidification, both triggering coral bleaching events (Grantham et al., 2011). If bleaching is prolonged or severe, corals may even die. Seagrass beds are lost all over the world, largely because of water pollution and nutrient run-off. Mangrove areas are threatened by clear cutting for fish and shrimp farming, upstream damming and reduction of sediment flows, changes in hydrology and other anthropogenic activities (Primavera, 2006; van Wesenbeeck et al., 2015). Large-scale degradation of coastal habitats and associated loss of ecosystem services such as loss of coastal protection and loss of fisheries have also resulted in growing awareness of the functional and essential roles of these ecosystems. However, land reclamation and development plans continue unabated and economic development often do not integrate these natural systems. A single focus on financial capital while neglecting social and natural capital will result in a loss of ecosystem services that are irreplaceable and that will result in large economic and societal costs in the longer-term.

4 HOW TO PERFORM A NATURAL SYSTEM ANALYSIS

4.1. STEPS FOR SYSTEM ANALYSIS

Natural system analysis is an iterative process which involves exploration of available data and subsequently gathering empirical and anecdotal information in the field. Depending on available time and resources, system analysis can be expanded with monitoring and measuring of important parameters. Each source of data should be scrutinised and double-checked. Global data should preferably be ground-referenced and local community anecdotes should be verified with expert knowledge and linked to larger-scale system understanding. In many cases, data may be lacking or difficult to access, which inevitably necessitates some assumptions based on expert judgment. System understanding will need to be enhanced during project implementation through a monitoring scheme, which may lead to adjusted solutions being implemented through adaptive management. When enough data is available, numerical modelling may aid in predicting the future development of the natural system.

A full system analysis requires a team of interdisciplinary experts to design and analyse site specific studies, including, as a minimum, a combination of engineers and ecologists. A combination of expert judgement, on-site assessments, field measurements, models and earth observation data, including satellite maps and images should be used to gather the right range of data (in time and space) on the different components of the natural system. Each case is unique and requires site-specific information and expert knowledge on coastal systems. Although the actual system analysis needs to be completed by experts, some basic steps can be distinguished (Box 10). For each step, more detail is given in the paragraphs below.

BOX 10: STEPS FOR NATURAL SYSTEM ANALYSIS

1. Global data inventory
2. Site visits and visual information
3. Community questionnaires
4. Field data collection and monitoring
5. Data analysis and modelling

4.2. GLOBAL DATA INVENTORY

A first impression of the natural system and its dynamics can be obtained by a review of global data. For example, Earth Observation Information (EOI) can help compile an initial overview of the geographic setting and how the area has developed over time. Starting the analysis with these data will make a site visit more focused and productive, through pinpointing areas crucial for understanding the problem and the natural system. A preliminary study of the geography, land use and the size of the human population can easily be undertaken by exploring satellite imagery on Google Earth. Features to observe related to geology, hydrology/hydrodynamics, morphology, ecology and the main anthropogenic factors that impact the natural system are listed in Table 2.

Dynamics of coasts and rivers are visible over longer time-scales using global tools, such as the Aquamonitor and the Shorelinemonitor (Table 3). These tools can be used to identify areas undergoing coastal erosion or accretion, or of changes to the course of a river. Supplementing visual information with other global data will help to build a more comprehensive picture of the geology, hydrology, morphology and ecology of an area. Geological data can often be found in articles and textbooks. Data on wind and wave patterns, tidal amplitudes, rainfall patterns, river discharges and typhoon tracks are sometimes available through the National Meteorological Office or in global databases (Table 3). Socio-economic data, such as population numbers and poverty indices, are often accessible through a country's statistical agency.

VISUAL ASSESSMENT OF EARTH OBSERVATION INFORMATION	
Geology	• What does the coastline look like: muddy, sandy or rocky? • Are there any intertidal flats? • Are there any beaches? • Are any intertidal areas, large or small?
Hydrodynamics and hydrology	• Are there any rivers or streams? • Are there many tributaries? • Is there a cycle of wet and dry seasons within a year? • Are there any signs of wet and dry periods between years? • What is the evolution of the river through time? • Does the river meander naturally? • What is the evolution of the coast through time? • Are waves visible? • Are any wave-breaking features visible?
Morphology and sediment	• Are there certain morphological features present, such as sand banks, spits or barrier islands? • Are there any sediment plumes visible around river mouths? • Is the coastline eroding or accreting over time?
Ecology	• Is there any coastal vegetation present? • Are there any mangroves, marshes or dunes? • Are there any barrier or fringing reefs present? • Is there any terrestrial vegetation present?
Human influence	• Are there people living in the area? • Is it rural or urban? • What is the main land-use? • Are there roads present? • Is the river channelised? • Is the river embanked? • Is there any coastal infrastructure present?

Table 2: Questions to guide the preliminary study of the natural and socio-economic systems through visual inspection of satellite images.

TECHNICAL TOOLS	SUMMARY AND URL	COMMENTS
Aqueduct water risk atlas	Compiles a map with an overall water risk index. https://wri.org/applications/aqueduct/water-risk-atlas/	Low resolution
Aqueduct global flood analyser	River and coastal flood risks for different protection levels. https://floods.wri.org/#/	Not all basins included
Aquamonitor	Surface water changes of shorelines and rivers. Assessment of river dynamics and erodible river corridor. https://aqua-monitor.appspot.com/	Quality and period depends on availability of satellite images
Shorelinemonitor	Long-term shoreline changes between 1984- 2016. https://aqua-monitor.appspot.com/?datasets=shoreline	Large area, low resolutions
Era5	Hourly estimates of a large number of atmospheric, land and oceanic climate variables. https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5	-
Glossis	Real-time water level and storm-surge forecasts with global coverage. https://www.deltares.nl/en/projects/global-storm-surge-information-system-glossis/	Run 4 times daily to produce 10 day water level and storm-surge forecasts, Delft-FEWS is needed
Census	Database for socio-economic data. www.census.gov	Large data base, focused mainly on the USA
EMODnet	Marine data contributed by 120 European partners. https://emodnet.eu/en	Mainly focused on the EU
FAO Soils portal	Soil maps. http://www.fao.org/soils-portal/soil-survey/en/	-
Global Mangrove Watch	Remote sensing data and tools for monitoring mangroves. https://www.globalmangrovewatch.org	-
Ocean wealth	Data on marine and coastal ecosystems and their effect on people. It includes global maps, region-specific studies, reference data, and a number of "apps" providing key data analytics. http://maps.oceanwealth.org/	-
Resource watch	Collections of curated data on the major challenges facing human society and the planet, including changes in wetland areas. https://resourcewatch.org/	-
Intertidal change	Intertidal change mapping based on supervised machine learning algorithm – nature publication. https://www.intertidal.app/	-
Reefbase	Global information system on coral reefs. http://www.reefbase.org/main.aspx	-

Table 3: Technical tools for rapid information gathering related to the occurrence of drought, fluvial flooding, erosion and other relevant data.

4.3. SITE VISITS AND VISUAL INFORMATION GATHERING

The field visit should be used to validate any hypotheses and observations based on the desk study and to further build a picture of the natural system and how it has been impacted by human influences. This is a good opportunity to gather more detailed visual information, to make sample measurements and to talk to residents. For measuring physical parameters, basic equipment can be brought along, depending on our focus and main interest. Examples are Global Positioning System (GPS) device, measuring rod, to quickly estimate water depths, refractometer for salinity, a flow velocity meter, e-coli strips to check drinking water pollution and cores or a simple shovel to determine soil composition. Table 4 gives an overview of questions to help characterise the natural system.

4.4. COMMUNITY QUESTIONNAIRES

On site, talking to people and communities can constitute a useful source of information to improve understanding of the problem and the natural system. From informal talks to community meetings to fully prepared questionnaires, all of these can provide valuable pieces of information comprised of traditional knowledge and local expertise. Another aim of communicating with people on site is to obtain bottom-up support for projects and involve stakeholders in the project. However, if tangible follow-up is uncertain, care should be taken to manage expectations. Community information will also be instrumental in developing a good problem comprehension. Getting input from people on what they perceive to be the main problem is crucial. For example, sometimes people are not bothered by flooding but more by the water being stagnant or by the water entering their house. Paying attention to what is perceived as a nuisance for local people, rather than inferring from observation alone, will result in better targeted strategies. Community contact during this phase can guide the development of intervention strategies. Therefore, if at this stage the community indicates a strong willingness to re-locate, expensive interventions focused on coastal protection can be eliminated. Finally, community livelihoods and their source of income should be carefully examined in a complementary socio-economic system analysis. *Intervention strategies should focus on increasing the resilience of people and communities. This also implies that intervention strategies that have negative impacts on the livelihoods of low- and middle-income groups should preferably be avoided.*

Although local communities possess knowledge on the system they live in, that understanding is often local and based on what they can see and what they experience. For example, local fisherman may know exactly where to catch the biggest fish, but year-on-year variation in fish populations is caused by factors that act on a larger scale. Hence, *local knowledge aids in problem understanding and analysis of the natural system, but should be complemented with large-scale information.* To obtain trustworthy information, tips for community interviews are presented in Box 11. and some examples of guiding questions are presented in Table 4.

PHASE	POSSIBLE QUESTIONS
Problem and causes	• What is the problem? • How long does the flooding last? • How often does it occur? • When did it start happening? • Where is the flooding? • Where is the erosion or accretion? • Where was the coastline before? • What are latest infrastructure developments? • What ecosystems are present? • How do you use the ecosystem? • Is there any logging activity? • Is there any mining activity for natural materials? • How is the land typically used?
Who is affected by the problem?	• Where does damage occur? • How many people are affected? • What are the main sources of livelihood? • Which people are most affected by the problem?
Strategies and interventions	• What agencies work here in the field? • Are resources or building materials available? • Where will building materials come from? • What are social habits and restrictions? • How are the stakeholders organised – who is in charge of what? • What interventions do people prefer? • What groups of people will benefit from interventions?

Table 4: Guiding questions for community interviews aimed at defining the problem, problem scope and objectives

BOX 11: TIPS FOR COMMUNITY INTERVIEWS

To obtain trustworthy information from community interviews it is best to:
1. Ask open questions that start with 'what',' when', 'why' and 'how'
2. Have a clear plan for questioning and what topics to discuss
3. Only ask people about things they experience themselves and that they can observe

4.5. FIELD DATA COLLECTION AND MONITORING

As part of project development, monitoring campaigns strive to obtain necessary data if resources and capacity is available. This data can be used for analysis of the natural system, but also serve as a basis for the design of interventions. Data on all the elements of the natural system may be required. Types of data that can be extremely useful but are usually difficult to collect are:

• Geology: the morphology and properties of the substrate at and below the surface
• Hydrology/hydrodynamics: river discharges throughout the year and for dry and wet years, current velocities and tidal data, wind and wave spectra for different events and recurrence periods
• Morphology and sediment: elevation or topography and bathymetry maps, sediment composition and availability
• Ecology: Presence, abundance and status of ecosystems and species

Campaigns are frequently started to collect data at an early stage of the project, as data is needed to develop suitable intervention strategies and to estimate the impact of each strategy using modelling. Monitoring will also play a role, after project implementation, to check whether performance criteria are met.

4.6. DATA ANALYSIS AND MODELLING

Numerical modelling, by running scenarios, can aid in understanding the potential future changes in the system. For example, the development of a coastal system under different sea level rise scenarios can help to evaluate the feasibility of any proposed intervention strategies. Importantly, numerical process-based models require essential inputs such as basic information about the hydrodynamics and morphological processes, bathymetry and boundary conditions, as well as realistic parameter settings, e.g. for available sediment. Additionally, basic data on response parameters, such as the morphological development of an area, or erosion and accretion areas, are essential for model validation. Hence, checking model outputs based on real-world data and expert understanding of the natural system, is essential.
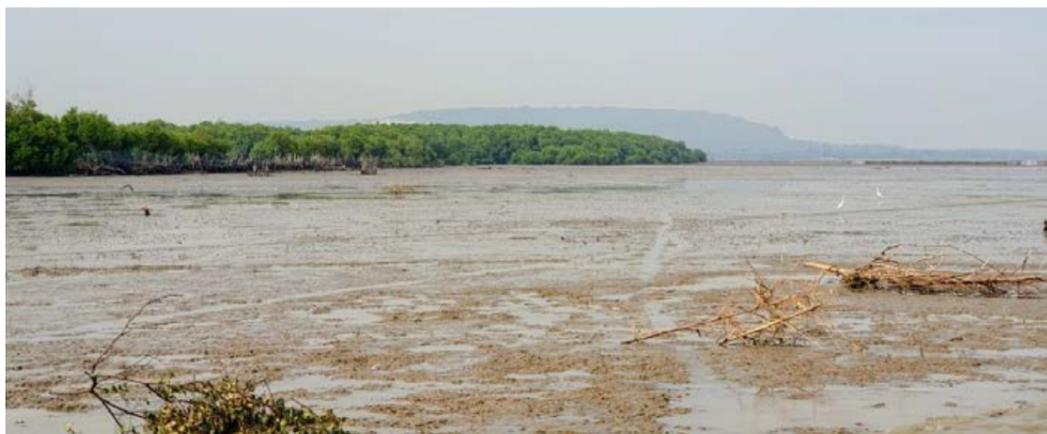

Figure 12: Mud flat transitioning into mangrove forest ©Joost Noordermeer

BOX 12: NORTH JAVA COASTLINE HUMAN IMPACT

In Demak, an explorative study was executed to identify project scope and objectives, using satellite imagery, a literature study, field trips and online sources of information (https://www.deltares.nl/app/uploads/2016/07/Deltares-WI-2014-Sustainable-solution-massive-erosion-Central-Java.pdf) (Step 1: Global data inventory and Step 2: Site visits and visual information). Upon programme inception, an in-depth baseline assessment of the natural and socio-economic system was performed to deepen our system understanding and complement the exploratory study with community questionnaires and focus group discussions (Step 3: Community questionnaires). This cumulated in a practical design and engineering plan, incorporating input from communities and other stakeholders (https://www.wetlands.org/publications/building-with-nature-indonesia-design-and-engineering-plan/). In this plan, an adaptive approach for design, implementation and monitoring was proposed. This allowed Indonesian stakeholders to play a major and decisive role throughout the process, but also enabled the consortium to deal with data scarcity and to adopt a pragmatic 'learning by doing' approach to optimise the design and mode of implementation along the way.

To stimulate stakeholder participation and learning by doing Coastal Field Schools were organised to empower coastal community members. Instead of instructing farmers on the technical steps of specific measures, the Coastal Field Schools used experiential, participatory and learner-centered techniques to build capacity of participants to analyse these measures and handle their own on-farm decisions. This involves experimenting, monitoring and evaluation. To inform project management decisions practical on-site monitoring was conducted to assess the effectiveness of mangrove restoration techniques and innovative aquaculture systems as well as needs for maintenance or corrective actions (Step 4: Field data collection and monitoring). To further enhance understanding of the system several in depth studies were executed, for example on integrated water resources management and climate change adaptation and mitigation potential (Step 5: Data analysis and modelling). Collaboration with local universities and governmental research teams was initiated and jointly coastal system dynamics and innovative aquaculture models were investigated.

Figure 13: Indonesian man monitoring between mangroves ©Kuswantoro

5 FROM A SYSTEM ANALYSIS TO A BUILDING WITH NATURE PROJECT

5.1. FROM NATURAL SYSTEM ANALYSIS TO AN INTERVENTION STRATEGY

A longer-term outlook on the development of a system over time benefits development of sustainable and climate resilient intervention strategies. Looking into both the past and the future as well as the present day, gives more insight into the causes, effects and impacts of the problems being experienced as well as any secondary effects. Ideally, this longer term, larger scale and cross-disciplinary outlook should be captured in a master plan focusing on increasing socioecological resilience. Building with Nature or nature-based solutions fit perfectly in such a strategy, as they are often considered a state of mind, a design/management philosophy and not a one-size-fits-all solution. They are location specific and they interact with hazards in different ways. *First and foremost, a master planning phase should set the basis for a coherent plan and for defining clear objectives and targets.* Coming up with strategies that include the full breadth of possible interventions aids a meaningful comparison and selection of optimal interventions. *Firstly, we should ask whether an intervention is necessary and feasible. If the answer is yes, different intervention strategies can be compared. Comparing a wide range of intervention strategies will include a full grey strategy, versus a full green strategy and possibly comparing with a mixed strategy.*

With respect to the natural system, the type of system and what processes form that system determine what measures are adequate and intervene in the system in the right way to meet objectives. Interventions can consist of non-structural measures, such as proactive spatial planning (risk prevention), early warning systems and evacuation plans (flood preparation), and structural measures. In general, non-structural measures are considered to reduce exposure to the hazard, while structural measures intervene by mitigating the hazard itself. Structural measures can be divided into 'hard' solutions such as seawalls, breakwaters and dams, and in 'soft' solutions such as nature-based measures. Principles and implementation guidance specifically for nature-based solutions are available and worth consulting before actual implementation (World Bank, 2017). Usually, projects develop several strategies to achieve their objectives and these strategies consist of multiple measures therefore can be a mix of structural and non-structural measures.
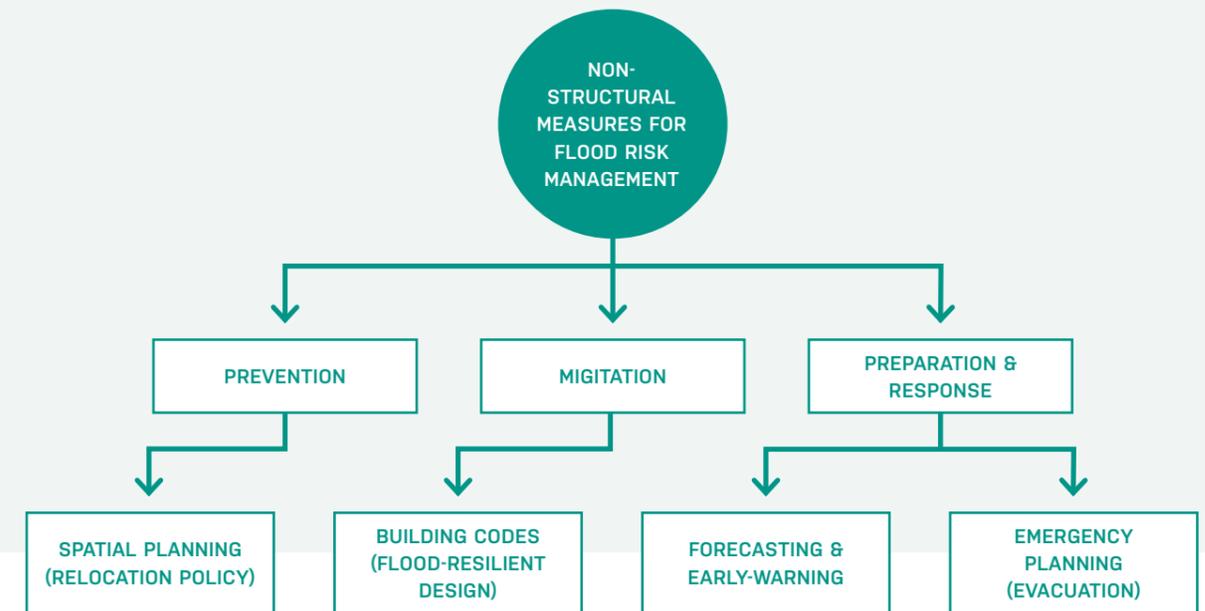

Figure 14: An overview of non-structural measures for flood risk management

5.1.1. Non-structural measures

Non-structural strategies for flood risk management aim at prevention, preparation, response and recovery (Figure 14). Spatial planning and reallocation policies, for example, are a form of flood risk mitigation. Land use and spatial planning can reduce flood exposure in the future by guiding housing, infrastructure and industry developments away from sites with high flood risk. At the same time, planning can be used to reduce habitat fragmentation and increasing ecological connectivity, which may result in strengthening ecosystem services that contribute to flood mitigation (see 'soft measures') (EC, 2010).

Another example of a non-structural measure is the use of building codes for flood-resilient design. Building codes should be applicable within the local context, particularly in informal and marginal human settlements, and should be applied concurrently with building the capacity to implement, survey and enforce such codes (UN, 2015). Finally, forecasts, early warning systems, emergency and evacuation planning are a form of preparation, and a response after a flood has occurred. Flood forecasting and warning systems can inform government authorities accurately when and where a flood is about to occur, providing them with information for an appropriate response. With extreme floods, emergency planning (including evacuation) should be part of the response.

5.1.2. Structural measures

'Hard' or traditional engineering solutions for flood risk management aim to optimise safety by interceding the hazard directly (Figure 15). Hard solutions are therefore designed to interact with a specific part of the physical environment: waves, sediment and/or water level. Breakwaters and seawalls both protect the coast, with breakwaters aimed at reducing wave energy and positioned perpendicular to the wave energy. Seawalls are structures built of concrete, wood, steel or boulders that run parallel to the beach at the land/water interface. Their main function is to protect the hinterland from floods and waves and unlike breakwaters, seawalls also protect against high water levels. Groins are rigid shore protection structures that are usually composed of large boulders placed perpendicular to the coast, interrupting longshore currents and trapping the longshore flow of sand.
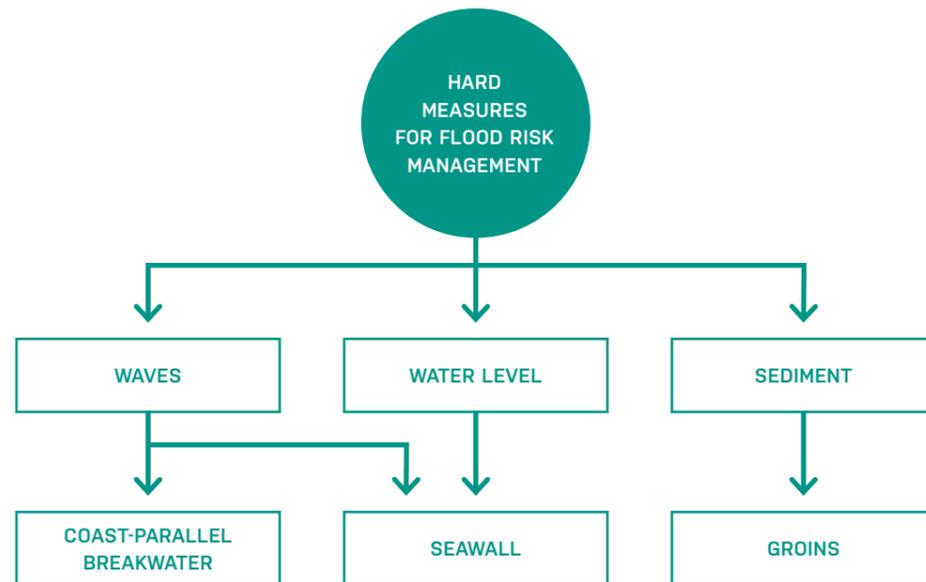
Figure 15: An overview of hard measures for flood risk management.

5.1.3. Soft measures

Hard measures are gravely challenged due to their continual and costly maintenance, as well as their heightening and widening requirements in keeping up with intensified flood risk and sea level rise (Temmerman et al., 2013). Instead of relying on 'hard' technical solutions, the integration of natural, socio-economic and governance processes with coastal and riverine protection could provide more sustainable, adaptable, multifunctional and cost-effective solutions (Slobbe et al., 2012). Key characteristics of soft flood risk management measures are utilisation of natural processes, optimising multiple functions, being adaptable to changing circumstances, cost-effectiveness and having an integrative approach (H. De Vriend & Van Koningsveld, 2012). Building with Nature offers a design philosophy to work with nature-based solutions to mitigate flood risk. Ecosystems and natural processes can then constitute an integral part of the intervention strategy, offering a certain level of risk reduction. Working with these Building with Nature measures requires solid understanding not only of the natural system, of the ecosystems that are present and of their functioning and behavior on different time scales, but also of the influence that these ecosystems can exert on natural hazards.
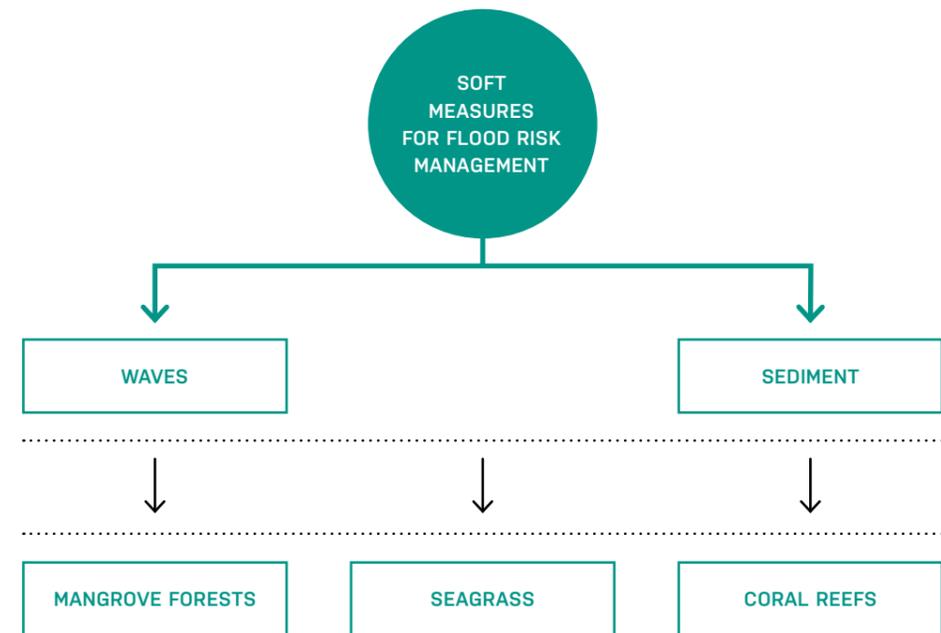
Figure 16: An overview of soft measures for flood risk management in tropical coastal areas.

BOX 13: NORTH JAVA COASTLINE, MANGROVES AS NATURE-BASED SOLUTION

Soft solutions aim to use ecosystem services for functional approaches. Hence, restoration of the ecosystem and its components are central to these types of solutions. The Demak project focused on restoration of the mangrove ecosystem that used to be present and on reverting coastal erosion to coastal expansion. Although restoration of mangroves seems like an attractive and easy intervention, many failures of mangrove replantation schemes indicate the need for expert knowledge and natural system analysis (Primavera & Esteban, 2008). For mangroves to recolonise or survive, the right combination of coastal morphology, submergence time, wave conditions, tidal motion, fresh water availability, sediment supply and plant species need to be selected (Lewis, 2005). Restoration by facilitating the right environmental conditions corresponding to a reference system has priority (McDonald, Jonson, & Dixon, 2016). This is what we call passive restoration. Yet, if it is decided to actively restore mangroves by planting, it is important to consider the appropriate species. For example, Avicennia spp are more resilient against highly energetic conditions than Rhizophora spp (Udomluck Thampanya, Vermaat, & Duarte, 2002), and are more resistant to fluctuations in salinity (Hossain & Nuruddin, 2016).

An important precondition of mangrove restoration is elevation and related submergence time. Often restoration projects achieve limited success due to planting at unfavorable locations, such as too low in the intertidal zone. Mangroves prefer a surface elevation between mean sea level and mean high tide (Clough, 1982). These topographies are flooded less frequently. Mangroves require areas inundated approximately 30%, or less of the time by tidal water (Roy R Lewis, 2005). Being inundated causes lack of oxygen, because their aerial roots are not able to breathe (Adams & Human, 2016). Likewise, it can cause lethal salinity levels in the soil (Hossain & Nuruddin, 2016). Inundation free moments are also necessary for seedling recruitment. If the bed level is high enough, seeds are only washed ashore during exceptional high-water levels. If thereafter lower water levels persist for a while, seeds can grow and establish themselves (Balke et al., 2011). Creeks and rivers mouthing in a mangrove system feed the mangroves with sediment and drain the soil (McLachlan et al., 2020). Obstructions of the flow that hamper sedimentation in the forest may affect the formation of sediment bed levels or cause water logging.

Possible interventions methods to ameliorate abiotic conditions, can consist of creek digging, sediment nourishment and erecting wave dissipating structures. Nourishment with sediment to increase bed levels and reduce submergence time for mangrove recruitment. In the Demak project, permeable structures were deployed to dissipate hydrodynamic energy, increase sedimentation and raise bed level above mean sea level. The advantages of permeable structures made of bamboo and PVC over concrete are that they do not sink into the soft mud, can be constructed by manual labor, are considered relatively cheap and can easily be adjusted. Mangrove seedlings can naturally colonise the sheltered areas landward of the dams. At Demak sites Avicennia spp. (A. alba and A. marina) recruits naturally.
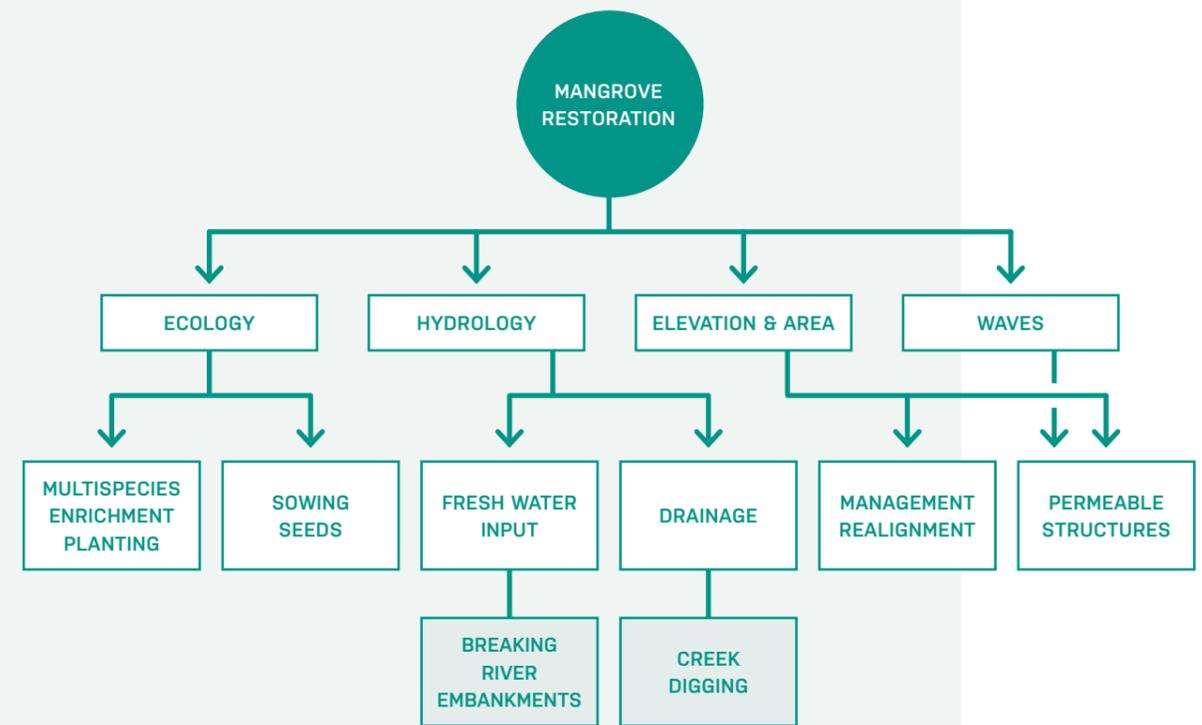
Figure 17: An overview of abiotic and biotic preconditions (second and third row) for mangrove restoration (first row) and associated measures (third and fourth row) that can be used to ameliorate abiotic conditions.

Figure 18: Women building permeable structures ©Nanang Sujana

Figure 19: Mangrove shoots coming out of the sediment ©Cynthia Boll

5.2. MEASURING AND MONITORING

Building with Nature projects should be monitored for performance similarly to conventional engineering projects. However, Building with Nature interventions are inherently dynamic, while standard hydrological infrastructure is static. To cope with dynamics and uncertainties, adaptive management can be applied, implying that a monitoring and management system that can respond to changes in performance of the intervention needs to be in place. Since a Building with Nature project works with natural processes and incorporates nature into the design, it is not possible to fully predict its future evolution. At the design stage, this can be tackled by considering a realistic range of possible scenarios for operation, management, monitoring and adaptation. An advantage is that having an adaptive management system in place prevents (costly) over-designing and that the design can be adapted to unexpected changes in the environmental conditions. Disadvantages are that manuals, protocols and institutions may not prepared for this.

Objectives and targets should be clear from project initiation, as these guide the setting of performance indicators for adequate monitoring. Good Building with Nature projects should have performance indicators that are focused on achieving functionality of the design in view of the objectives. These include whether enough sediment has accreted, whether wave attenuation is sufficient and whether the flood risk is reduced to acceptable levels. Structural integrity of the design can be monitored as well, indicating which elements remain in place and whether there are any signs of failure. Another set of functional indicators, specific for Building with Nature projects, could focus on natural objectives. For example, whether certain biodiversity targets have been met or species abundance has increased.

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Figure 20: Flooded house in Demak ©Nanang Sujana

APPENDICES

X

Various tools that help disentangle causes and effects exist. Here, we cover 1) the problem tree 2) DPSIR (drivers, pressures, states, impacts, responses) 3) Ishikawa or fishbone diagrams. We applied these frameworks to coastal erosion in Demak, Java, Indonesia. The three schemes use different approaches. The problem tree helps find solutions by mapping out the anatomy of cause and effect around an issue (Figure 21). The DPSIR framework unravels a problem in a chain of causes starting with driving forces such as economic sectors, human activities. Driving forces steer pressures such as emissions or waste. The pressures lead to certain to states (physical, chemical and biological) and impacts on ecosystem like human health and functions. Ultimately, responses (prioritisation, target setting, indicators) are sequential to these impacts (Tscherning et al., 2012)(Figure 22). The Ishikawa diagram organises the understanding of the causes affecting the variation in the problem (Best & Neuhauser, 2008)(Figure 23). The Ishikawa diagram categorises causes per system.

One of the advantages of a problem tree is that it enhances the understanding of the problem and its interconnected and contradictory causes. It gives an instant overview of all causes and effects. The DPSIR has an advantage when causes are sequential, and it is important to find the root cause of an impact. After all, every cause succeeds the other, which ultimately leads to the main effect, the impact.

EFFECTS

LOSS OF SHRIMP PONDS
FLOODING OF HOUSES
LOSS OF INCOME
SALINATION OF DRINKING WATER
ISOLATION OF VILLAGES
FLOODINGS IN GRAVEYARDS
LOSS OF ROADS
CONTAMINATION OF DRINKING WATER
DYING OF TREES AND CROPS

CORE PROBLEM

COASTAL RETREAT

CAUSES

SEALEVEL RISE
HIGHER WAVES
DEFORESTATION
SEDIMENT SHORTAGE
EROSION
CHANNEL NORMALIZATION
SUBSIDENCE
DISCONNECTED RIVERS FROM FLOOD PLAIN

Figure 21: Problem tree: coastal retreat of the coast of Demak.
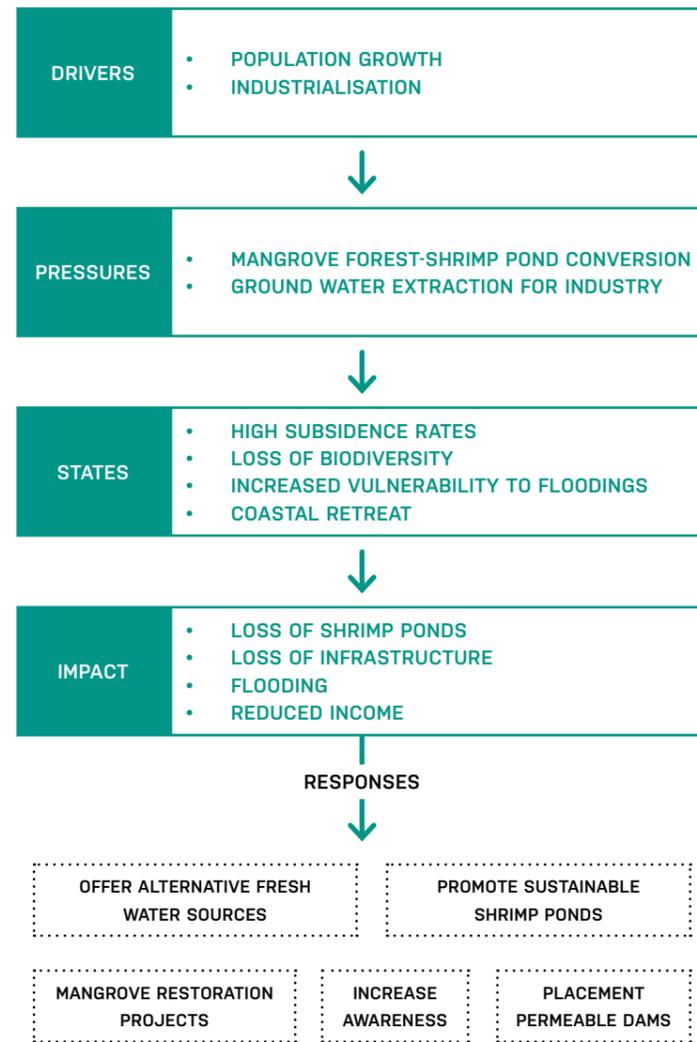
Figure 22: DPSIR: coastal retreat of the coast of Demak.
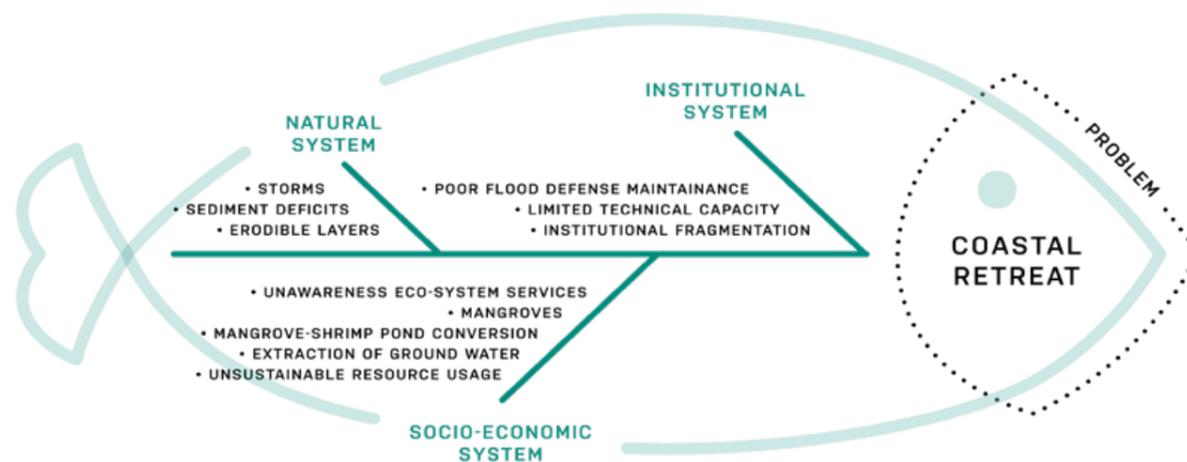
Figure 23: Ishikawa coastal retreat of the coast of Demak.

X **APPENDIX 2: SPATIAL AND TEMPORAL VARIATION IN NATURAL SYSTEMS**

X2.1 GEOLOGY

The sediment supply process depends on flow in different lobes of the river delta. When a river abandons its course in favor of a new one, this is known as avulsion. If an avulsion occurs upstream, the mouth of the old course suddenly receives less sediment than before. Insight into processes triggering avulsions helps to unravel the causes and effects of spatial variation in sediment distribution over longer timespans. This is vital for understanding sediment starvation in deltas, because avulsions occur once in the 100-1000 years (Kleinhans et al., 2013), while human induced sediment starvation, caused by building dams, had only come about in the last century. Avulsions occur if the slope of a new course is steeper than the slope of the existing channel. Factors triggering the redirection of rivers on geological timescales are subsidence due to compaction of peat and clay, neo-tectonics, relative sea level changes and patterns of sedimentation (Stouthamer & Berendsen, 2007). For example, young volcanic regions have steep slopes and are easily erodible, and therefore deliver more sediment to downstream deltas, compared to older volcanic regions (Major et al., 2016). Rivers at the foot of these relatively young and steep volcanos are likely to avulse faster, because thick layers of unconsolidated Holocene and/or Pleistocene deposits accumulate in their deltas with high sedimentation rates. An avulsing river causes the river mouth and its distributaries (fans of smaller streams) to shift location, whereby a new area of the delta becomes active. Consequently, a new delta lobe expands seaward due to sediment input. If the old delta lobe is not receiving sediment anymore, it will compact under its own weight over time (Figure 24). The coarsest material is deposited in the active distributaries and on its fringing natural levees (Fisk, 1960). The low-lying areas between the distributaries form flood plains, only inundated during floods overtopping the levees. During these episodic events, the flood plains receive fine, organic-rich material.

Delta and river systems often show dynamics and changes on different timescales. Some delta formation processes in coastal systems act beyond any engineering timescale, taking place on geological timescale instead. Most of the coastal deltas we view today were formed 6000-8000 yrs. before present (B.P.) when the sea levels were relatively stable for a longer period of time (Renaud et al., 2013). These deltas continued to expand seaward due to a combination of sediment supply and the creation of space available for potential sediment accumulation by sea level rise during the Holocene, the epoch that started 12000 yrs. B.P. (Stouthamer & Berendsen, 2007). Subsequently, global sediment fluxes from land to sea peaked around 1000-3000 yrs. B.P. due to increased deforestation by human activity. This triggered the seaward expansion of coastal systems worldwide (Syvitski & Kettner, 2011). Nevertheless, this sediment disturbance signal reversed by the end of the 1950s due to the proliferation of dams and embankments. As a consequence of reduced sediment fluxes from upstream river catchments to coastal systems, sediment starvation in deltaic areas is currently an urgent issue (Kondolf et al., 2014). Thus, on a geological timescale, deltas expanded 1000-3000 yrs. B.P., but human activity reversed the trend in the last century, inducing coastal retreat.
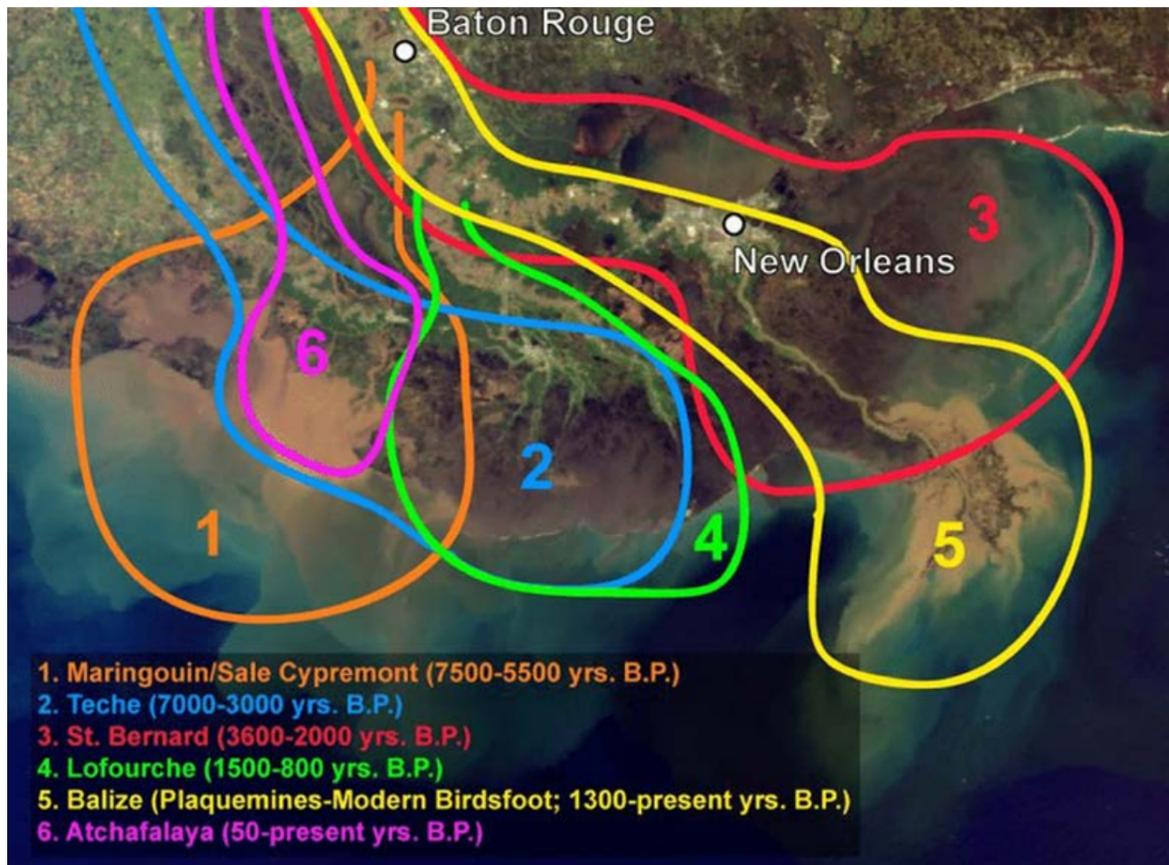
Figure 24: Various active delta lobes in the Mississippi delta over time. The oldest lobes disappear because of a lack of sediment input in combination with subsidence due to compaction (Bloom, 1998).

X2.2 HYDRODYNAMICS

Sediment is brought to the coastline amongst others by rivers and transported to different locations by waves and currents. Coastal erosion of older or recent deposits is often an important source, often the larger. Any natural process or human intervention that modifies those circulations may intercept or change the pathways of sediment, nutrients, seedlings, or any other particle that is carried by currents. If the sediment transported by rivers is blocked by a dam, it will not reach the coastline, starving the coast of sediment and leading to erosion (Inman, 1985). Local groundwater extraction can cause sinking of the ground and flooding of coastal areas (Erkens et al., 2015). Another potential consequence of human interventions is habitat degradation. Dikes and embankments can block tidal inundation or cut off the inflow of freshwater into a mangrove forest (López-Portillo et al., 2017). Understanding how the physical processes are interlinked is essential to predict the effect of natural phenomena and human actions, and how to reverse or mitigate their effects if necessary.

Coastal processes vary over several timescales. Understanding the evolution of the inner coastal shelf, over spatial scales of hundreds of km, requires looking at natural processes over thousands of years. For example, the dynamics of a smaller spatial domain, such as a 1 km-long stretch of coastline, will be dominated by processes acting over a smaller period of time (Thom & Cowell, 2005). For instance, wave generation by the wind, or the influx of freshwater by rivers fluctuate with seasonal and yearly

weather cycles and may modify the shape of the coastline during those cycles. Humans also interact with these natural processes in different ways, at time scales that range from years to centuries. People extract water from streams and rivers, store it using dams, or extract groundwater, for agriculture or industrial uses. They also use embankments to regulate rivers, build dikes to prevent flooding from the coastline, or coastal structures to attenuate waves. These interventions can also have unintended consequences for the complex natural coastal system, as explained in the next section.

PROPERTIES OF TIDAL FLAT PROFILES
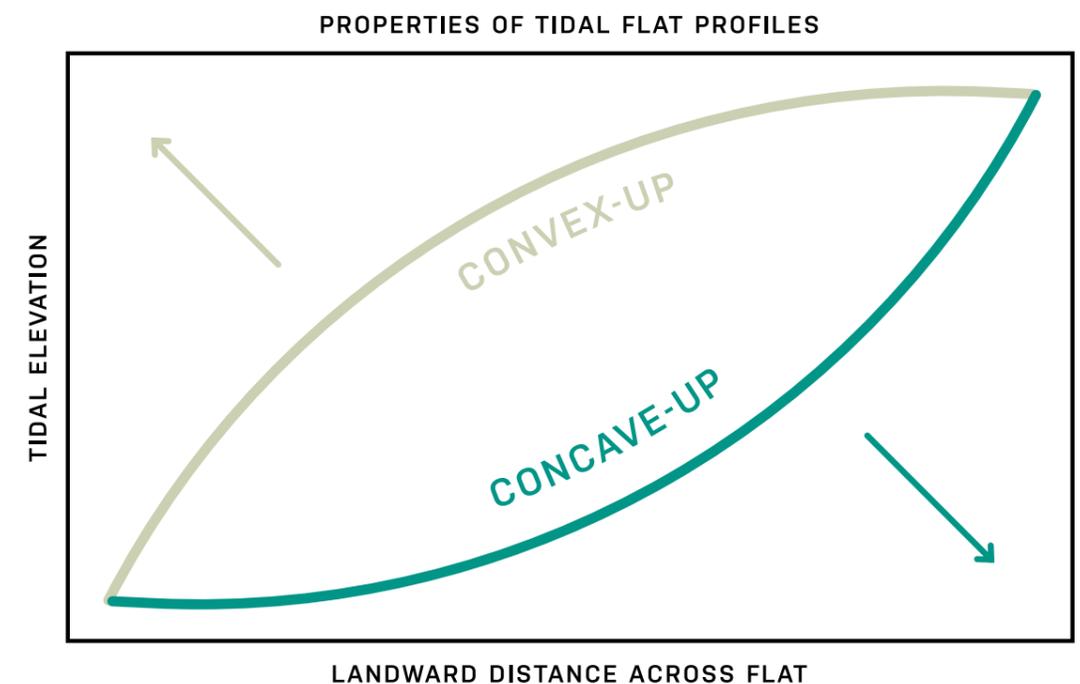
INDEPENDENT FORCINGS	INDEPENDENT FORCINGS
• Increased tide range; • decreased wave height; • increased external sediment supply; • bioaggregation, bioadhesion; • faster-rising tide with longer duration high water (HW) period.	• Decreased tide range; • increased wave height; • decreased external sediment supply; • bioturbation, human disturbance; • faster-falling tide with shorter duration HW period.
DEPENDENT RESPONSES	**DEPENDENT RESPONSES**
• Net shoreward sediment transport; • increased deposition; • decreased grain size; • increadingly convex-up profile; • prograding profile; • locally shortened HW slack.	• Net seaward sediment transport; • increased erosion; • increased grain size; • increasingly concave-up profile; • retreating profile; • locally lengthened HW slack.

Figure 25: Conceptual diagram showing the relation between forcings, dependent responses and the change of tidal flat morphologies (Friedrichs, 2012).

X2.3 SEDIMENT TRANSPORT AND MORPHOLOGY

To understand sediment distribution in a delta and the different morphologies it produces, it is important to ask what formative stories they tell. For example, in muddy systems the shape of the mudflat platform reveals which processes are at play, and whether the system is eroding or not. When suspended sediment concentrations are high and the impact of waves is relatively low, convex-up platforms are formed, whereas concave systems arise at low sediment concentrations and high wave impact (Friedrichs, 2012). Concave-up systems are typically undergoing erosion, and convex-up systems are generally stable or accreting (Figure 25).

Also, in sandy systems, understanding the morphology helps to interpret the processes at work. Dissipative beaches are wide mild sloped beaches with fine sediment. These beaches are formed by large waves with small periods generating an offshore directed return flow induced (Masselink et al., 2011). Dissipative beaches have wide surf zones with at least two bars on which wave break and dissipate energy. The other morphological end-member is a reflective beach, which is characterised by a steep beach face with largely coarse sediment (Aagaard et al., 2013). Waves break by surging at the base of the beach face. This morphology is shaped by primarily onshore transport by small waves with long periods (Figure 25). An intermediate beach is in general a less stable morphology, which reflects a transition from dissipative to reflective or vice-versa. Yet, an intermediate beach can have various distinct morphologies as well (Masselink & Short, 1993). Most distinctive of this morphology is the presence dynamic bars dissected by strong seaward directed rip currents. These bars either work their way towards the beach to form a reflective beach or migrate seaward to form a dissipative beach. The same beach can have different states in time depending on the prevailing wave climate. This wave climate is often seasonal, which explains the cyclic appearance of these morphologies (Roberts et al., 2013). In the context of larger tidal basins, changes in morphological appearances may reveal which processes are at play. For example, a reduction of cross-sectional area of a tidal inlet is indicative for a decrease in tidal prism (total volume of water that flows in and out during one tidal cycle). This morphological response tells you that former connected sub-basins are disconnected with the main basin, or that past sedimentation decreased the overall volume of the basin (Major et al., 2016). In this case, dredging the tidal inlet is useless, since it does not address the main cause, a reduction of tidal prism.

Intrinsically, beaches and other soft sediment coastlines are dynamic and go through erosion and propagation within a year but also within multiple years. In addition, effects of these events can differ spatially. For example, storm events can result in both large erosion and deposition events, depending on local conditions. In general, processes and interventions that change current patterns, wave input and discharge quantities of rivers, are likely to influence sediment transport processes as well, by affecting the type and amount of sediment that is transported and where it is deposited. Overall, sediment that is found along shorelines is related to hydrological forcing: muddy shores indicate low wave energy (Anthony et al., 2010; Quartel et al., 2007; Sheremet & Stone, 2003). In areas of high energy, waves bring more sediments into (re)suspension and logically larger waves can bring larger particles in suspension from the seabed (Hoefel & Elgar, 2003; Madsen et al., 2001; Ward et al., 1984). Forces that transport sediment act on different time scales and result in different morphology. For example, the day to day orientation of the beach with respect to the dominant wave direction determines whether it is sheltered or exposed. Likewise, the daily sway of the tides entering the coast can alter local sediment budgets (Allen, Salomon, Bassoullet, Penhoat, & Grandpré, 1980). An example of the latter is a process known as the settling lag which facilitates landward transport of fines, because of a decreasing flow rate, landward locations import more fines than seaward locations, resulting in accumulation of fine particles at landward locations (Straaten & Kuenen, 1958). Over multiple years, other events come into play and yearly variations of large atmospheric events, such as El Nino, influence the frequency of storms (Rasmusson & Wallace, 1983), which regulates swell direction and therefore can alter wave impact on certain stretches of the coast (Restrepo & López, 2008). Large rainfall events trigger erosion on land which feeds rivers with additional sediment loads. Once rivers enter the coastal domain, sediments precipitate (Fraticelli, 2006). Human impact related to morphology and sediment transport on an entire delta scale is discussed above in the section about geology, but humans can also have a direct effect on morphology. Examples are reflective structures and groynes orthogonal to the coast line. They trap sediment locally, but locations leeside of the structures experience sediment shortage upon implementation (Rijn, 2005). On slightly longer timescale, human impact on morphology is also recognised. For example, the main channel system in a tidal basin called the Waddenzee is still in search of a new equilibrium after construction of the Afsluitdijk in 1932 (Dastgheib et al., 2008).
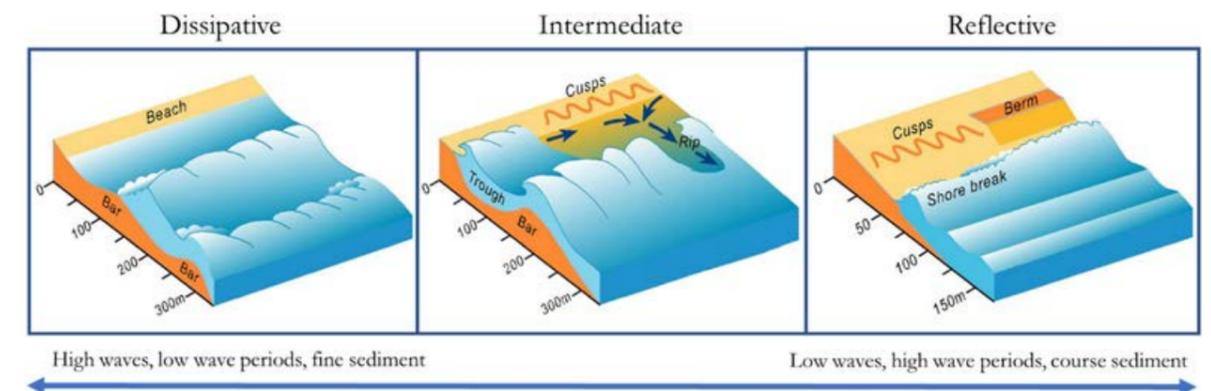

Figure 26: Dissipative and Reflective beach. Dissipative beach has a broad surf zone with foamy waves that break far off shore, which we call spilling breakers, while a reflective beach has a narrow surf zone with waves that roll up the steep face of the beach rather than breaking, which we call surging breakers. The Intermediate beach morphology that is portrayed is termed longshore bar and trough and is one of four recognised intermediate beach morphologies (Masselink & Short, 1993).

X2.4 ECOLOGY

Ecosystem type is determined by climate, submergence time, nutrient availability, salinity and sediment type, the latter strongly influencing nutrient availability. Coastal systems usually contain a variety of ecosystems that interact with each other by altering abiotic conditions and are spatially distributed according to physical gradients. For example, coral reefs provide sheltered conditions for sea grasses, and seagrasses buffer between mangroves and coral reefs by reducing acidity, a factor increased by mangroves, but damaging to coral reefs. Furthermore, the persistence of an ecosystem type is not only determined by abiotic parameters, often also depends on positive feedback loops. Typically, organisms that initiate certain positive feedbacks are ecosystem engineers (Jones et al., 1994). Corals are important ecosystem engineers, as they build complex reef structures in which both coral skeletons and living corals modify the abiotic environment by reducing currents but also provide the reef crest on which many other species can settle. Another term for species that provide a habitat for other species to settle on is foundation species (Ellison et al., 2005). A foundation species is a single species which creates locally stable conditions for other species by modulating and stabilising fundamental ecosystem processes which define much of the structure of a community (Dayton, 1972). Some organisms that inhabit the coral reef, also graze and keep it clean from invasive macro-algae (Mumby & Steneck, 2008), thus creating a positive feedback loop that maintains the ecosystem. In the intertidal zone, mangroves and salt marsh species cause wave attenuation and flow reduction with roots and shoots (Mazda et al., 1997; Schwarz et al., 2014), facilitating sedimentation and thereby creating an elevated bed level, which not only ensures persistence of the engineering species (Van Wesenbeeck et al., 2008), but is also suitable for many other organisms (Alongi, 2009). Species composition varies heavily along salinity gradients (Crain et al., 2004, 2008) and few species occur in areas where the salinity is in constant flux such as in estuaries or river deltas. Nutrient availability can also determine species occurrence, as coastal ecology and biological processes are governed by the fluxes of nutrients (Howarth, 1988).

Processes that govern coastal ecosystems, such as salinity, sediment input and nutrient fluxes, are strongly influenced by people. The high productivity of coastal areas that makes them so attractive to humans, is a derivative of services provided by coastal ecosystems. The heavy demand on these ecosystem services, also imposes enormous stress on coastal ecosystems. Direct overexploitation of ecosystem services such as over-fishing and clearcutting of mangrove forest are evident stressors (Blanco et al., 2012; Hoq, 2007). However, there are also numerous anthropogenic influences that indirectly put major stress on coastal ecosystems. In rivers and coastal water for instance, eutrophication often results in massive micro and macro algal growth, leading to anoxic conditions and deterioration of coral reefs and other marine ecosystems. In rivers and intertidal zones there are major effects of roads, dams and sluices, which not only impair fresh water and sediment input into the system, but also hamper drainage of water to the sea and migration of fish and other species. In mangrove forests, poor hydrological connectivity has been known to lower establishment rates due to reduced seed dispersal (Lewis, 2005), and poor seedling anchorage in waterlogged and unconsolidated sediment (van Bijsterveldt et al., 2020). Reduced sediment influxes can be even more detrimental to mangrove ecosystems, as existing mangrove forests need sediment

input to keep up with sea level rise and land subsidence (Sasmito et al., 2016). Mangrove forests are well adapted to changing environments however, and paleo-environmental studies have shown that forests have been able to move inland with increasing water levels provided that enough sediment is available and sea level rise does not unfold too fast (Ellison, 2008; Saintilan et al., 2020). Yet, it is important to note that anthropogenic disruptions (e.g. clearcutting of mangroves, damage to coral reefs by mining, fishing or pollution) have an instant degrading effect, while coastal ecosystems recover/develop over longer timescales.

MANGROVE → SEAGRASS MEADOW ⇄ CORAL REEF *→

MANGROVE
PREVENTS EROSION
ABSORBS NUTRIENTS*
INTERRRUPTS FRESH WATER DISCHARGE
EXPORT OF FISH AND CRUSTACEANS

SEAGRASS MEADOW
BINDS SEDIMENT
ABSORBS NUTRIENTS*
EXPORT OF MATURING FISH

CORAL REEF
BUFFERING OF WAVES AND CURRENTS
EXPORT OF FISH AND INVERTEBRATE LARVAE
MIGRATION OF ADULT FISH AND INVERTEBRATES (INFLUENCING PRODUCTIVITY OF SEAGRASS MEADOWS THROUGH GRAZING AND NUTRIENT EXPORT)

* MANGROVES AND SEAGRASS MEADOWS SOMETIMES EXPORT NUTRIENTS (ESPECIALLY ORGANIC NUTRIENTS).

*→
EXPORT OF ORGANIC MATERIAL AND NUTRIENTS SUPPORTING THE PELAGIC FOOD WEB
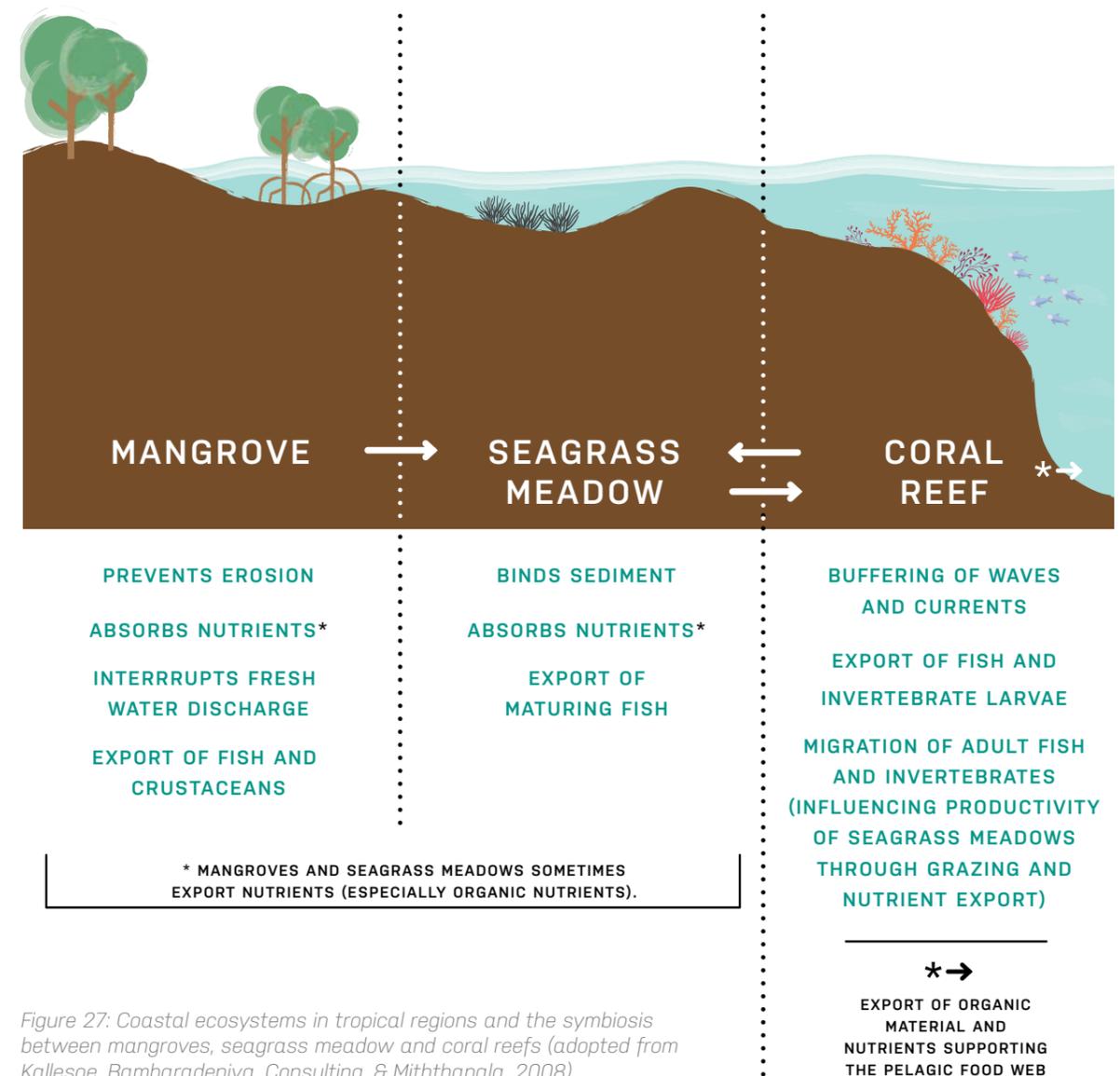
Figure 27: Coastal ecosystems in tropical regions and the symbiosis between mangroves, seagrass meadow and coral reefs (adopted from Kallesoe, Bambaradeniya, Consulting, & Miththapala, 2008).

X APPENDIX 3: COASTAL TYPOLOGIES

Classification of coastal typologies is typically done using biophysical parameters, such as hydrological conditions (tide, wave or river dominated coasts), sediment composition (mud, sand, gravel shingle or rock and cliff coasts), and/or geomorphological features (delta coasts, dune coasts, cliff coasts etc.). Although classification schemes may appear independent, these characteristics are tightly interlinked. Each component influences the other and their interaction results in the formation of distinct coastal systems (Figure 28).
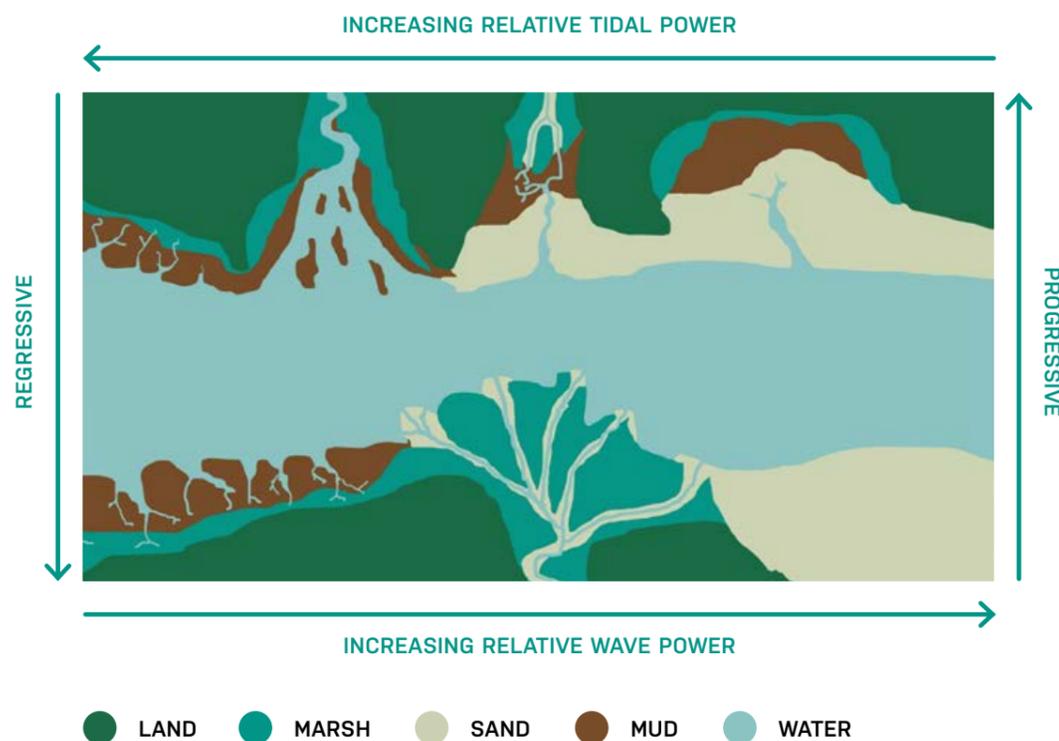
Figure 28: The relation between soft coastal ecosystems and the relative dominance of tidal power versus wave power; and the distinction between accreting and eroding coasts (Boyd, Dalrymple, & Zaitlin, 1992; after Heward, 1981 and SEPM, 2015).

For example, hydrodynamics largely influences sediment composition, as low-energy conditions are often characterised by fine silty material that deposits easily, resulting in the development of muddy coastlines. Energetic hydrodynamic conditions, such as high wave impacts and strong current velocities, generally result in development of sand and gravel beds or even strip a coastline right back to its foundation of solid rock.

Hence, hydrodynamic forces are generally a good indicator for distinguishing between broad coastal typologies (Figure 28). Therefore, we elaborate on these typologies in the context of their dominant hydrodynamic forcing: tide dominated coasts, wave dominated coasts and mixed energy coasts. In this system characterisation, the focus is on soft sandy and muddy coastlines, and on more specific factors and processes that determine development of these coastlines.
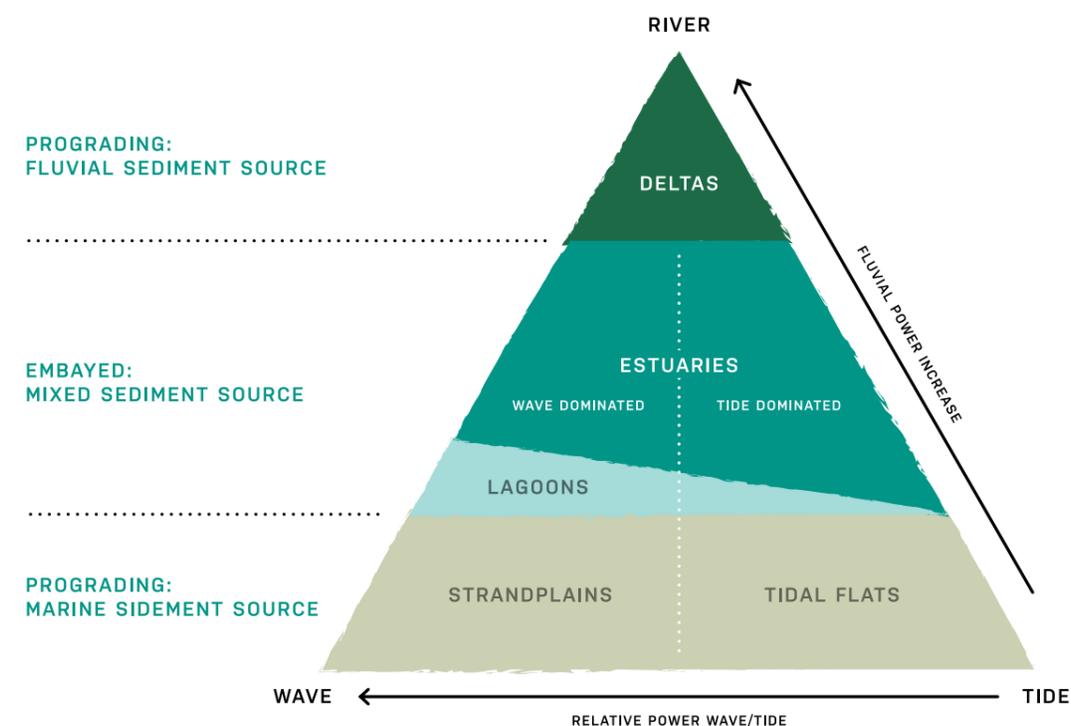
Figure 29: Coastal depositional environments are governed by wave, tide and fluvial power (Adopted from Boyd et al., 1992).

X3.1 TIDE DOMINATED COASTS

Tide-dominated coastlines are characterised by a relatively large tidal range (distance between mean low water and mean high water) relative to the height of incoming sea and swell waves with a marine sediment source (Boyd et al., 1992; Carter, 1988; Davis & Hayes, 1984). Bays are tide dominated typologies, characteristic for 'open' coasts without barriers. They are often relatively shallow and, as a result, wave dissipation is high, and most wave energy is lost before shore-breaking. These coastal bays show gradual land-water transitions and have intertidal areas characterised by mud substrates. Landward fringes of wetlands are formed in the transition zone between sea and land. Although there is no large river discharge, small terrestrial streams may flow into the bay. The substrates of tidal bays are biologically productive areas (Carter, 1988).

Another feature of tide-dominated coasts are tidal flats, with the development of extensive tidal flats being favoured by macrotidal conditions, but some flats also occurring in mesotidal or microtidal coasts (Daidu, 2013). In this document we define tidal flats as the intertidal zone that comprises bare mudflats or sandflats (long inundation time) and vegetated intertidal flats (shorter inundation time) that are directly open to the sea. Tidal flats often flank chenier plains, which are stabilised wave-built ridges of coarse sediment deposited above the level of high tide and separated from the shoreline by a marshy area comprised of fine-grained sediment (Harris & Heap, 2003; Otvos, 2005). Because tides can penetrate lagoons, estuaries and deltas, tidal flats can be developed in numerous environments. These tidal flats play a vital role in shoreline environments as they create intertidal habitats that are important foraging grounds for birds. However, they also attenuate or break waves and reduce fetch and wind driven wave set-up.

X3.2 WAVE DOMINATED COASTS
Wave-dominated coasts with marine sediment supply are characterised by linear coastlines with strand plains and often with well-developed beach ridges (Nyberg & Howell, 2016). Strand plains typically consist of three zones: shoreface, beach and dunes (Masselink et al., 2011; McLachland & Brown, 2006). The shoreface is the permanently submerged zone that is highly dynamic due to constant wave impact. Adjacent to the shoreface, the beach emerges at mean tidal level. A beach is a deposit of sand found along the shoreline and placed there by waves (Masselink et al., 2011). The beach is defined as the shore profile that extends from the spring low tide level to the maximum spring high tide level. This high tide level is mostly defined by a change in topography, such as a cliff or a dune, or where permanent vegetation is established (Masselink et al., 2011). Shoreline position can change over time. For example, tidal processes induce changes in water levels and these affect wave height, which causes the shoreline to shift across the intertidal zone (Masselink et al., 2011; McLachland & Brown, 2006). Depending on the wave conditions, different beach configurations may arise. Further away from the coastline, beyond the reach of waves, wind is the driving force of sand transport. Above the supratidal zone, pioneer plant species can grow. Vegetation decreases the wind velocity and facilitates sediment deposition, which results in the formation of embryonic dunes (Masselink et al., 2011; McLachland & Brown, 2006). With this increase in elevation, changing microclimate offers opportunities for other species. That is why dune plant communities change from pioneer species at the coast to forests on the mature dunes inland. Sand dunes act as a buffer to extreme waves and winds, and play a key role in coastal flood defence (Carter, 1988).

Lagoons and coastal barriers are found on mainly wave-dominated, accreting coasts enclosed by barriers, such as sand banks, barrier islands or coral reefs (Nyberg & Howell, 2016). They have shallow and relatively calm waters that are commonly elongated and orientated parallel to the coastline (Dürr et al., 2011). Generally, river input is negligible and the water of lagoons has a degree of salinity (Boyd et al., 1992). Lagoons are formed by flooding of beach ridges or by partial closure of a coastal embayment by a coastal barrier (Harris & Heap, 2003). Coastal barriers are elongated coastal ridges of sedimentary deposits which are situated above high tide level and built-up by wave action (Bird, 2005). There is a gradation of barrier morphology between fine and coarse sediments, also determined by wave impact (Carter, 1988). Therefore, barriers can be composed of sand along more wave exposed coasts and of more silty sediment along coasts with milder wave conditions. Barrier islands are a form of coastal barriers and, similarly, can be transgressive, regressive or stable, depending on sedimentation rates, sea level change and subsidence (Heward, 1981). Barriers and ridges formed in coastal environments are often essential elements of the landscape, as they often support the formation of ecosystems that need more sheltered conditions, such as marshes and mangroves. Due to the lack of any significant river input, the sediment of lagoons has marine origin (Boyd et al., 1992). The complete enclosure of the embayment by the barrier or bar may result in the formation of a (often brackish) lake (Harris & Heap, 2003).

III.3) MIXED ENERGY COASTS
Although they are distinct systems, both deltas and estuaries are formed when rivers flow into the sea or ocean along soft sediment coasts. Deltas are formed when river discharge dominates over marine hydrodynamic forces. Additionally, deltas are excellent examples of how both tide and waves shape this morphology. The relative forces of tide, waves and fluvial sediment input characterises the delta's configuration (Figure 29). Generally, deltas are defined as coastal landforms made of sediments transported by rivers that have formed a platform of deposited sediments at the mouth of the river (Penland & Kulp, 2005). As deltas are characterised by an accumulation of sediment from the river, their coast is progressive (Carter, 1988). River discharge not only affects sediment supply, but also temperature, salinity and nutrient distribution in the coastal environment (Lane et al., 2007). Nutrient transport from the hinterland to the coast via river discharge makes deltas nutrient rich and productive systems. Even though deltas are progressive, and land is being gained, this land should only be claimed for human purposes with sufficient caution. Delta areas are prone to regular flooding both by rivers and the sea, putting at risk housing, infrastructure, agriculture and aquaculture.
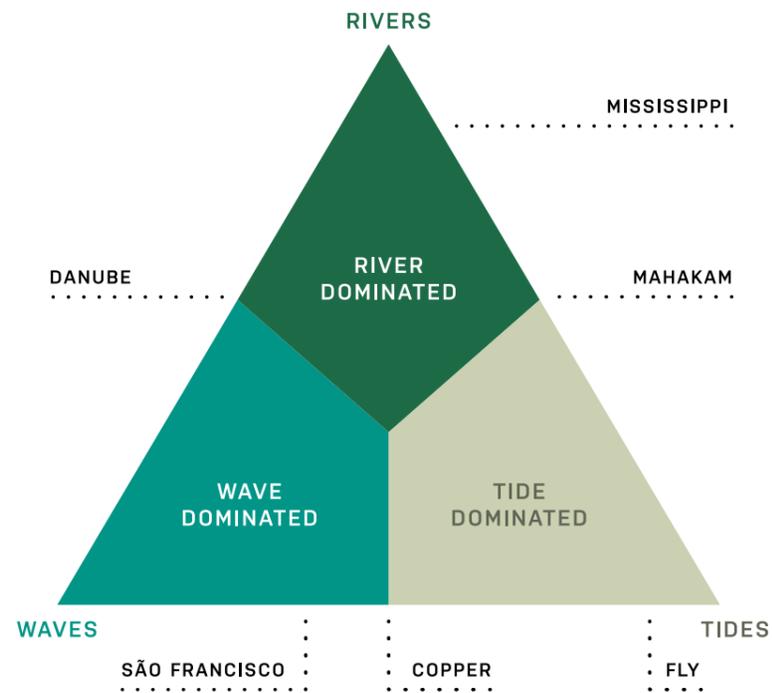
Figure 31: The occurrence of coastal depositional environments depends on the relative strength of wave, tide and river forces (Seybold et al., 2007).

Estuaries are situated in areas that experience influence from both river and sea (Boyd et al., 1992). They are characterised by a salinity gradient and by sediment supply both from riverine and marine sources. Estuaries are semi-enclosed water bodies which are connected to the sea, within which seawater is diluted by freshwater by freshwater discharge (Cameron & Pritchard, 1963). Estuaries are originally non-marine basins that have been invaded by the sea, often in the form of marine flooding due to post-glacial sea level rise (Carter, 1988). The interaction of currents, waves and river discharge creates a variety of intertidal habitats, such as mudflats, salt marshes, fresh water wetlands and barrier islands. Estuaries act as buffer zones between river and ocean environments, receiving an inflow of both fresh water and salt water due to tidal waves resulting in a salinity gradient (Wolanski, 2007). In contrary to delta systems, in estuarine systems the sediment is driven landwards due to tidal and wave energy and results in infilling of river valleys (Doody, 2001). The inner and outer zones of an estuary, with significant river or marine influences respectively, are most energetic and are thus zones of sediment transport (Masselink et al., 2011). Like deltas, estuaries also act as a nutrient sink and have high natural and commercial value as habitat for many species (Carter, 1988).

X APPENDIX 4: COASTAL ECOSYSTEMS AND THEIR ROLE IN REDUCING HAZARDS

ECOSYSTEM	ROLE IN HAZARD REDUCTION	REFERENCES
Beaches & dunes	Block waves	(Mascarenhas & Jayakumar, 2008)
Coral reefs	Wave breaking and attenuation, tidal current speed reduction	(Costa et al., 2016; Ferrario et al., 2014; Harborne et al., 2006)
Mangroves	Wave attenuation, sediment deposition, erosion reduction	(Barbier, 2016; Gedan et al., 2011; Mazda et al., 1997; Mcivor et al., 2012)
Salt marshes	Wave attenuation, sediment deposition, erosion reduction	(Foster-Martinez et al., 2018; I. Möller, 2006; I. Möller & Spencer, 2002; Iris Möller et al., 2014)
Shellfish reefs	Wave breaking and attenuation	(Borsje et al., 2011; Shah et al., 2019)
Sea grass	Wave attenuation, sediment deposition	(Christianen et al., 2013; Fonseca & Cahalan, 1992; Luhar et al., 2017)

Table 5: Coastal ecosystems and their role in reducing hazards

X LIST OF FIGURES AND TABLES

LIST OF FIGURES

LIST OF TABLES

X APPENDIX REFERENCES

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SYSTEMS
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