Systematic investigation of the coral-inclusive potential of marine infrastructure

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by

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Preface

Over the last year, I have thoroughly enjoyed working on my MSc graduation project. I am proud and pleased to present my research by means of this thesis and I would like to express my gratitude to the people who have supported and inspired me during this graduation project. Furthermore, this research is the result of a collaboration between the TU Delft and Van Oord. The work has been carried out at the Environmental Engineering department of Van Oord in Rotterdam and in Sint Eustatius, where I spent more than four months.

First, I want to thank my graduation committee members, starting with Mark van Koningsveld. Mark, thank you for giving me the opportunity to work on this subject and assisting me with obtaining the right knowledge to jump in the gap between engineers and ecologists. You always surprised me with useful feedback and thanks to you I have gained a lot of knowledge in the field of nature-inclusiveness and the concretization of the discussion between different stakeholders in this area. This has opened up an area for me in which I would like to work in the future. Secondly, I want to thank Remment ter Hofstede for the excellent coaching on a weekly basis. During the graduation period and also during my stay in St. Eustatius, I benefited from your extensive knowledge in the field of ecology. You taught me a lot through your open communication with well-founded criticism including positive points. Michel Ruijter, with your infectious enthusiasm for measurement and data and by showing me the perspective of a civil engineer, you helped me to approach this research objectively. In addition, you gave me the opportunity to partially carry out this research in St. Eustatius, so that I learned a lot about coral and civil processes and was able to execute the necessary jobs together with Mike, such as installing measuring equipment to a depth of 8 meters without diving equipment. Mark Voorendt, I am grateful for the personal guidance and the very useful feedback on, among other things, the structure of my report. Your personal advice and conversations, also about other matters, enabled me to continue working on my thesis with great enthusiasm. And last but definitely not least, Martin Kershaw, thank you for your energy, enthusiasm and conviviality that you brought to our (weekly) meetings and for arranging all peripheral matters within Van Oord. You have helped me tremendously with this.

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Enjoy reading,

J.C. (Joost) van Arkel
Rotterdam, March 2022

Abstract

Ecosystems are under pressure worldwide, due to both natural and anthropogenic stresses. Stresses on ecosystems can cause a decline in biodiversity, a loss of habitat and a deterioration in ecosystem services. To avoid further pressure on ecosystems caused by advancing economic development, new infrastructure projects should be integrated into the ecosystem. Environmental Impact Assessments (EIAs) are now mandatory for projects that are likely to have significant environmental effects. EIAs have primarily focused on mitigating negative impacts. However, recently new design philosophies have emerged such as ‘Engineering with Nature’, ‘Working with Nature’ and ‘Building with Nature’ which also focus on promoting positive impacts.

Constructively realizing nature-inclusive projects is complicated due to involving stakeholders with differing perspectives. Therefore, in an integrated approach towards new marine infrastructure development, the next step is to promote constructive collaboration between stakeholders to systematically investigate the nature-inclusive potential of infrastructure. This thesis describes a proposed strategy for doing so, within the context of nearshore infrastructure development located in or nearby coral ecosystems. The focus is on how nature-inclusive potential of new marine infrastructure might be maximised, taking into account the local ecosystem.

The aim of this research is to find an optimal approach to develop coral-inclusive infrastructure. This is done by structuring the required discussions between stakeholders considering socio-economic, ecological and engineering perspectives regarding the nature-inclusive design potential of new marine infrastructure. For this purpose, a method was developed that proposes a step-by-step strategy to promote constructive collaboration between relevant stakeholders, consisting of the following five steps:

1. project description, outlining the basic challenge at hand
2. project location analysis, involving a systematic assessment of the relevant ’natural system’ as well as the ’anthropogenic system’
3. Development of marine infrastructure design applications, involving an inventory of project elements that can have negative or positive effects on the overall ecosystem
4. inventory and ranking of potential measures, objectively outlining feasibility and potential effectiveness of measures and design modifications
5. summary of sustainable design recommendations, leading to a systematic ranking of potential measures proposed to support further decision making.

We have investigated the effectiveness of the systematic method, by applying it to a case study in Sint Eustatius that investigates whether the intended extension of a breakwater in Sint Eustatius can be designed as a coral-inclusive project. Sint Eustatius was chosen because Rijkswaterstaat offered research opportunities on location. In an ideal case, the use of long-term consistent data maps the natural factors over a longer period of time. This provides greater certainty of results and recommended actions. However, the values that were reported for the Sint Eustatius case were not derived from long term systematic data collection. Furthermore, the substrate from the existing breakwater looks to be promising for coral recruitment. However, there is not a lot of coral development evident on the existing breakwater. Possible negative factors hindering coral development on the existing breakwater are: 1) poor water quality; 2) high hydrodynamic circumstances with high wave action in shallow waters which limits the type of coral species; 3) inconsistent larval supply through ocean currents.

Coral reef connectivity seems sufficient and potential substrate is already present in the existing breakwater. Extension of the breakwater will lead to substrate increase which could improve the chance for coral recruitment in a hurricane-risk area as Sint Eustatius. A valid next step that could be proposed to aid a better understanding of this habitat is to invest in an extensive and dedicated data gathering

campaign.

In conclusion, the main improvements derived from the application of the systematic approach for nature-inclusive potential for infrastructure projects are:

- providing an overview of the steps required to create coral-inclusive infrastructure,
- instigating the investigation of the status or the possibilities for coral development,
- assisting ecologists and engineers to structure the discussion on coral-inclusiveness,
- lowering the barrier to use (new) design philosophies,
- and stimulating coral development and decreasing negative effects by providing design recommendations.

Bringing stakeholders with different perspectives together in one nature-inclusive project plan remains challenging. Environmental data can play a role in arriving at a realistic approach supported by ecologists and civil engineers to realize nature-inclusivity for infrastructure. This requires knowledge, money and time and could provide insight into the threats and opportunities. The systematic approach, derived in this thesis, has been proven to support stakeholders in assessing the nature-inclusive potential of marine infrastructure.

Contents

1 Introduction

1.1. Motivation for this research

1.1.1. Infrastructure in marine environments

Marine infrastructure can be found in many places around the world. Examples of marine infrastructure developments are harbours, breakwaters, beaches and shipping channels. This infrastructure can negatively impact the natural and socio-economic environment by putting even more pressure on habitats (Brown et al., 1990; Vermeij, 2017; Dunning, 2021). With increasing economic development, more attention was paid to sustainable development in the 1970s (e.g. the limits to growth (Meadows et al., 1972)). To more explicitly weigh the cost of a new development (in terms of natural- and socio-economic hindrance and damage) against the economic benefits, environmental impact assessments (EIAs) became mandatory near world-wide from the 1970's onward (Munn, 1979; Morris and Therivel, 2001 Glasson and Therivel, 2013; Laboyrie et al., 2018). Unfortunately, EIAs frequently focus more on minimizing negative effects and less on maximizing positive effects. As a result, reduced or small negative impacts for each project can potentially lead to general habitat destruction and biodiversity loss (Laurance, 2010). Therefore, at the beginning of this century, increasing attention was generated for more nature-inclusive solutions (working with nature, engineering with nature, building with nature). The aim of these design philosophies is on designing infrastructure without net loss or, ideally, to create added value for the natural and social environment. However, more tools are needed to actually extract that potential and put sustainability into practice in order to create nature-inclusive infrastructure that can be implemented by various stakeholders.

This thesis builds on nature-inclusive development and suggests a method for systematically exploring the nature-inclusive potential of new infrastructure. The knowledge gap is substantiated by means of literature in Section 1.2.3. Ultimately, the focus of designing new infrastructure should be both on minimizing negative impacts as well as on maximizing the positive effects.

1.1.2. Coral ecosystems

Different types of animals, plants, microbes and other sea creatures are included in this marine world. Functioning as one of the most diverse of all ecosystems, coral reefs (i.e., reefs) are relevant for nature and humanity by providing coral values; a safe habitat, ecosystem services and including rich biodiversity (Huston, 1985; Spalding et al., 2001; Hughes et al., 2017). As coral reefs are frequently threatened, a shift in focus towards increasing ecosystem values could be helpful (Hughes et al., 2003). Marine life experience stresses from environmental and human impacts, which could result in affecting corals (Poloczanska et al., 2013). Different stresses arise and are categorised in global, regional and local trends.

<u>Global trends</u>: The world is facing a threat from climate change, due to human interference, resulting in altered atmospheric balance (Poloczanska et al., 2013; Karl and Trenberth, 2003). Energy usage can play an important role in this field. Modifications in land use and urbanization tend to cause increased

climate change effects (Karl & Trenberth, 2003). Some marine environmental effects are rising temperatures, ocean acidification, increased ocean volume and decreased salinity values (Poloczanska et al., 2013; Karl and Trenberth, 2003; Houghton et al., 1990). The rising of ocean and sea temperatures, frequently results in exceeding coral and zooxanthellae thermal tolerance values (Hoegh-Guldberg, 1999). This can potentially lead to zooxanthellae perishing and subsequently could result in coral bleaching and therefore coral loss (Hoegh-Guldberg, 1999).

Ocean acidification is another factor that possibly threats coral reefs. The carbon dioxide increase can lead to decreasing oceanic pH values. Lowered pH values are often associated with less carbonate accretion and calcification (Hoegh-Guldberg et al., 2007). Since calcium carbonate is the building block for coral reefs and carbonate values decrease, coral development tends to decline.

Increasing oceanic volumes can belong to the consequence of ice melting events. More melt water is often observed as a consequence of rising temperatures (Hoegh-Guldberg & Bruno, 2010). During favourable circumstances with much sunlight intrusion and clear water, average coral growth can be around 1 cm/year (Meesters et al., 2019). Even though corals are quite resilient, coral growth should keep up with sea level rise. When sea level rises faster than the coral growth rate, coral cannot keep up and will probably 'drown'. Factors such as increased sea temperatures, spread of diseases, hurricanes or food chain interventions can result in less coral resilience and therefore lower coral development (Meesters et al., 2019).

Decreased salinity values, can be the result of increased fresh water flow into oceanic systems due to increased melt water (Hoegh-Guldberg & Bruno, 2010). Preferably, coral cells need constant salinity levels to survive. A change in salinity, could lead to inter cellular balance disturbance and hence to metabolism difficulties (Coles & Jokiel, 2018).

Regional trends: Pollution from land-based activities is one of the anthropogenic stress effects that might impact coral habitats. Nutrient loading, sedimentation, rubbish and toxic components can be consequences of human activities based on land that end up in coastal waters. This possibly affects coral regions. In addition, the impact on corals tend to increase simultaneously with local population growth (Meesters et al., 2019). For the region of the SSS-islands of the Dutch Caribbean (Saba, Sint. Eustatius and Sint Maarten), the inhabitants are becoming more dependent on import of food and materials (Cado van der Lely et al., 2014). This could result in waste processing related issues and in potential nutrient and organic materials increase in coastal regions (Meesters et al., 2019). Eutrophication - the addition of nutrients to a marine environment - can cause explosive algal growth. Under 'optimal' circumstances for coral ecosystems, algae live in symbiosis with coral reefs. Eutrophication can possibly disturb this process and algae could subsequently overgrow coral ecosystems. Increased algal growth could hinder larval recruitment by threatening settlement, growth and survival of larvae, inducing coral starvation (Box and Mumby, 2007; Dixson et al., 2014).

Regional erosion could be another issue. Sediment flow can cover coral reefs and possibly counteract the development of corals by blocking sunlight (Meesters et al., 2019). Pollution such as rubbish and toxic components could end up in regional waters due to human activities. Adding toxic components can increase the probability to intoxication of coral ecosystems, potentially causing coral decline. (Johannes, 1975)

Natural stress sources like diseases and pests, could also originate from human activities. For example, in the Caribbean region the Stony Coral Tissue Loss Disease (SCTLD) is becoming an increasing problem for coral reef health (LNV & IenW, 2020). The release of ballast water has been connected to the spread of these infections, resulting in possible coral degradation (Dahlgren et al., 2021). Other pathogens could also lead to coral degradation or mortality in the region (Kitson-Walters, 2017; ; Sharma and Ravindran, 2020).

Another local stressor could be the impact of overfishing. The coral food cycle can be interrupted by overfishing of tertiary consumers. The lower-ranked consumers will likely not have natural enemies and therefore, they can outrank other ranks. This can possibly lead to less grazers (herbivores) that consume algae. Resulting in possible algal overgrowth and coral mortality in the region (Dasgupta, 2021).

Local trends: Local trends generally have an overlap with regional trends but because of their potential local impact, a distinction is made. Firstly, infrastructure development belongs to possible local coral stressors. This will be covered in more detail in the subsection below. Harbour development, breakwaters and dredging works are examples of infrastructure projects. Another local trend could be the increase of coral mining activities to obtain raw materials, also called coral harvesting. Examples are materials used for aquariums, jewellery, building materials or medicines. Mining these materials, can lead to the destruction of local coral reefs (Dulvy et al., 1995). According to Kuyper (1991) 'stresses' in light availability, wave actions, tidal range and hydrodynamic patterns may also lead to local coral impacts.

1.1.3. Infrastructure in coral ecosystems

Economic pressures may give rise to a continued desire to further develop marine and coastal infrastructure. Ports can feel a need to expand, to ensure their competitive position in the global, regional and local trade networks (Valadez-Rocha & Ortiz-Lozano, 2013). Additionally, the protection of coastal regions against rising water levels (due to climate change) becomes increasingly important. There are many viable management strategies to protect coastal regions against rising water levels as the 'holding the line' strategy and the 'managed realignment' strategy (R. K. Turner et al., 2007; Dafforn et al., 2015). However, many coastal protection strategies and other marine infrastructure implementations are likely to leave a 'footprint' on marine habitat such as coral reefs (Dunning, 2021). However, near-coast marine infrastructure might also provide opportunities for enhancing coral value.

1.2. Problem analysis

1.2.1. Infrastructure development

As explained in Section 1.1.3, infrastructure development is frequently associated with economic development and coastal protection. Unfortunately, natural ecosystems are frequently under pressure where ecosystem degradation can be one of the consequences of infrastructure development. Since coral ecosystems could be beneficial for natural and social environment (described in Figure 2.3.6), (coral) ecosystem degradation can influence natural and social values (Dasgupta, 2021; Cesar, 2000; Wilkinson, 2000). However, economic development means that construction of marine infrastructure generally continues. Avoiding tailoring designs in a nature-inclusive way to local conditions, will potentially degrade coral ecosystems even further. Elements (explained in Section B.1.1 and Section 4.2.1) such as the placement area and increased turbidity values, could influence corals negatively. Therefore, a way to work which will lead to a nature-inclusive method is important. Other possible causes of coral reef degeneration are explained below.

1.2.2. Causes of coral reef degeneration

Coral tends to degenerate globally and different factors contribute to this deterioration. Think of anthropogenic stress and environmental factors (Wilkinson, 2000). Hughes et al. (2003) relates the exponential growth in the volume of human influences on coral reefs to increased global population and increased transport capability. Important factors that can cause coral deterioration are (Naughton and Jokiel, 2001; Lindeboom, 2017; Wilkinson, 2000):

- Pollution
- Coral mining
- Global warming (bleaching and coral death)
- Eutrophication - (excessive enrichment of water with nutrients/minerals)
- Erosion
- Overfishing (starfish invasion)
- Dredging
- Ship grounding (anchoring)

- Impact of marine structures
- Direct tourism activities
- Coral diseases

The temperature of the ocean surface tends to rise as a result of global warming (Masson-Delmotte et al., 2018). Larger temperature differences between land and water can cause steeper temperature gradients, resulting in stronger flow patterns and in risks due to unstable weather circumstances. Wind and precipitation intensities are expected to rise as a result of the increased instability and available energy. As a result, storms and hurricanes look likely to become more intense (Hardy, 2003; Houghton, 2005; Michener et al., 1997). The intensified occurrence of hurricanes could lead to coral destruction (Wilkinson and Souter, 2008; C. S. Rogers et al., 1991; Gardner et al., 2005) but also to increased dredging activities to keep harbours navigable for vessels. This again could have its impact on coral reefs. In this way, many of above-mentioned deterioration factors are related.

Case examples
Two examples of infrastructure implementation in coral ecosystems are set out below to illustrate the magnitude of the damage that can be inflicted to coral reef systems. The first example is that of the Cayman Islands.

The Caymanian government wants to expand the port to construct a cruise berthing facility (Dunning, 2021). This would indicate the building of two piers, land reclamation and dredging activities. The cruise ship industry for the Cayman Islands is responsible for 22% (Dunning, 2021) of the total tourism revenue. The impact of the port expansion on nearby coral reefs is estimated to damage around the 60.000 m^2 of local coral reef habitat (Dunning, 2021).

Another infrastructure example is the construction of a new pier in Curaçao. On the original location before the pier construction, coral coverage of approx 30% was relatively high compared to the rest of the island. The pier was built to stimulate the cruise tourism in Curaçao and was completed in 2017 (Bam international, 2017). The activities associated with the construction of this pier caused severe coral damage. Within the surveyed area, consisting of 90 sites with 4 quadrats (2.0 x 1.2 m), 33.2% of all surveyed coral colonies were damaged in some way (dislodged, fragmented, scarred, etc.) (Vermeij, 2017). A few years later, the reefs condition is even more declined due to observed bleaching. However, since volunteers stabilised dislodged coral colonies after the construction phase, some of the corals survived. Other colonies which escaped from these impacts are still in good health according to Vermeij (2017).

The Cayman and Curaçao cases are examples in a world where protection against rising water levels and the expansion and modernisation of harbours keep continuing in favour of the regional economics. A method that assists in systematically exploring nature-inclusive potential for new infrastructure, could possibly provide the necessary support to decrease negative effects and improve positive effects for the marine environment.

1.2.3. Knowledge gap

The implementation of maritime projects in or near marine ecosystems is an area where additional research is needed. The focus of EIAs tends to be on negative impacts of marine infrastructure on corals (Foster et al., 2010; Vermeij, 2017). Building with Nature (BwN), Engineering with Nature (EwN) and Working with Nature (WwN) are a few of the different strategies that are emerging to better cope with fitting infrastructure in environments, considering the ecosystem values by promoting the positives of yet to be built infrastructure (Bouw and van Eekelen, 2020; Cooper and McKenna, 2008). However, it is not easy for ecologists and engineers to integrate these design philosophies into new infrastructure development. Environmental parties are most likely concerned with nature conservation (Pickett et al., 1992), whereas engineers are more focused on the 'functional' requirements of a construction (e.g. strength) (Malan, Bredemeyer et al., 2001). This demonstrates the different perspectives between engineers and ecologists. Some management approaches to enhance coral development, focus on small scale projects or on coral enhancement solely (Edwards and Gomez, 2010; M. Y. Hein et al., 2020), while marine infrastructure could function as potential sources for coral development. Information about artificial reefs is available and could be used. However, artificial reefs do mostly not include all functional aspects that also other marine infrastructure have to offer. In addition, planned artificial reefs have frequently failed across the world owing to poor site selection, insufficient planning, a lack of monitoring, or a lack of effective management (Baine, 2001; Erftemeijer et al., 2003). Therefore, project stakeholders (e.g. ecologists and engineers) need an approach to assist in creating coral-inclusive structures.

Starting point
This research is being approached from a civil engineering perspective, considering other stakeholder perspectives as the ecological point of view. The starting point is at the project development phase. This is between the initiation phase and the tender phase. See Figure 1.1. At this stage, initial project plans are ready, and the focus is on designing the project. Therefore, 'conservative' project development could be transitioned into sustainable project development. Therefore, the question is not *if* a project is going to be executed, but is on **how** the nature-inclusive potential of marine infrastructure might be maximised.

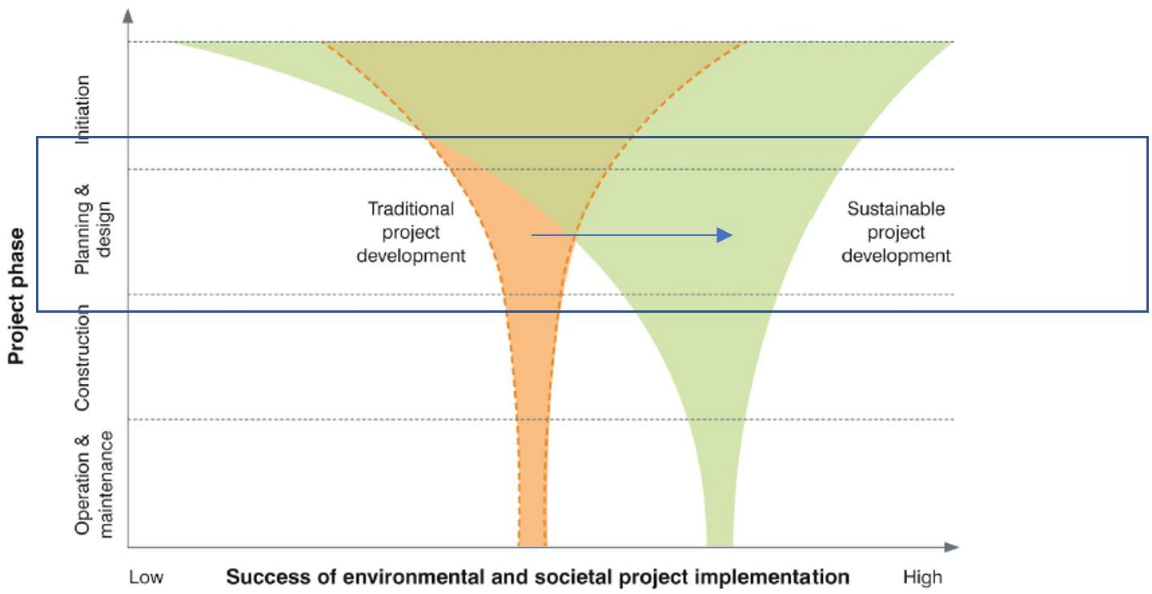

Figure 1.1: Project implementation (Laboyrie et al., 2018)

1.2.4. Research objective
The main objective of this research is to find an optimal approach to develop nature-inclusive potential for new marine infrastructure, to optimally support the local coral ecosystem. The overlap of ecological and technological knowledge, should be considered at all times during the approach. The aim is to hereby transform a traditional project design into a more sustainable project design with a focus on coral habitats.

1.2.5. Scope
Firstly, the scope is on coral ecosystems since coral performs important functions for human and marine life as or will be discussed in section 1.1.2 and 2.3. Corals frequently experience stresses, therefore solutions for the enhancement of coral ecosystems are required. Secondly, frequently observed conflicts between marine infra projects and coral ecosystems are within coastal regions, since the majority of marine projects take place here (Vermeij, 2017; Dunning, 2021; Nelson et al., 2016; Valadez-Rocha and Ortiz-Lozano, 2013; Maragos, 1993). For this reason, the focus of this research is on nearshore marine infrastructure. Other places further offshore still have the potential of coral development due to marine infrastructure implementation but they are not being studied as implementation objectives during this study (Tillinghast et al., 1987; Hovland et al., 2002). Furthermore, the focus is tightened to

the functional life and not to the construction phase of marine infrastructure. The construction phase is focused on mitigation, while focusing on the functional life creates possibilities towards potential coral development (see Chapter 4).

1.3. Research questions

The main research question is:

How can marine infrastructure projects be assessed and developed, considering the value of the local coral ecosystem ?

This research question will be answered by the following related sub-questions:

- Which criteria can be identified that determine the value of coral reef ecosystems that face infrastructure development?
  - Which criteria define the value of a local coral ecosystem?
  - How can coral ecosystems be influenced?
  - How can the value of a local coral ecosystem be quantified?
- What type of marine infrastructure projects can affect coral ecosystems?
  - What are the project elements that affect the coral environment?
  - What can be the effects of infrastructure projects on coral habitat?
  - Which measures can be taken to reduce impact on coral ecosystem values and how can these be tailored to local conditions?
  - Which measures can be taken to increase coral ecosystem values and how can these be tailored to local conditions?
- What is a systematic method to assess the potential coral-inclusivity of infrastructure projects and to select recommendations resulting in highest value of a local coral reef ecosystem?
  - What combination of elements and measures result in the most effective strategy, considering the environment and cost-benefit?
  - Which method can be used to quantitatively select the infrastructure project approach with the highest coral ecosystem value?
- How can this method be applied in practice?
  - Which case study and why?
  - What would be the preferred design recommendations considering a coral ecosystem, following a selection method?
- How can this method be globally implemented?
  - What are the flaws and points for discussion for global implementation?

1.4. Methodology

1.4.1. Introduction

The type of method concerns a design methodology, since new knowledge about methods or deepening of existing understanding of coral enhancement is needed (Wasmus et al., n.d.). A design methodology is proposed, to include knowledge, implement methods and design an overview to integrate civil works in coral ecosystems.

Which methodological steps are needed to achieve the goals is explained below. The 'Engineering Design cycle' is an example of an iterative engineering design approach and is used as information source for the approach of the methodological steps below (Molenaar & Voorendt, 2020). An iterative process is needed, since every situation is unique and commonly several optimal technical solutions exist. This makes the design process a 'self-developing and learning system' by reconsidering earlier made assumptions and decisions (Molenaar & Voorendt, 2020).

1.4.2. Methodological steps

1. **What is a systematic method to assess the potential coral-inclusivity of infrastructure projects and to select recommendations resulting in highest value of a local coral reef ecosystem?**
   Interviews, literature and own knowledge are used to systematise findings into a general method. In this way, a comprehensive plan of approach is generated. During this step, an iterative approach towards steps 2 and 3 is necessary because coral and infrastructural factors should be taken into account and are discussed extensively in these two steps. Methodological step 1 is executed through the assistance of professors, ecologists, civil engineers, marine biologists and other persons concerned. These persons provide multi-aspects and perspectives due to their difference in backgrounds. In addition, they verify obtained knowledge, explained in steps 2 and 3.

2. **Which criteria can be identified that determine the value of coral reef ecosystems that face infrastructure development?**
   Deriving of coral ecosystems, this consists of literature research and interviews. In addition, results of abiotic and biotic parameters in this step have to be obtained by two actors: literature and/or measurements. Data should function as the baseline for this research, while literature functions as a secondary check.
   This part includes elaboration on different coral reef system types. What is the value of coral and how are the values influenced? At the end, this should result in the quantification of these values.

3. **What type of marine infrastructure projects can affect coral ecosystems?**
   (a) Analysing and selecting different infrastructure projects and their elements is done by literature review, interviews and own observations. Both the usage function and the life cycle are components of the expectations of a civil construction and will be discussed accordingly.
   (b) The impact that infrastructure projects have on coral environments is being studied in this part. The step from system definition towards infrastructure projects is made. The focus is on a general type of infrastructure projects and what elements interact with the coral environment.
   (c) The consequence of implementing measures is taken into account and the recommendations (for human interventions) to reduce impact and promote positive effects is described. The choice is based on the type of system and impact case. Per system and impact case, different recommendations will be applicable for coral enhancement.

4. **How can this method be applied in practice?**
   The application of the systematic method is done using a case study. This application step evaluates the functioning of the systematic method. The case study needs to have a construction purpose in an area where coral development could eventually be possible. The case study should be based on a project that aims to build marine infrastructure in a location where coral development is desired. Coral should be found in the vicinity of the project site. Otherwise, coral formation

will be unlikely. Following the systematic method from methodological step 1, assists in following the approach for the practice application to design a coral-inclusive marine infrastructure. The methods guides the user through necessary steps. Information can be gathered by observations of coral development and how this came about is checked and verified through literature. Furthermore, interviews and gathering of data are providing the information needed.

5. **How can this method be globally implemented?**
   The application of systematic method is analysed through own knowledge, interviews and literature. A verification with people who are working in the field of infrastructure/ecology is involved to assess the method for global implementation. Furthermore, other areas with different marine constructions will be assessed to check whether the method suffices worldwide.

1.5. Reading Guide

The Report body consists of the following chapters and sections:

2. Background information to introduce the systematic method - Methodological step 1
    - nature-inclusive methods
    - Coral as a focus species
    - Components of marine infrastructure projects
    - Development of the systematic method
3. Approach for coral to use in the systematic method - Methodological step 2
    - Coral reefs systems approach
    - Natural system overview of coral reefs
    - Anthropogenic system approach of coral reefs
    - Quantification of coral ecosystems
4. Approach for marine infrastructure to use in the systematic method - Methodological step 3
    - Elements of marine infrastructure
    - Potential effects of marine infrastructure on corals
    - Potential measures for coral-inclusive marine infrastructure
5. Application of systematic method (case study) - Methodological step 4
    - Step 1 - Project description
    - Step 2 - Location analysis
    - Step 3 - Development of marine infrastructure design applications
    - Step 4 - Inventory and ranking of potential measures
    - Step 5 - Summary of sustainable design recommendations
6. Discussion about applicability - Methodological step 5
7. Conclusions and recommendations

2

Background information to introduce the systematic method

This chapter describes methodological step 1, whereby a systematic method is developed to assess the potential nature-inclusivity of marine infrastructure and to select recommendations resulting in highest value of a local coral reef ecosystem. This chapter takes applicable methods through selection criteria, resulting in new sustainable design recommendations.

The aim of this chapter is to convey the approach to coral-inclusive infrastructure by providing coral principles, infrastructure information and the systematic method. This is relevant because the systematic method can be a potential tool to improve coral ecosystems by integrating new infrastructure project design recommendations.

2.1. Introduction

Hydraulic engineering structures could potentially offer coral-inclusive potential as will be discussed further in Chapter 4. An approach is needed to be developed to better structure decisions to utilize these nature-inclusive potential. Effectiveness regarding function improvement and a method to compare recommendations with one another will be part of this chapter.

2.2. Nature-inclusive methods

2.2.1. Nature based design philosophies

Traditional approaches tend to re-actively focus on realising the primary functionality of the project and minimising or compensating the negative impacts as done in an Environmental Impact Assessment (EIA) (Linde et al., 2013). Since the 1970's Environmental Impact Assessments became obligatory for any large infrastructure project (Glasson & Therivel, 2013). To react pro-actively and to provide opportunities for nature, the following nature-inclusive design philosophies have emerged (de Vries et al., 2021):

- Working with Nature (WwN) (Van Der Burgt, 1994)
- Engineering with Nature (EWN) (Bridges et al., 2018)
- Building with Nature (BwN) (Bouw & van Eekelen, 2020)

The BwN method aims to embed natural processes in engineering solutions by providing opportunities for nature (Bouw and van Eekelen, 2020) and is comparable to the other nature based design philosophies (de Vries et al., 2021). The five building with nature design steps are (Bouw & van Eekelen, 2020):

1. Understand the system (physical, ecological, societal)
2. Identify alternatives that use or provide value for nature and humans

3. Evaluate each alternative to select an integral solution
4. Refine the selected solution
5. Prepare the solution for implementation

2.2.2. Sustainability in marine infrastructure

One of the nature-based solutions according BwN is the use of infrastructure according an ecosystem-based approach (Bouw & van Eekelen, 2020). Marine infrastructure projects should remain functioning for extended periods of time during its life cycle. Because marine infrastructure could imply environmental consequences, sustainability is an essential concern in hydraulic engineering (De Vriend et al., 2015). According to Laboyrie et al. (2018), the moment of implementing sustainability efforts for hydraulic structures is of importance. Increased influence is generated by early use and implementation of the desired strategy during the project development process. This is needed for all types of infrastructure, including pro-actively adapting the designs and tailor solutions to optimally support the local environment.

It is inconvenient to change direction in a design process during further development in projects phases. Therefore, it is essential to start with a sustainable approach by involvement of key stakeholders (Laboyrie et al., 2018). In the case of retrofitting, it is likely that the environment is already affected by design choices in the past. This could lead to the conclusion that more restoration effort may be needed and it may therefore not be the optimal solution (Dafforn et al., 2015).

The Building with nature (BwN) concept, tends to implement social and natural systems within design steps by changing the way stakeholders think, act and interact (Vriend and Koningsveld, 2012; de Vriend et al., 2014; Bouw and van Eekelen, 2020). Following this line of thoughts, coastal infrastructure is likely to become of added value for environmental processes and for social value. However, added value for the environment can only be generated when the construction contains natural components which support local ecosystems.

2.3. Coral as a focus species

2.3.1. Introduction

Coral reefs contribute to all forms of life on our planet by providing shelter for marine life, species interactions, coastal protection, economic welfare and numerous other functions (Richmond, 1993; Hughes et al., 2003; Knowlton, 2001; Spalding et al., 2001; Dasgupta, 2021; Costanza et al., 1997). These functions lead to the enrichment and healthiness of their direct and indirect environment, not only for marine life but also for humanity.

2.3.2. Coral habitat

Coral reefs

Corals are part of the *cnidarian phylum*, which encompasses water-based animals (Ritchie & Roser, 2021). On top of substrates, microscopic polyps are attached, which forms a tissue layer around the calcium carbonate structure in the case of 'hard' or scleractinian corals (T. F. Goreau et al., 1979). Soft corals do not form a calcium carbonate skeleton but are formed by accumulation of polyps (Humann and Deloach, 2013; Spalding et al., 2001). However polyps for both hard and soft corals function similarly with an opening for food and waste exchange (Humann & Deloach, 2013). On the entire earth, we acknowledge more than 2000 different coral species (Ritchie & Roser, 2021). Colonies of corals, held together by skeletons of calcium carbonate, form different structures called: coral reefs (or referred to as reefs). Reef building corals (scleractinian corals) are corals which form the basis of these reefs and are therefore of importance for the development and survival of corals all over the world (Carpenter et al., 2008). Coral reefs come in different shapes and sizes. Two important findings to remember are that corals require hard substrate to grow on (Spalding et al., 2001; Vermeij, 2006; Tomascik, 1991; Creed and De Paula, 2007; Harriott and Fisk, 1987; Fitzhardinge and Bailey-Brock, 1989) and that corals can only survive in waters with specific water quality characteristics that are within their tolerance levels. (T. Oliver and Palumbi, 2011; Wooldridge, 2009; Crabbe, 2008; Brainard et al., 2011; Knowlton, 2001). In the world, there are two main coral reef types. Tropical (shallow-water) coral reefs and deep sea (cold water) coral reefs (Teichert, 1958). Focus during this study is on tropical coral reefs. These coral reefs occur frequently in seas where the yearly temperature range is within 4 °C. However, thermotolerance values varying from 16 to 36 °C is not uncommon (Henkel, 2010). According to Kuyper (1991), reef development generally occurs at sea temperatures between 25 and 29 °C. However, varieties in temperature tolerance remain possible (Kinsman, 1964). Coral propagation and growth occur in order to compete in a reef ecosystem owing to light availability (for zooxanthellae) (Humann & Deloach, 2013).

Zooxanthellae

Microscopic plant cells, called Zooxanthellae, offer pigment to corals resulting in a range of colourful coral habitats (Pearse & Muscatine, 1971). Zooxanthellae is located within coral tissues (polyps) (Spalding et al., 2001). Water turbidity levels should remain relatively low, since sunlight needs to penetrate the water column in order to reach zooxanthellae. These symbiotic algae, are able to live due to the protected coral environment and through the reception of sunlight and other compounds that are needed for photosynthesis (Pearse and Muscatine, 1971; Berkelmans and Van Oppen, 2006). On its turn, zooxanthellae produce oxygen that is being consumed by coral species and other photosynthetic organisms (Muscatine, 1980). The algal species provide organic materials as nutrients and energy for corals through photosynthesis (Pearse and Muscatine, 1971; Muscatine, 1980; Berkelmans and Van Oppen, 2006). Due to this principle, reef-building corals can grow through the formation of calcium carbonate (Pearse & Muscatine, 1971). Zooxanthellae also remove waste that could harm or affect corals (NOAA, National Oceanic and Atmospheric Administration, 2021a).

Coral propagation

Coral propagation or reproduction takes place in sexual and asexual ways (Spalding et al., 2001). Sexual propagation involves the production of gametes by genetic recombination (Humann and Deloach, 2013; Sorokin, 2013). Two different coral types for sexual propagation exist. One of these types is the coral brooder; which includes the production of fertilized gametes within coral polyps, also called planula larvae (Humann and Deloach, 2013; Spalding et al., 2001). Humann and Deloach (2013) explain that the other type are broadcast spawners and are releasing eggs, sperm or a bundle of the two into the water. Broadcast spawner- coral colonies could be female, male or hermaphrodite. The female (eggs) and male (sperm) colonies (gonochoric species) release the individual gametes for cross fertilisation in the water. The hermaphrodite colonies (majority of the spawners) have both feminine and masculine traits in each polyp. Eggs and sperm are combined into gamete bundles and released in the water for reproduction. Spawning events tend to be caused by lunar, tidal and 24h-light cues. (Humann and Deloach, 2013; Ayre and Resing, 1986; Sorokin, 2013; Spalding et al., 2001; Glynn et al., 1991).
Sexual reproduction through genetic recombination creates genetically varying coral species (Ayre and Hughes, 2000; Humann and Deloach, 2013).

Overall, reef building corals release gametes every year during spawning events (Humann & Deloach, 2013). During these events, gametes from a coral specie are all spat out during the same spawning event. This enables for gamete combination, where they swim or are transported by currents and tides. In the end, larvae settle on suitable substrates by sending 'cues'. These cues are signals, leading to the attraction and attachment of larvae towards substrates (Meyer et al., 2011; Vermeij et al., 2010).

The other form of coral propagation is asexual reproduction. Explained as: producing clones of exciting corals. This happens through budding or fission of polyps during corals life and through fragmentation by natural circumstances as storms. Asexual reproduction produces identical genetic corals (Ayre and Hughes, 2000; Humann and Deloach, 2013).

2.3.3. Coral reef types

Over time, corals grow and form coral reefs. Different reef types exist with specific characteristics. Each reef type requires specific developing and formation conditions. The type of coral reefs, presented in this marine world are:

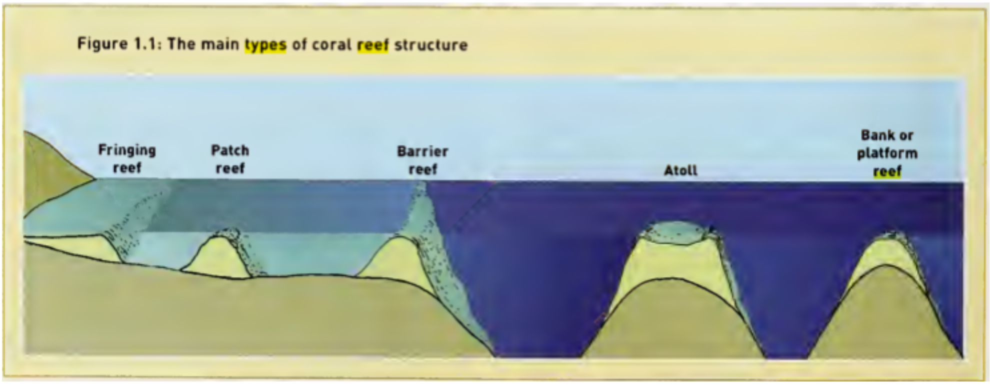

Figure 2.1: Different reef types (Spalding et al., 2001)

Fringing reefs

Fringing reefs are type of reefs that occur frequently over half of the global coral reef coverage (Hopley et al., 1978). Hopley et al. (1978) explains that this reef type grows close to shore on sloping coasts, as continental shelves or volcanic islands. These structures are relatively elementary built and evolve on shelving coastlines by the upward growth of calcium carbonate on a rocky substrate. In addition, these type of reefs are relatively young. Therefore, coral species diversity is lower compared to other reef types. (Hopley et al., 1978; Smithers, 2011; Spalding et al., 2001)

Patch reefs

Frequently, patch reefs are located in depths between 2 and 9 meters (Hopley et al., 1978). These reefs seem to have elliptical or circular shapes. The reefs are separated by sand and form individual 'islands' or patches. These patches are small and could be scattered within an atoll or in lagoons. (Spalding et al., 2001)

Barrier reefs

Barrier reefs are reefs that lie a little deeper offshore than the fringing reefs. They are separated from land by a lagoon (Battistini, 1975). These barrier reef structures are relatively older than fringing reefs. These reef types occur at all coral reef locations. Barrier reefs could also be formed out of fringing reefs if the coastline subsides or is flooded. Lagoons will then be formed in between, separating the reef from the shore. (Spalding et al., 2001 and Andréfouët and Cabioch, 2011)

Atolls

These type of reef formations are more unique and found even further away from shore and continental shelves, commonly in deep sea. Atolls occur mainly in the Pacific Ocean and Central Indian ocean (Woodroffe and Biribo, 2011; Moberg and Folke, 1999). Atolls are typically roundish shaped coral structures, because they initially form as fringing reefs around an existing (volcanic) island (Spalding et al., 2001). The island part above water, subsides below water level. Coral, continuously grows in the form of a ring around the subsided island and forms an enclosed lagoon. (Spalding et al., 2001)

Bank or platform reefs

Bank reefs can be found in lagoons created by atolls and barrier reefs (Moberg & Folke, 1999). These reefs are singular structures, without a clear structure such as for barrier reefs or atolls. The origin can differ per bank and could also be named a shoal when submerged. (Spalding et al., 2001)

Other reefs are: Near-Atolls, Bank barriers and Submerged reefs (Spalding et al., 2001)

2.3.4. Global distribution

The global distribution of tropical reefs worldwide can be seen in Figure D.1. Southeast Asia has the largest coral cover, followed by the Pacific and Indian ocean, Caribbean, the Atlantic and the Middle East (Spalding & Grenfell, 1997). The status per region can be found in: Status of Coral Reefs of the World (Wilkinson, 2000) and can be helpful as background information for the user of this study.

Wilkinson (2000) indicates that for example, the biodiversity in the Indo-pacific is much higher than in the Caribbean and Atlantic region. In the Great Barrier reef in Australia and Belize, frequently platform and barrier reefs are located. In the Indo-Pacific, Caribbean and East Africa commonly fringing reefs are present, while Atolls are typically found in the Indo-pacific. (Moberg & Folke, 1999)

2.3.5. Coral economical value

According to Costanza et al. (1997), coral ecosystems contribute with 375 billion US$ to 1.8 per cent of the total global biosphere value and services. The biosphere refers to the parts of the earth that support life (Souter & Linden, 2000). Bryant et al. (1998), states that reefs only cover 0.2 per cent of the total marine ecosystems worldwide. This indicates that the contribution of reefs to the global biosphere is relatively large and is therefore of great concern. (Costanza et al., 1997; Cesar et al., 2003)

2.3.6. Coral ecosystem services

The ability of natural systems and species to support human life is referred to as ecosystem services. (Daily et al., 1997). Included are the production of goods such as seafood, timber, fuels etc and the life support functions such as natural recycling or renewal. Furthermore, aesthetic and cultural values belong to the ecosystem services (Daily et al., 1997). The ecosystem services generate human prosperity and are therefore defined as the advantages that people gain from nature (Laboyrie et al., 2018; Reid et al., 2005; Ring et al., 2010). The services are subdivided in four categories, i.e. supporting, provisioning, regulating and cultural services (Laboyrie et al., 2018).

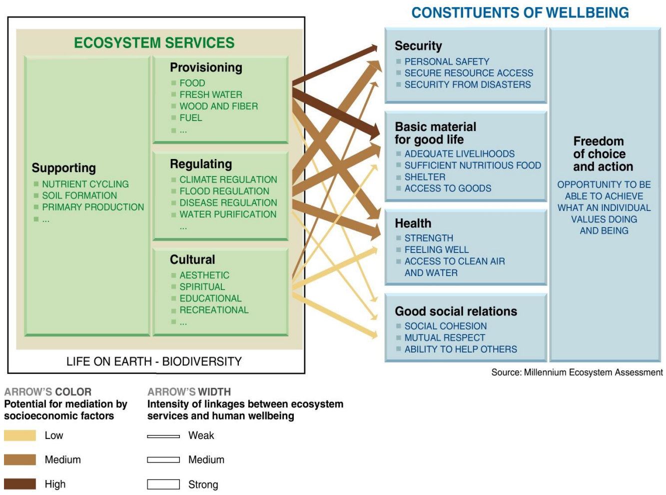

Figure 2.2: ecosystem services (Laboyrie et al., 2018)

Coral ecosystems also have 'services', since coral reefs have benefits and are functioning as a habitat for millions of marine species (Dasgupta, 2021). The services and benefits belong to the four categories mentioned above and are according to Moberg and Folke (1999), Cesar (2000) and Wilkinson (2000):

- Disturbance regulation (Coastal protection)
- Biochemical/Waste treatment (Nitrogen fixation, waste assimilation etc.)
- Biological control (Feeding places, shelter for fish)
- Refugia (Nurseries and habitats)
- Food production (Fish, seafood)
- Raw materials (Seaweed, medicine, coral blocks, sand etc.)
- Recreation (Tourism)
- Cultural (Aesthetic, religious values etc.)

2.3.7. Influences on coral habitats

Corals are delicate marine species, which are not able to handle small temperature fluctuations (Henkel, 2010). Even increase in surface temperatures (SST's) of a couple degrees Celsius, could induce the extermination of zooxanthellae by mortality and release of zooxanthallae components, identified as loss of colors and called: coral bleaching (Glynn, 1993; Brown, 1997; Loya et al., 2001). Bleaching decreases the resilience of corals by non-functioning zooxanthellae (Brown, 1997). When lower tolerance corals are subjected to other stress factors, coral mortality occurs more quickly (Hoegh-Guldberg, 1999; Brown, 1997). However, coral bleaching is not the only factor that causes coral degradation, also coral diseases and other factors (human induced stress factors) are initiating coral loss (Pandolfi et al., 2003; G. P. Jones et al., 2004; De'ath et al., 2012). Coral habitat health is therefore in decline due to subjection of different items, as described below (Naughton and Jokiel, 2001; Spalding et al., 2001; C. S. Rogers, 1993; Lindeboom, 2017; Szmant, 2002; Mumby and Steneck, 2008).

- Storm waves
- Fresh water floods
- Pollution
- Coral mining
- Global warming (bleaching and coral death)
- Eutrophication
- Erosion
- Over fishing (starfish invasion)
- Dredging
- Ship grounding (anchoring)
- Impact of Marine structures
- Direct tourism activities

2.4. Components of marine infrastructure projects

2.4.1. The use of marine infrastructure

Originally, marine infrastructure projects cover all nautical related infrastructure development necessary to protect the hinterland from flooding or accessibility for ports and waterways. During the last century, accessibility to fossil fuels became more important and nowadays, the world fully relies on fossil fuels (Höök and Tang, 2013; Covert et al., 2016). A reversal has been put in motion by using alternative renewable energy sources such as the use of wind and solar energy. For all these types of projects, from fossil fuels to renewable energy but also for the protection against floods and opportunities for economic growth by building harbours or implementing recreational space, the marine environment offers plenty of space to satisfy all demands. Many different marine infrastructure projects have been and will be executed in the marine environment.

Marine infrastructure can be located further and closer offshore such as oil platforms, pipelines, wind farms, floating solar farms and artificial islands. Closer to shore, breakwaters, groynes, jetties, mooring constructions, harbours and much more infrastructure can be observed. Different types of materials such as concrete, stone, timber, and steel are being used for the construction of marine structures.

As explained in Section 1.2.4, the focus of this study and therefore this section, lies on infrastructure projects in the coastal marine environment.

2.4.2. Classification of marine infrastructure projects

Dafforn et al. (2015), categorises marine infrastructure in the following categories:

- Recreational infrastructure: marinas/yacht harbours
- Coastal and foreshore defence infrastructure: hard engineering solutions
- Offshore energy resources: wind farms, oil gas offshore
- Artificial reefs: concrete materials/modules, steel, limestone
- Artificial resident waterways: canals and lakes

In addition, management of execution of marine infrastructure projects is also divided in categories (Dafforn et al., 2015):

Hard Engineering
Preventive engineering through man-made shoreline armouring and the development of hydraulic structures. These works are executed to avoid erosion, floods, and other water-coastal occurrences by damping and alteration of waves and altering currents or sediment flows. Hard engineering works are also used for functions such as transportation, fishing and distribution of natural resources or energy. The 'hold the line' strategy uses hard engineering as approach. Examples are e.g. breakwaters, seawalls, groynes, dikes. (Dafforn et al., 2015; Cooper and McKenna, 2008)

Eco Engineering
With eco engineering, hard engineering is combined with ecological principles to retrofit existing- or implement new marine infrastructure to benefit the environment. Examples are e.g. artificial crevices, rock pools, bioblocks. (Dafforn et al., 2015; Chapman and Underwood, 2011)

Soft Engineering
Soft engineering includes human controlled engineering through dredging, nourishment and reclamation activities to protect hinterlands, increase recreational possibilities or for artificial land creation. Examples are e.g. beach nourishments, artificial dune construction, salt marsh creation. (Dafforn et al., 2015; Cooper and McKenna, 2008)

Habitat restoration
Ecosystems that have been damaged or malfunctioned need help to be restored. People play an important role in this by providing recovery assistance. Coastal habitat restoration (mangroves, salt marshes etc) is done according to Building with Nature (BwN) implications in soft engineering. Examples are e.g. mangrove-, saltmarsh-, dune-, oyser reef- restoration. (Dafforn et al., 2015; SER, 2002; Laboyrie et al., 2018; Bouw and van Eekelen, 2020)

On the basis of overlap in construction type, space occupancy (footprint) and wet surface area, the categorisation in Table 2.1 is made. Some examples are also provided in the table.

Soft Engineering	**Hard Engineering**			
Dredging works	**Rubblemound structures**	**Gravity based structures**	**Pile foundations**	**Floating/anchoraged structures**
Port, shipping channel and waterway deepening	Groynes	Gravity type piers	Pile supported piers	Floating docks
Construction or maintenance of beaches	Jetties	Tunnels	Pile supported jetties	Platforms
Excavation of harbours, terminals and mooring piers	Breakwaters	Quay walls	Curtain wall breakwater	Solar farms
Land reclamation	Rubble sea walls	Pipelines	Bridge pillars	Anchorage system
Restoration of wetland ecosystems	Piers	Breakwater	Pile supported mooring system	
Excavation for pipelines, cables and tunnels	Pipelines covered with rubble		Jackets	
Mining of aggregate			Jack-ups	

Table 2.1: Marine infrastructure categorisation with examples of marine infrastructure in coastal regions (Ekun et al., 2016).

The division in hard engineering is based on structural differences and footprint coverage. Gravity based structures (GBS) are structures that are located on the bottom by its own structural weight. Rubble mound structures have the same 'gravity based' function but differ in structural profile, which could possibly have different effects on coral development. The third category are the pile foundations. Piles are structurally different than other categories by taking up less space. The last category is the floating structure. These are structures that are anchored on the sea bottom. The Hard Engineering categories are explained in detail in Appendix Section C.3. Soft engineering only includes the dredging works category.

2.5. Development of the systematic method

A stepwise approach is proposed, containing all crucial elements to come to new sustainable design recommendations. The design of the main method, can be seen in Figure 2.3.

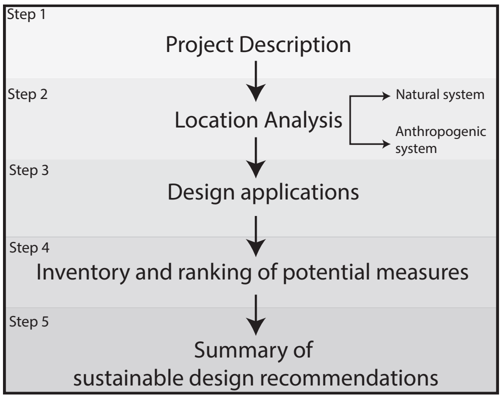

Figure 2.3: A schematized version of the main method. See for the detailed version: Figure A.1

The 'main' systematic method shows 5 steps. With in each step, questions should be answered. Each step is followed by another (Figure 2.4). Firstly, step 1 is addressed and contains the project description. A description of the project plan, together with the incentive for the location analysis should be studied and written out. Included are the main location characteristics; the initial problem is addressed and tackled by the description of an initial design plan. Secondly, step 2 elaborates on the location analysis. This analysis is done by looking at two systems: the natural system and the anthropogenic system. Two possible outcomes are presented. This could be a location which is either suitable or unsuitable for coral- marine infrastructure interaction. During the step 2 process, measures arise that could change an unsuitable situation for coral- marine infrastructure interaction into a situation that could become suitable if measures are applied correctly. Nevertheless, ending up with an unsuitable system for coral development remains possible. This occurs when, for example, coral will not develop in a specific location due to environmental, hydrodynamic or anthropogenic circumstances and can be checked by following figures 2.6 and 2.9. Step 3 contains the design applications which could be categorised either as soft or hard engineering by using figure 2.10. In both categories, positive and negative effects arise (section 4.3.1, B.2.1). Measures to increase the positive and to reduce the negative effects are also presented in section 4.4.1 and B.3.1). After creating an inventory and ranking of potential measures in step 4, new sustainable design recommendations are proposed in step 5 (section 2.9).

2.6. Clarification of Step 1 - Project description

Background information is needed as a starting point for any project in this area. In relation to coral development, available background information needs to be assessed firstly. Thereafter, a location introduction should be provided together with the design objective (Molenaar & Voorendt, 2020). Requirements, evaluation, criteria and the boundary conditions where the original design of the yet to be built construction is based upon should be assessed. This design will be turned into a nature-inclusive solution with the goal to enhance coral development.

Apparently, a marine construction is needed. What is the underlying cause? One has to analyse/define the problem or need and the initial design plan with altered conditions needs to be explained. The following are all points to elaborate upon (Molenaar and Voorendt, 2020):

- Location description - short summary of important aspects of the area in general
- Problem analysis/definition - define the problem(s) such as degrading ecosystems, problems leading to infrastructure development etc.
- Design definition - requirements, evaluation, criteria, boundary conditions
- Design of original infrastructure (if present) - when infrastructure is currently present on location and will be used for the new design (pier extension, breakwater enlargement etc.), provide information about the original design.
- New initial design - what is the general plan/what is going to be built? (Detailed design is for step 3)

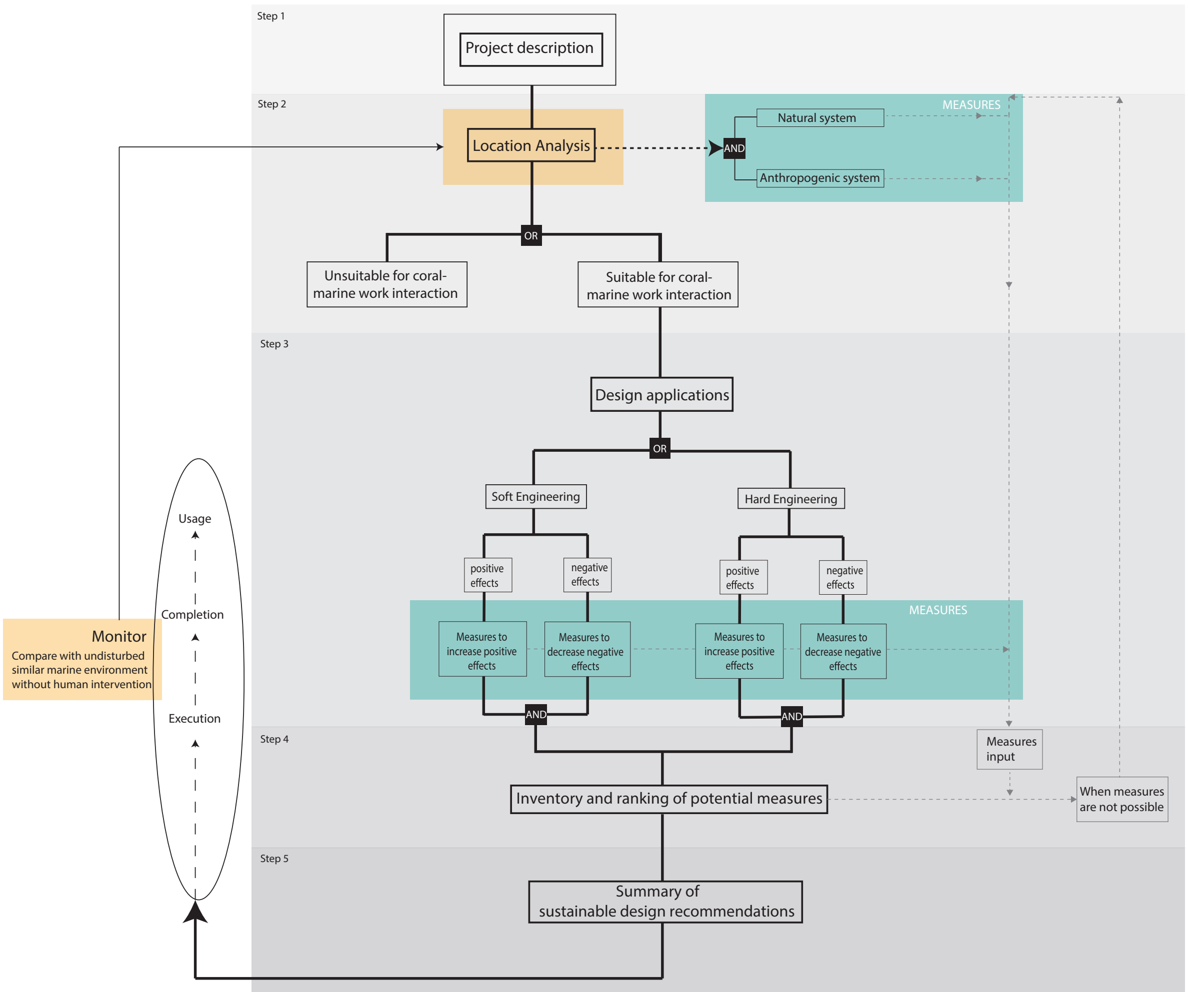

Figure 2.4: Detailed version of the main method. A larger version can be found in Appendix Figure A.1. For the selection towards the suitable/unsuitable coral-marine infrastructure interaction (figures 2.6, 2.9), hard/soft engineering (figure 2.10) and inventory and ranking of potential measures; requirements or criteria are needed (section 2.9)

2.7. Clarification of Step 2 - Location analysis

2.7.1. What is included?

The location analysis is needed to describe specific location characteristics. Making use of two systems, the natural system and the anthropogenic system. The purpose of this step is to indicate all natural (abiotic and biotic) and human components to check whether the area/exact location is suitable for coral development. This results in potential measures to enhance coral development.

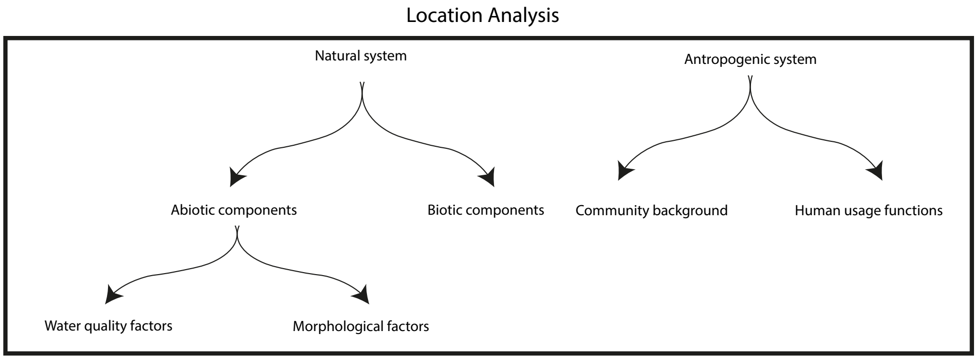

Figure 2.5: Location analysis interaction scheme. Water quality and morphological factors are elements in abiotic components, where both abiotic and biotic components are part of the natural system. The anthropogenic system consists of community background information and human usage functions.

2.7.2. Natural system approach

The 'natural system method' provides guidance through components and factors that will clarify whether coral development in the current system is possible and how to stimulate coral development according to certain measures. Both abiotic and biotic divisions should be completed to provide answers. The natural system can be observed in Figure 2.6.

Is coral present?

The first question that is asked in the natural system is whether coral is present, yes or no? Due to the biotic background of this question, it actually belongs to the biotic system. However, this is a prevailing question that needs to be answered before continuing into both the abiotic and biotic system.

The area of interest to indicate if coral is present, is within and directly around the greenfield. Follow 1 when coral is present, follow 2 when coral is not present in this area.

When coral is present, the type of coral species should be investigated. This is done with the assistance of coral reef identification literature or through one of the coral databases. In the following list, some examples of a book and databases are provided. In addition, area-specific literature could be used to identify coral species.

- Reef Coral Identification (Florida, Caribbean, Bahamas) (Humann & Deloach, 2013)
- IUCN red list database (IUCN, 2021)
- ReefBase database (Base, n.d.)
- Corals of the World database (Veron et al., 2016)
- Coral trait database (Data, n.d.)
- Nature Serve database (NatureServe, n.d.)
- Animal diversity web database (Myers et al., n.d.)
- Saltcorner's species library (Goemans, 2012)

When coral is not present, possibilities for coral development have to be investigated. This is firstly done through the abiotic assessment.

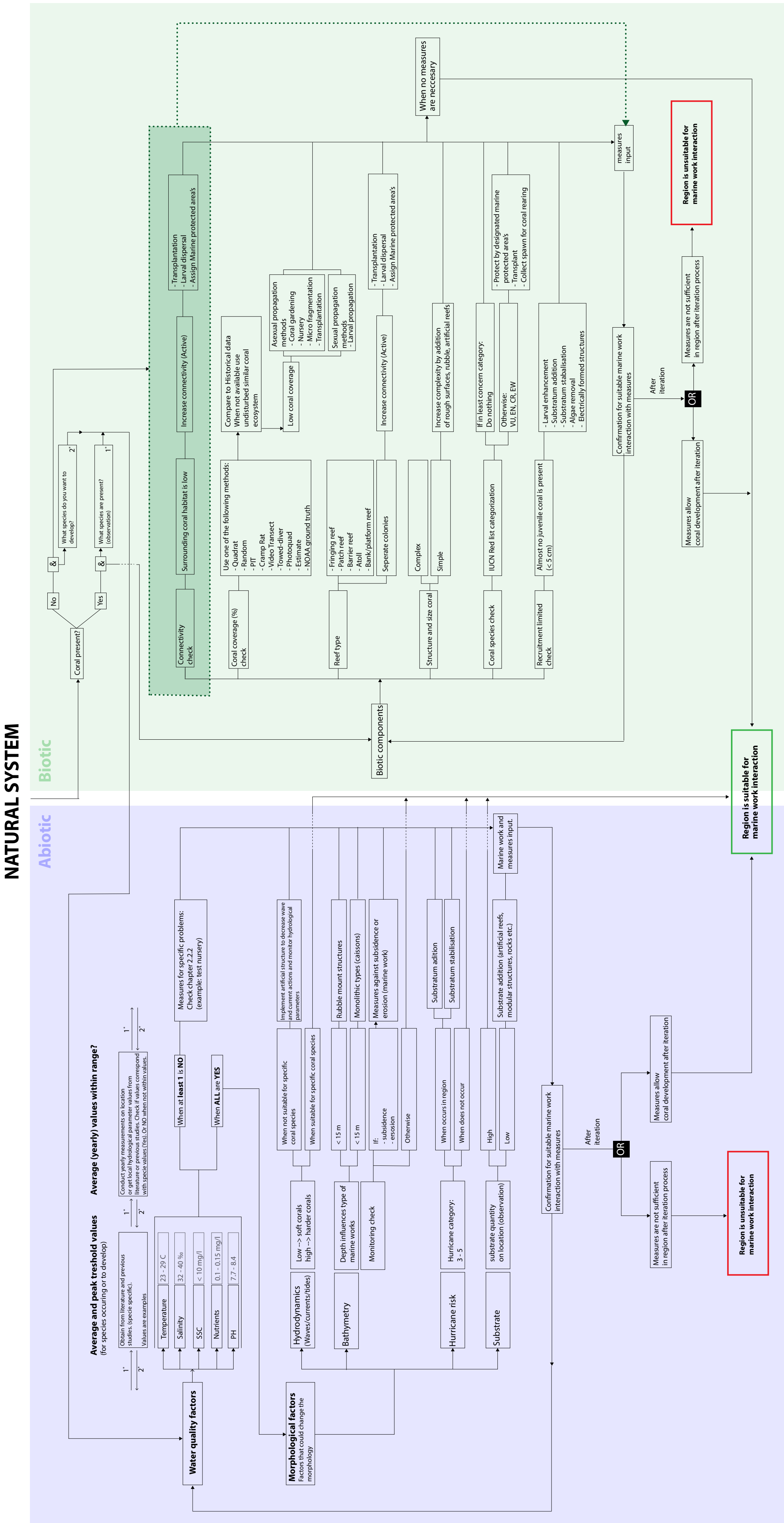

Figure 2.6: Natural system components with abiotic and biotic factors. For a better visible version Figure A.2

Abiotic components

Water quality factors

If coral is present and species are defined, the number 1 arrows should be followed. This starts by obtaining average and peak species specific water quality thresholds which are obtained through literature and species specific studies (see Section 2.7.2.1).

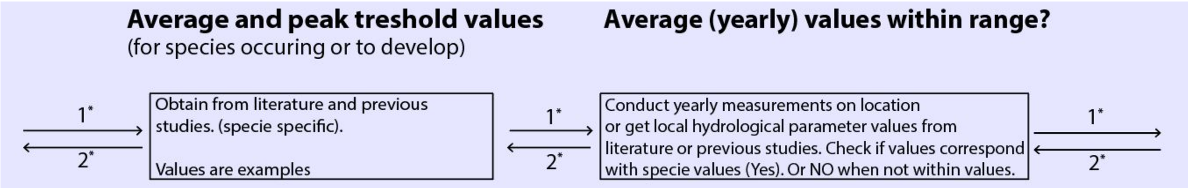

Figure 2.7: Follow arrows 1 or 2. Follow 1 if coral is present on/close to the greenfield. Follow 2 when coral is not present on location.

As explained in Section 3.2.1.1, the significant water quality factors are:

- Temperature
- Salinity
- Suspended Sediment Concentration (SSC)
- Nutrients
- PH (Acidity)

Overall quantification of above factors can be difficult since optimal factors depend on the type of species and on local circumstances. However, indications of quantification is described through Chapter 3.

By data gathering on or close to the greenfield (footprint), water quality values can be obtained. These measurements should be performed on a yearly basis, preferably for as long as possible. This produces more accurate data since more measures means a better indication if the coral species can survive or if degeneration is the case. Leading to a more specific problem-solving approach. When species specific values are in accordance with the (yearly) measurement values, the morphological factors should be checked. If values are not within the water quality values per species, future degeneration of corals in this area is more likely to occur and measures to these specific problems should be assigned. These measures or recommendations can be deducted from Section 3.2.1.1 and have the purpose to make this area suitable for future coral development. After measure application, the water quality parameters should be authenticated. When all local water quality parameters are within correct species specific values, the next step within abiotic factors: is the assessment of the morphological factors.

If coral is not present within the location of interest, the number 2 arrows should be followed. The aim is to develop corals on and with marine infrastructure to enhance coral value. When coral development is not observed before the construction phase of a marine work, the natural system does not allow coral development. This could be the consequence of influences from: water quality factors, morphological factors, biotic components or anthropogenic implications (see Chapter 3). The first step performed is to check if coral development is possible. The optimal solution to check which species thrive under local circumstances, is using a sea based coral nursery/garden (explained in Section 3.3.2.1). This makes it possible to determine which coral species are appropriate and which are not. Coral growth will be observed when the natural system allows coral development. Conducting water quality measurements (and other factors described later) at the same time leads to insight in possible hampering of coral development. Measurements as the implementation of a (test) nursery should be monitored as long as possible (>1 year) to obtain reliable results.

Morphological factors

In this part, factors are highlighted that could lead to a change in morphology, as indicated in Section 3.2.1.2:

- Hydrodynamics: currents have to be measured constantly over a longer period (year).
- The bathymetry needs to be monitored to check whether erosion or subsidence are occurring problems.
- Hurricane risks, indicate if coral reefs undergo 'system resets'. These can be found on for example: the National Hurricane Center (https://www.nhc.noaa.gov/).
- Substrate availability on location around the (future) footprint.

When measure recommendations within the morphological factors want to be applied, the confirmation for suitable marine infrastructure interaction with these measures should be verified. This is done by checking the entire abiotic list again after application of measures and/or to develop a nursery in place. If after iteration, coral is not able to develop, the region is not suitable for coral - marine infrastructure interaction. If coral is developing or is suitable according to measurements and literature, the region is suitable for coral - infrastructure interaction on behalf of the abiotic components of the natural system.

Biotic components
The biotic components start at the same point as the abiotic components: Is coral present, yes/no?

If coral is not present, biotic factors could be the cause for this problem (e.g. coral predators, algae overgrowth, low connectivity) (Rotjan and Lewis, 2008; Venera-Ponton et al., 2011; Aerts, 1998; Humann and Deloach, 2013; Hoegh-Guldberg, 1999). In order to stick to a manageable approach, a nursery 'test' can be applied to identify if coral development is possible. This would also be an idea if a degenerating coral reef is observed. This can be observed by checking among others the following factors: damage, tissue loss, diseases, mortality or bleaching (Loya and Rinkevich, 1980; Glynn and Wellington, 1983; Henkel, 2010; Naughton and Jokiel, 2001; Lindeboom, 2017; Meesters et al., 2019). Additionally the connectivity of the reefs nearby the location of interest should be assessed. The connectivity, together with abiotic factors and time of spawning could possibly lead to limited larval supply (paragraph 3.2.2). Therefore, assessing these components tends to obtain information about coral absence. If coral is present in and/or close to the greenfield, the following biotic components are focused upon (see: Section 3.2.2)

- Coral coverage check
- Connectivity
- Type of reef
- Structure and sizes of corals
- Coral species check (IUCN Red list)
- Recruitment limited check

To know if the reef health is within proportions, coral reef cover should be measured. The possible ways to measure the coral cover in an area is defined in paragraph 3.2.2. One of the metrics from Section 3.4 for quantification should be used. An easy example is the Reef Health Index (RHI). the RHI indicators can be used easily and provides a quantitative analysis of the area. Indicators within RHI are; coral cover, macro algae cover and fish presence. To get a quick overview, only coral cover measurements are needed. (Kramer, 2003; McField and Kramer, 2007). This includes grades from one (critical) to five (very good/healthy) (see fig: Figure 2.8. An example can also be found in Kitson-Walters (2017).

REEF HEALTH INDEX (RHI)					
Reef Health Index Indicators	Very good (5)	Good (4)	Fair (3)	Poor (2)	Critical (1)
Coral Cover (%)	≥40	20.0-39.9	10.0-19.9	5.0-9.9	<5

Figure 2.8: The Reef Health Index, only with the coral cover percentage Kramer, 2003; McField and Kramer, 2007; Kitson-Walters, 2017

All necessary steps with measures are indicated in Section 3.2.2. Two outcomes are possible: no sufficient coral development after measures or measures allowing coral development. If all arrows point towards the suitability coral marine infrastructure interaction, the following system should be analysed: the anthropogenic system approach.

2.7.3. Anthropogenic system approach

Community background information

The anthropogenic systems approach is created to determine the human usages in the area of interest. Furthermore, the effects of human usages functions on corals and the dependence of human uses on corals are evaluated. Closing in measures and passive or active application of these measures. The anthropogenic structure can be found in Figure 2.9.

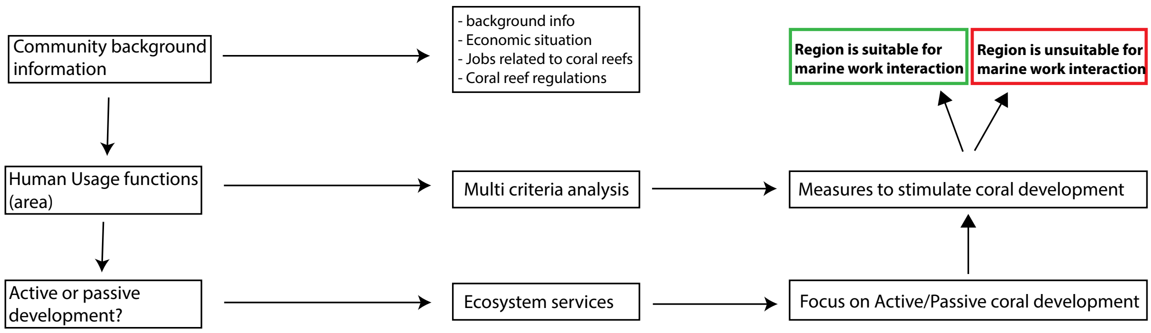

Figure 2.9: Anthropogenic method

First, community background information is needed. By mapping and listing this information, residential needs and opinions are believed to be better understood. Local inhabitants should be involved in the decision making process to improve planning and functioning of projects (Corburn, 2003). First an understanding is needed to cover social information of the local population, altered from Bunce and Townsley (2000):

- Background information
  - Inhabitants and households
  - Residency status
  - Ethnicity. religious background
  - Age and gender
  - Education
  - Social status
- Economic situation
- Jobs related to coral reefs (Fishermen, Marine park rangers, recreational (diving..) etc.)
- Coral reef regulations

Secondly, start with the ecosystem services; supporting, provisioning, regulating and cultural services (see Section 3.3). The services lead towards human usage functions as indicated in Section 3.3. A multi criteria analysis is used to see if the specific human usage functions are dependent on corals and if these usage functions affect corals. The human usage functions with the highest scores (both coral dependent and coral influences), should be assessed and taken into account for the development of coral and the marine infrastructure.

Human usage functions	Coral dependent 0 - 4	Coral influences 0 - 4
Food provisioning Recreational (tourism) Natural resources: Mining, drilling Coastal Protection MPAs Transportation and navigation Storage Reclamation Power generation		

Table 2.2: Multi criteria analysis of human user functions with regard to coral dependence and the degree of influence on corals.

Coral dependent
The extent to which the function is dependent on local coral reefs has to be rated. Rating goes from zero to four. With zero the least dependent on local coral reefs and four for the most dependent on coral reefs. All the human usage functions should be assessed. For example; food provisioning at the Maldive islands. Population of the Maldives is dependent on coral reefs, with the fishing industry being one of the main services (Jaleel, 2013). Fish (e.g. tuna) is dependent on coral reefs around the Maldives, used for local consumption and for export (Jaleel, 2013). Without these reefs, local economy would be less supported by the fishing industry.

Dependence on coral reefs				
0	1	2	3	4
Not Dependent	Almost no dependency	Dependency is present but not critical	Critically dependent	Fully dependent

Table 2.3: Score for dependency of human user functions on coral reefs

Translating the story of the Maldive islands to a score for the food provisioning function results towards a four, since the country is fully dependent on fish that live there due to coral reefs and is used for local consumption and export. All other human usage functions have to be analysed and rated with a score of zero to four.

Coral influences
Human activities regarding to human usage functions, could have consequences for coral reefs (Meesters et al., 2019; Hughes et al., 2003; Lindeboom, 2017; Naughton and Jokiel, 2001). How activities affect coral reefs differs per type of activity and is explained in Section 3.3. These effects could be both positive well as negative. A similar score as for coral dependence is provided:

Coral influences				
0	1	2	3	4
No (neg/pos) effect	almost no effect	effects are felt but are not critical	critical effects	Largely affected

Table 2.4: Scoring to which extent human usage functions influence coral reefs. This could both be positive as negative.

The influence of human usage functions on local coral reefs is illustrated with the following example. According to Berg et al. (1998), rural areas in Sri Lanka are prone to coral mining due to the short term yield of money. Mined coral is used for decorative applications or for lime and building material production (Dulvy et al., 1995; Brown and Dunne, 1988; Coughanowr et al., 1995; Berg et al., 1998). Coastal regions of Sri Lanka which are subject to mining, observe destruction and degradation of entire coral reefs (Rajasuriya et al., 1995; Öhman et al., 1993; Berg et al., 1998). Since mining could critically influence affected areas (Brown & Dunne, 1988) and when mining is done on a regular basis, a score of 3-4 is assigned. In addition, all other human usage functions should be rated in the same way.

Active or passive development?
Two alternative methods are in place for coral development, namely: active and passive techniques (see: Section 3.3.2.1). In order to succeed and pick the correct (human driven) development method, the social added value of coral development on a marine infrastructure project needs to be assessed. This is done by checking if one of the following ecosystem services/benefits can be answered with yes. (Acquired from Kittinger et al. (2012); (Moberg and Folke, 1999; Beaumont et al., 2007; Holmlund and Hammer, 1999))

- Food provisioning.
  Will coral on the future marine structure, perform a step in providing food? This is only possible when access to the source of food (corals) is possible. For example, harbours are excluded. Coral development will probably enhance fish occurrence but when fishing in harbours is not permitted, this is not possible and is answered with a no.
- Recreational
  This is the case if coral fulfils a recreational purpose with added value for humans (e.g. diving). Will the structure be available for recreational purposes?
- Natural resources
  Natural resources exist without human interventions but can be used by humans. Think of coral or sand mining etc. Is this the case?
- Coastal protection
  Coastal erosion and flooding became and become more worldwide problems (Hallegatte et al., 2013; Kron, 2013). Will coral development on the marine infrastructure regulate disturbances induced by storms, hurricanes etc. and protect the hinterland? Only developed coral reefs have a chance to mitigate wave impacts or decrease erosion rates etc. (Reguero et al., 2018; Harris et al., 2018; Guannel et al., 2016)
- Cultural services
  Will coral development in this area, enhance cultural, religious, aesthetic or spiritual values? (Kittinger et al., 2012)
- Biochemical cycling
  Will developed coral contribute to e.g. detoxification, nutrient cycling or waste removal? (Kittinger et al., 2012)

When one of the questions above is answered with a yes, the anthropogenic system sees coral development as contributing to the ecosystem services in the area. In this way, humans will benefit from corals on site. For example, think of the food provisioning service. According to literature, presence of corals stimulate fish (Cesar, 2000; Syms and Jones, 2000; Komyakova et al., 2013; J. E. Smith et al., 2006; Feary et al., 2007; Hicks and Cinner, 2014; Kittinger et al., 2012; Spurgeon, 1992). If fishing is allowed, the probability of catching fish is increased. This could generate more revenue and better circumstances for fishermen. This is an example of how coral might enhance the designated ecological services.

The questions above are asked to check whether active stimulation of coral is preferred according to the anthropogenic system. Active techniques generally require more effort and are more costly than passive techniques, while passive techniques are frequently easier to apply. However, active stimulation of coral could sometimes be necessary or required. Active techniques go hand in hand with passive techniques. When none of the above is answered with a yes, then the focus lies on passive coral development techniques (see Section 3.3.2.1).

Measures for coral development
This is dependent on the type of human usage functions and its score. A high coral dependency score asks for coral stimulating and protection measures since the communities usage function is dependent on coral reefs for different purposes (fishing, coastal protection, recreational etc. (Cesar, 2002)). Measures per usage function are described in Section 3.3. When anthropogenic pollution takes place in a region, coral development may not be possible. By taking measures to tackle the source of the problem, the area can be made suitable. If it turns out that the measures are not effective, the area remains unsuitable for coral development. Suitability for coral development can be assessed by going back through the natural system.

2.8. Clarification of step 3 - Development of marine infrastructure design applications

2.8.1. What is included?

This design step is included in the process of transforming a traditional design into a coral-inclusive design. The original design concept should be explained within the 'design' step, which includes a soft or hard engineering work with negative and positive effects, as well as measures on how to improve coral development on marine infrastructure. See Figure 2.10 for an overview of the design application.

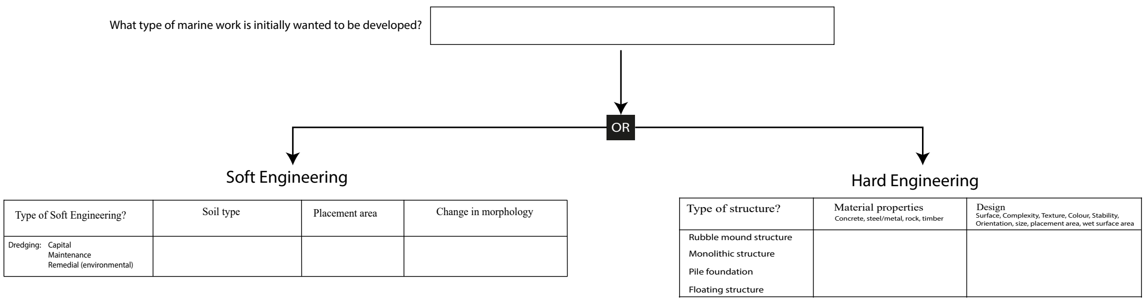

Figure 2.10: Design method

2.8.2. Detailed design of new infrastructure

The question of what is going to be built was already answered in step 1. Here a more detailed version should be provided.

Different type of construction projects are possible with other implications on nearby coral reefs. In order to perform coral enhancing methods, the type of marine infrastructure and elements exposed to coral habitats should be known. This results in the following procedure, dependent on a hard or soft engineering project.

2.8.3. Soft Engineering

This included the case if a soft engineering work will be implemented. Examples of soft engineering projects can be found in Section 2.4.1. The type of dredging should be examined. Is it capital dredging, maintenance dredging, or remedial dredging?
Furthermore, the following elements should be known:

- Soil type
- Placement/mining area
- Change in morphology

Use obtained data and knowledge from Sections B.2.1 and B.3.1 to fill out the table in Figure 2.10.

2.8.4. Hard Engineering

For hard engineering infrastructure, a similar principle as for soft engineering applies. Other categorisation and elements are taking part of marine infrastructure and therefore interact differently with coral ecosystems.

The type of structure could fall in: rubble mound structures, monolithic structures, pile foundations or floating structures. The following elements indicate the impact of hard marine infrastructure on corals:

- Material properties (Concrete, steel/metal, rock, wood/timber)
- Design (Size, placement area, surface orientation etc.)

In sections 4.3.1 and 4.4.1, effects and measure recommendations are illustrated for constructions in the coral marine environment.

2.9. Clarification of Step 4 - Inventory and ranking of potential measures

2.9.1. What is included?

Steps 2 and 3 result in measure recommendations applicable for different sites. Since the list of recommendations is long and not applied to specific circumstances, the bibliography of recommendations should be confined. This is done by making use of the effectiveness versus feasibility matrix (Figure 2.11).

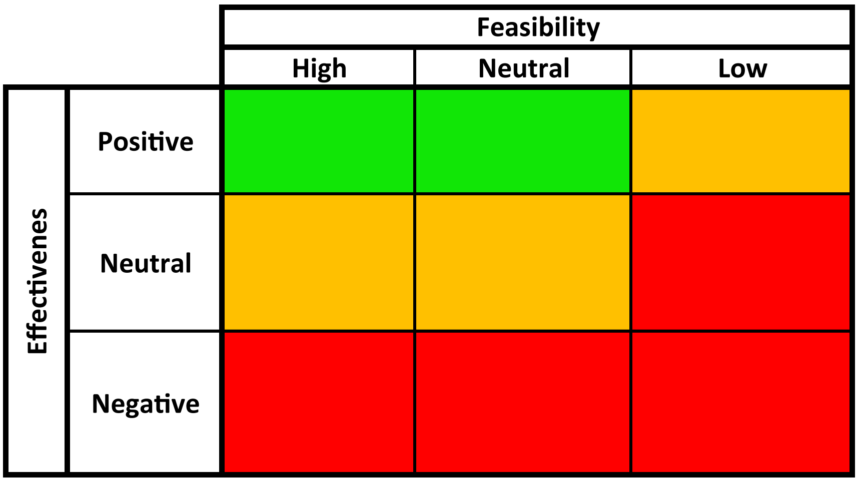

Figure 2.11: Matrix with effectiveness versus feasibility. Red: do not execute the measure or action, Orange: take measure into consideration and Green: definitely execute.

Measures effectiveness versus feasibility is assessed to come up with better fitted possibilities to local circumstances for creating coral-inclusive infrastructure.

2.9.2. Feasibility

The feasibility of concepts cover the following three aspects:

- Technical feasibility
- Operational feasibility
- Economic feasibility
- Environmental feasibility

For every measure, all four feasibility aspects should be summed up and averaged. Subsequently, the score falls in a category (High, Neutral, Low). This score is used for the matrix in Figure 2.11.

		Technical	Operational	Economic	Environmental	Average
Feasibility	High	1	1	1	1	≥ 0.5
	Neutral	0	0	0	0	0 ≤ x < 0.5
	Low	-1	-1	-1	-1	< 0

Figure 2.12: Technical, operational, economic and environmental feasibility schematized in a table. The last column, is the average of the four columns an provides and overall feasibility score which needs to be used in Figure 2.11

Technical feasibility
For the technical feasibility, it is checked whether it is technical possible to implement a measure. Technique per action depends on factors such as; the use of advanced materials and methods, the difficulty in applicability and the proof of concepts. Especially, the last factor illustrates if the concept is performed previously and if it worked properly. This provides an indication of the technical challenges that await.

Operational feasibility
Operational feasibility is how effectively the proposed measure handles the problem regarding safe and reliable conditions. This includes organizational issues, operability, accessibility of location, effort- and legal aspects. Effort may be defined as the length of time it takes for a measure to be functional before it is applied. Effort is also defined as the amount of labour required to make the application functional. Legislation describes the possibility of execution of a measure in an area. Legislation can imply: MPAs, no fishing zones, no construction etc. For example, in India the following law and policies for the conservation and management of reefs apply (Panini, Hoon et al., 1997):

- Environment (protection) Act. 1986
- Coastal regulation zone (CRZ) 1991
- Wildlife (protection) Act (WPA) 1972
- Indian forest act 1927
- Forest conservation Act 1980
- Indian fisheries act
- CRZ 1991

Only within the CRZ 1991, coral mining is prohibited. The same goes for new industries in coastal areas, land reclamation, construction activities etc. However, the CRZ is not applicable everywhere and frequently, coral reefs appear to be unprotected. (Panini, Hoon et al., 1997)

Economic feasibility
Costs are different for every project and location. Therefore, the costs should be checked site specifically. Specific material costs for the use in rural areas, are probably much higher than if these materials are used in close proximity to the production or manufacturing site. In addition, actions such as the use of coral larvae or nubbins are significantly more expensive than pruning branches or using small colonies for reef restoration (Epstein et al., 2001). Furthermore, ex-situ culturing of coral can be costly, followed by an in-situ nursery and cheapest: direct transplantation (Edwards & Gomez, 2007). According to Edwards and Gomez (2007) transplantation per ha costs between $2.000 - $13.000 (low cost) and $40.000 (high cost). Artificial reefs such as reefballs cost between $1 and $ 10 million per kilometre (Edwards & Gomez, 2007).

Keep in mind that expenses vary depending on the location and conditions of the project. When the procedure's efficiency (juvenile survival) or relative costs per developed colony are assessed, some pricey approaches turn out to be relatively cheaper. To present an indication of overall coral development methods, the accompanying table roughly illustrates initial expenses of active measures. See for explanation of coral development/enhancing methods: Section 3.3.2.

Method			Costs	Info
Active			High(++++)/Low(+)	Keep in mind that costs variate per project location and circumstances.
Transplantation/Relocation	Direct transplantation/relocation		+	Low costs, since actions are not difficult and no intermediate gardening phase is necessary. (Boström-Einarsson et al., 2018)
	With intermediate nursery phase (Coral gardening)	In-situ	++	Is done on regular basis and relative easy to execute. Still a costly process. (Edwards and Gomez, 2010; M. Y. Hein et al., 2020)
		Ex-situ	+++	Process of Ex-situ gardening is more expensive due to higher setup costs. (Edwards & Gomez, 2007)
	Micro fragmentation (Nubbins)		++++	Only when coral materials are limited and time for coral development is long. Long mariculture period and difficult techniques make this a costly procedure. (Boström-Einarsson et al., 2018; Epstein et al., 2001)
Larval propagation	Industrial scale		++++	Project costs are in general high but costs per colony are low. Is a viable option if receptor area is large and time of spawning is known. (Doropoulos, Elzinga et al., 2019; Doropoulos, Vons et al., 2019)
	Juvenile scale (reefguard)		+++	More labour is needed. But relative costs per colony are lower than for regular transplantation techniques. (van Koningsveld et al., 2017)
	Small scale		+	Easy performable actions, no ex-situ or in-situ techniques are used but time of spawning should be known in advance. (Barton et al., 2017)
Substrate enhancement	Substrate addition		++++	Artificial reefs: expensive to design and deploy but when integrated in the design of a marine work; costs would be relative low. (M. Y. Hein et al., 2020; Boström-Einarsson et al., 2018)
	Substrate stabilisation		++	Expensive, since actions are not performed on large scales. (Edwards and Gomez, 2007; M. Y. Hein et al., 2020; Boström-Einarsson et al., 2018)

Table 2.5: Costs of active coral developing methods (Boström-Einarsson et al., 2018; Boström-Einarsson et al., 2020; Omori and Iwao, 2014; Epstein et al., 2001; Barton et al., 2017; Edwards and Gomez, 2007; Edwards and Gomez, 2010; Boström-Einarsson et al., 2020; M. Y. Hein et al., 2020; Doropoulos, Elzinga et al., 2019; Doropoulos, Vons et al., 2019; van Koningsveld et al., 2017)

The costs of other active measures, such as the use of extra substratum or design alterations, depend on different factors as material, location, complexity etc. Passive actions are generally less expensive than active actions, since these actions require less labour, technologies and personnel and require more strategies implemented through management (Fox et al., 2019). Actions such as limiting fishing or conducting water quality measurements belong to 'passive' measures.

Environmental feasibility
This considers the health factors of certain measures relevant to human health and the environment. Environmentally friendly actions, such as using rocks that are locally produced, decrease transport activities and leave a smaller environmental footprint. Therefore, these could be scored with a "one".

2.9.3. Effectiveness
The aim is to be as effective as possible. However, this depends on the location, action or circumstance. The effectiveness of a measure is provided through this report. Additional measures could be assessed, but this would require extensive additional research. The effectiveness per measure is positive, neutral or negative (Figure 2.11).

2.10. Clarification of Step 5 - Summary of sustainable design recommendations
This step concludes the main systematic method by summarizing recommendations for potential measures to stimulate coral development and creating the highest value for local coral ecosystems including the new designed marine infrastructure. A graphic representation of the new design can eventually be added. The 'sustainable' design recommendations should better be monitored constantly starting with the execution phase, the completion and the usage phase. No further details are provided, since this is outside the scope of this project. If problems or questions arise after step 5, the location analysis (step 2) can be reassessed.

2.11. Conclusion
In Chapter 3 and Chapter 4, information was provided to determine the values of a coral reef ecosystem and to consider possible types of marine infrastructure together with how they affect coral ecosystems. This chapter describes a systematic method on how to determine the values considered in the previous chapters and how to implement this knowledge towards coral value increase. A systematic method is composed to simplify and illustrate steps needed for stakeholders without knowledge of coral ecosystems. Ecologists and civil engineers are frequently opposed on marine infrastructure implementation. This method provides guidance within this conflict by taking all factors into account which could affect,

and which could promote coral development. This integrative approach aims to improve cooperation between stakeholders with different backgrounds in the same work field. Guidance is provided by dividing this method in 5 steps. Step 1 describes the project shortly to become familiar with the location, the problem, design requirements and the initial concept of this design. Step 2 guides the reader with the location analysis through the natural and anthropogenic system. The value of the local coral ecosystem is defined and potential threats to corals induced by humans or nature emerge. Measures are suggested to counteract or to enhance coral value. Step 3 analyses the design applications. The type of marine infrastructure and elements that could affect corals are studied. Actions to potentially transform the structure are appointed. Step 4 shortens the possible measures towards feasible and effective recommendations for a specific case. Active coral propagation is an option when the anthropogenic system allows and/or when larval supply is limited. However coral development should be possible on location which is checked by an analysis of the natural system. Passive coral development methods are easy to implement and less expensive than active methods. Step 5 summarizes the information by concluding towards new sustainable design recommendations. Each step is developed in such a way that it can be handled by all parties concerned. Each project, and every location is unique. Therefore, every single project should be treated separately with the assistance of this systematic method, the involvement of environmental parties and the engineering firm.

3
Approach for coral to use in the systematic method

This chapter elaborates methodological step 2. The aim is to identify coral reefs in order to gain knowledge to use in the systematic method. This is done by making an inventory of coral reefs. Typical coral reef types and values of local coral ecosystems are described. In addition, criteria that define values of local coral ecosystems are discussed together with possible positive and negative influences on coral ecosystems. In conclusion, a quantification of coral ecosystems is provided to understand and describe the health of a local coral ecosystem.

The purpose of this chapter is to provide the user of the method with recommendations for coral development to create an optimal environment for coral. This is done by providing understanding of factors influencing coral development and means of understanding the quality of a coral reef.

3.1. Coral reef systems approach

3.1.1. The need for a systematic approach

This section covers a systems approach for coral reefs in order to map out the possible causes of coral degeneration and possibilities to improve coral growth. A systematic approach is needed, because:

- Plenty of different coral species with each specific characteristics are living in the oceans, which makes coral identification complex (Humann & Deloach, 2013).
- Coral species characteristics are dependent on water quality, morphological and biotic factors, with the location acting as the main driver (Wooldridge and Done, 2009; Wooldridge, 2009; Erftemeijer et al., 2003; Spieler et al., 2001; Fabricius, 2005; Venera-Ponton et al., 2011; Anton et al., 2014; McCook et al., 2001; J. Bell and Galzin, 1984). These factors should be included in the approach, since these diverse factors are contributing to the health of coral reefs.
- These three 'main' factors are subdivided into parameters which should be translated towards species specific threshold values, in order to obtain tolerance values per species. This is necessary to deal with the local conditions and allow for tailor-made marine infrastructure in coral habitats.
- In addition, coral experience consequences of impacts by human factors, which is another element that should be included in the plan of approach (Naughton and Jokiel, 2001; Lindeboom, 2017).
- To keep details manageable, subdivision in different sections is necessary. Therefore, a categorisation should be made. When coral is considered as a system, all underlying factors that influence coral can be structured. Hereafter, questions as the following can be answered:
  - Why is coral not observed in an area where coral development could be possible
  - What are the reasons for coral mortality
  - What are the reasons for hampering of coral development

– Why does a location face healthy coral development

Categorization of coral reef systems should provide guidance and provoke as little discussion as possible. Sometimes, coral reef categorization is based on differences in coral reef morphology (Rioja-Nieto & Álvarez-Filip, 2019). This geo-morphological mapping, is explained in Section 2.3.3. However, this categorization does not sufficiently meet the categorization that will be required for this research since corals are not only dependent on reef structure for their survival. For the implementation of infra works in coral ecosystems, categorisation based on coral ecosystem services (Section 2.3.7) in combination with natural components is preferable. As explained in the introduction, in making the choice for mitigation and alteration in an area, the combination of elements and measures should be chosen which results in the highest profitability for the environment, cost-benefits and sociological aspects. Therefore, a layered approach is needed, consisting of a natural system and an anthropogenic system (Van der Weide et al., 1993; Koningsveld, 2004).

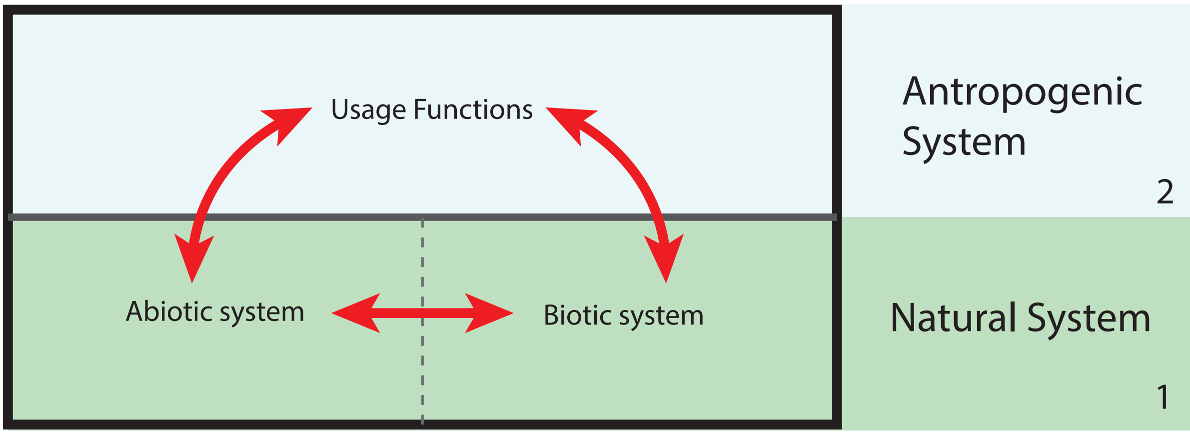

Figure 3.1: Layered system approach (made in adobe illustrator)

The first layer, is the natural system and consists of abiotic and biotic components (Figure 3.1). The second layer covers the anthropogenic system, which includes user functions that (in)directly affect coral reefs and usage functions that profit from coral reefs. The rectangular shaped sketch from Figure 3.1, provides oversight of the different systems and indicates that the systems are equal (based on effects and consequences on corals) but are interacting with one another. For example, (over)fertilization for agricultural purposes, could lead to increased nutrients ending up in coral waters by run-off (Fabricius, 2005). Increased nutrient values (increased abiotic parameter), can lead to decreased coral health (paragraph 3.2.1.1). Decreased coral health influences usage functions of coral reefs as food provisioning, since unhealthy coral reefs frequently provide less shelter or food for fish (paragraph 3.2.2). This is an example of how the layered system approach connects with each component. Further explanation on how to approach this system is found in Chapter 2.

3.2. Natural system overview of coral reefs

The natural system includes all the non-living and living components of an ecosystem, indicated as 'Abiotic' and 'Biotic'. The abiotic and biotic factors are strongly related to each other, therefore they belong to the same 'Natural system' layer. For an overview of this natural system, check Figure A.2.

3.2.1. Abiotic system overview

Abiotic factors are components that do not exhibit life. However, these types of components influence habitat functions towards self-sustaining ecosystems (Levin and Dayton, 2009; Dasgupta, 2021). The abiotic system is further divided into water quality factors and morphological factors to make a distinction within abiotic components. In this way, measures could resolve abiotic issues which are not beneficial or could become beneficial for coral species. All abiotic factors are based on measurements with a corresponding literature check.

Water quality factors
This section discusses the factors that can alter the hydrologic 'cycle', thereby possibly impacting coral development. Successful settlement of new coral recruits but also their growth rates and propagation rates depend on environmental factors (Fabricius, 2005; Glynn, 1993; Wooldridge and Done, 2009; Crabbe, 2008; Wooldridge, 2009). The following is a list of abiotic water quality factors that could influence coral development (Erftemeijer et al., 2004; Kuyper, 1991; Inniss et al., 2016):

- Temperature
- Salinity
- Suspended Sediment Concentration (SSC)
- Nutrients
- PH

As explained in Section 2.3.2.2, these parameters are equivalent to coral mortality, growth and recruitment. An important note needs to be made. Difference exists between thresholds and triggers. Thresholds are maximum levels coral can tolerate before impacts become apparent. Triggers are early warning levels that are set below threshold levels for the management of ,for example, dredging plumes. Because each site is unique, it is critical to use the water quality factors exclusively on a location-specific basis. Threshold levels from one part of the world cannot be applied in another part. Thresholds tend to be site- and species- specific, and are ideally based on available scientific literature on local species and studies. (P. Erftemeijer, personal communication, August 20, 2021; Brainard et al., 2011; Li et al., 2008). Hence, site- and species-specific research is needed to come up with solutions for the implementation of infrastructure projects. Literature provides average coral threshold values and its spatial variability or diversity. This does not entirely indicate that coral recruitment is or is not possible in a specific area, since coral development is also dependent on other factors which are further elaborated in this chapter and Chapter 2. When site selection is being executed, local, site- and species-specific data is needed, which will be based on local measurements (data gathering) and scientific literature on local species to come up with correct threshold values.

The water quality parameters, which can be sensitive to corals, are explained below.

- Temperature

  In general, sea water temperatures should not out step the range of a coral species temperature threshold (Glynn, 1993; Henkel, 2010). Elevated (2 °C) temperatures could lead to bleaching (Glynn, 1993), slowing coral development (Cantin et al., 2010) and increasing likelihood of disease outbreaks (Bruno et al., 2007). Exceeding thermal tolerance for days to weeks could already lead to coral bleaching and mortality of entire coral ecosystems (Crabbe, 2008; T. Oliver and Palumbi, 2011). Coral responses due to sea water temperature change can nowadays be checked since near-real-time satellite based information on sea surface temperatures (SST) is available (Liu et al., 2006). NOAA provides notable features and alert where terminal stress reaches pre-defined levels (NOAA, 2021). As explained in Section 2.3.2.2, zooxanthellae are responsible for the development of calcium carbonate (coral) structures. Per coral species and location, optimal temperature values and growth range differ. As an example, the growth rate (by weight) of the species *Acropora palmata* is provided versus the rate of temperature change in Figure 3.2.

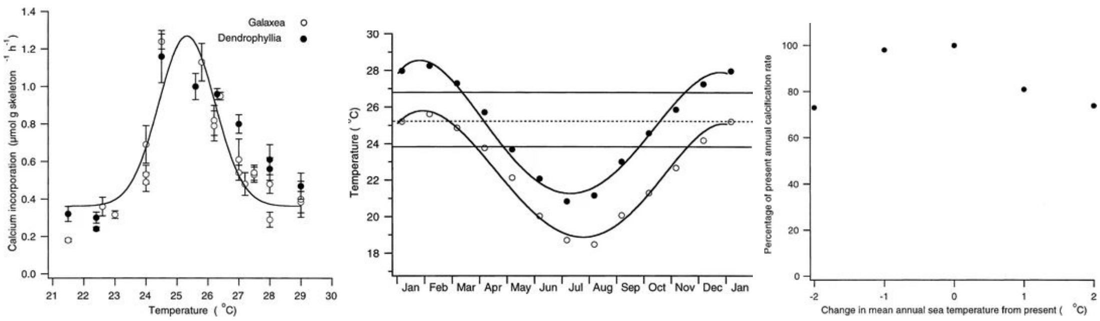

Figure 3.2: According to the Gaussian curve (left figure) that is fitted through the *Galazea fascicularis* species data (zooxanthellate coral), dependency of calcification rate (calcium incorporation per unit mass of skeleton) versus the temperature rate is observed. In the middle graph, monthly average sea temperatures were measured in the harbour of Heron Reef in the Great Barrier Reef. These first two figures, provide an index of annual calcification rate for increases and decreases of all mean monthly sea temperatures and results in the right graph. This graph shows the change in mean annual sea temperature from the present situation in Heron Reef, for the *Galaxea fascicularis* species (x-axis). Change to higher temperatures tend to directly decrease in percentage of calcification rate. Change towards lower than the present mean annual sea surface temperature leads also towards lower calcification rates for *Galaxea fascicularis*. (Marshall & Clode, 2004)

What is trying to be explained by Figure 3.2 is that the rate in temperature is related to the calcification rate which is a measure for coral development in growth, mass and density (Marshall and Clode, 2004; Crabbe, 2008; Bak, 1976; Kružić et al., 2012). According to this literature is the rate in which coral develops on behalf of temperature change, dependent on a coral species. Bak (1976) and Crabbe (2008) demonstrate that within a temperature range of a *Acropora palmata* species in Curaçao, this species could also respond to temperature change and could potentially benefit from higher temperatures within their temperature tolerance values. Temperature and coral growth therefore tends to be related.

Maximum and minimum species specific temperature threshold values should indicate if the coral occurring in an area, is or is not challenged by temperature values exceeding these threshold values. When temperature change falls outside the tolerable values, this region is not likely suitable for coral development of this specific species. This can be observed in the left image of Figure 3.2. *Galazea fascicularis* thrives best in temperatures between 24.5 and 26 °C, however the tolerance values of this species roughly demonstrate to fall between 23 and 27 °C.

The following are possible strategies that could assist corals to overcome heat disturbances (West & Salm, 2003):

- Use natural occurring coral species in the area for coral propagation (rearing, transplanting, seeding etc.) that demonstrate high thermo-related tolerance to bleaching or mortality (high resistance).
- Use local species for coral propagation that recovered from elevated temperature values (resilience).
- Reduce other stresses and increase recruitment space to improve coral healing capability. Improve connectivity with adjacent reefs for natural recolonization.
- Legal regulation of activities (Riegl et al., 2009).
- Relocate bleached coral species to cooler waters, if a decrease in SST is not expected and when thermo tolerance values are transcended.

• Salinity

Well functioning corals commonly live in salinity levels between 32 and 40 ‰(Henkel, 2010). Transcending coral salinity tolerances can influence coral habitat and especially the metabolism of corals. Literature reveals that corals in general have low tolerance to salinity fluctuations (Muthiga & Szmant, 1987). Salinity values could decrease by freshwater inflow due to floods and increase by droughts due to evaporation.
Gegner et al. (2017) conducted research of salinity value influences on the coral species: *Aiptasia*.

In this case, high salinity values lead to increased thermo-tolerance within corals. So, for some species in high saline environments, tolerance or heat resistance increases (Gegner et al., 2017). This should still not indicate that exceeding of salinity tolerance limits is always possible, since this can lead to sub-lethal changes in coral reef metabolism (Coles & Jokiel, 2018). Therefore it is important to identify the tolerance values of a coral species and the salinity values in a location. When non fluctuating salinity values are observed, and the values stay within threshold boundaries, the area is mostly suitable for coral development.

Erftemeijer et al. (2003) and Kuyper (1991) mention the following overall salinity levels for coral development:
Salinity > 50 ppt: Unsuitable
Salinity 46 - 50 ppt: moderate
Salinity < 46 ppt: Optimal

However, these values could differ per site and species but provide an indication of coral states within salinity levels.

In the case that salinity values are exceeding coral tolerant limits, recommendations are:

- enhancing (fresh) water circulation in the area if high saline waters and low circulation patterns are observed and
- use locally occurring resilient or resistant coral species to high salinity values for coral development methods. (Coles & Jokiel, 2018)

• Suspended sediment concentration

Another important characteristic is the suspended sediment concentration (SSC). Suspended sediment concentrations to an increased extent, commonly limit light intrusion and therefore photosynthesis by zooxanthellae. This can reduce coral development due to potential lowered carbon reception and calcification rate which causes reduction of the tissue thickness (C. S. Rogers, 1979; Telesnicki and Goldberg, 1995; Anthony and Hoegh-Guldberg, 2003). Raised suspended solid values frequently have a negative impact on the primary coral development stage. This stage includes fertilisation, larval development and settlement (Humphrey et al., 2008; Gilmour, 1999; Ricardo et al., 2016). One of the reasons can be the decrease in fertilization success. The sediment and sperm will then become entangled and will therefore not become available as proper larvae. A longer exposure tends to lead to lower larvae settlement (Ricardo et al., 2015). Rogers found out that excessive sedimentation with an average SSC above 10 mg/l, affects the function and structure of coral reef ecosystems in general (C. S. Rogers, 1990; Nemeth and Nowlis, 2001; Kuyper, 1991). Coral species diversity and the coral cover growth rate could decline, caused by long term attenuation of light availability. Still, it is important to remember that all coral species react differently to sediment concentrations and should therefore be studied individually (species specific). When beaches are formed naturally, this will generally not cause any trouble for the living environment of corals. When extra sediment is supplied (beach nourishment), this extra amount of sand will be transported due to hydrodynamic processes towards coral reefs and therefore can increase SSC values in this area. Coral larvae is unlikely to attach to sand but need 'hard' substrate to settle. (Meesters et al., 2019; Edwards and Clark, 1999; Clark and Edwards, 1994; Spieler et al., 2001; Oren and Benayahu, 1997) Other factors that contribute to elevated SSC values are human interventions such as dredging activities, mass movements, erosion during and after construction and increased runoff. Or natural changes as landslides, increased runoff through more intense rain events due to climate change and increased erosion through cattle and grazers. (Meesters et al., 2019)

According to studies such as McClanahan and Obura (1997), coral areas exposed to high sediment concentrations are commonly monopolized by sediment tolerant species over time, whereas low sediment concentrations are frequently observed by species with low sediment tolerance. SSC values can be obtained by turbidity measure devises.

  - To enhance coral development, local resilient or resistant coral species can possibly be used for coral development methods.
  - If SSC concentrations are elevated through dredging works, the source can be tried to tackle as described in Laboyrie et al. (2018).
  - Another possibilities is when SSC values are not constant and fluctuating; find the source and implement e.g. erosion mitigation measures (Meesters et al., 2019).

- Nutrients

  Nutrients is one of the other water quality parameters that has an effect on coral ecosystems. Water quality is likely to shift due to its dynamic behaviour induced by environmental components (Houk et al., 2020). This makes it difficult to set an exact threshold for nutrients in coral environments. Dissolved Inorganic Nitrogen (DIN) is one of the nutrient components that is essential for all living creatures. A balanced supply of nitrogen is favourable for corals to develop. Increasing DIN values result in coral growth limitations (Pupier et al., 2021). An elevated amount of DIN, which is mainly caused by human activities such as waste water outlets and agricultural induced runoff (D. Baker et al., 2013), can lead to reef degradation in terms of increased algal development which attenuates light intrusion and can result in anoxic marine environments (eutrophication) (Bricker et al., 2008). Algae (seaweeds) tend to flourish under these nutritious circumstances, where they compete against corals for space opportunities (Meesters et al., 2019). The same goes for Phosphorus which can have consequences for photosynthesis activities of zooxantallae (Houk et al., 2020) and therefore contribute to marine eutrophication. Exposing corals to increased DIN values, tends to result in lower thermo-tolerance of coral species (Wooldridge & Done, 2009). Therefore, corals will likely become more sensitive to bleaching. Wooldridge and Done (2009) explain this by using Figure 3.3. An increased runoff risk leads to higher coral bleaching probability in the area that is indicated as 'low resistance to thermal stress'. Moving over to the graph in this figure, illustrates a similar but elevated and steeper trend for higher coral bleaching probabilities (red line) compared to a linear increase in SST values than for lower coral bleaching probabilities (green line) (Wooldridge, 2009). Therefore, the runoff risk and thus the risk of nutrient inflow in coastal waters, is related to the bleaching probability (Cortés & Risk, 1985). 0.1 - 0.15 mg/l is noted as an overall benchmark for DIN values to protect corals against poor water quality but remains species dependent (Houk et al., 2020).

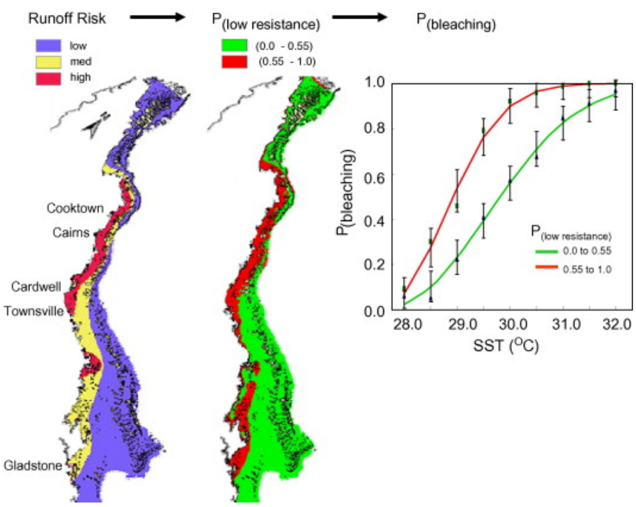

Figure 3.3: Probability of bleaching resistance for sea surface temperature increase and runoff risk (Wooldridge, 2009).

What can be done to avoid nutrient overloads in coastal regions? To overcome this, the source of the problem should be found. For Saba; land degradation together with steep coastal slopes, lead to leaching of nutrients plus other organic and sandy materials (Meesters et al., 2019). Meesters et al. (2019) implies that on this Dutch Caribbean island, the increasing need and dependence on import of goods and food is one of the underlying causes. The solution can be found in waste management, increasing the capacity to store (rain) water to prevent runoff, and decrease erosion and sedimentation. As a summary and to name possible recommendations, the following list is applicable (Adapted from Meesters et al., 2019):

- Waste management
- Water storage capacity increase. This can be done by building catchments, reforestation projects, digging channels etc.
- stimulate a more circular economy by localising food production and other circular ideas.
- Anti erosion measures: e.g. Replant vegetation to decrease the likelihood of erosion and sedimentation, Fence stray cattle.
- Restore or build ecosystem relations. Mangrove forests could stop e.g. nutrients due to their filtration capacity.
- Construct dams to hinder water runoff.
- Reduce sewage dumping in coral areas.
- A long term policy, focused on sustainability, should be realised.
- Improve regulations and enforcement.
- Raise awareness through education.

The above- mentioned measures can be applicable for the Dutch Caribbean islands and could also assist in reducing nutrient runoff at other locations. The causes of increased nutrient values should however be checked for every location separately. Per cause, tailored measures can help decreasing the nutrient overload.

- pH (Acidification)

Ongoing carbon dioxide (CO_2) addition to the atmosphere, leads to elevated sea water temperatures and lowering oceanic acidic pH values as can be seen in Figure 3.4 (Wooldridge and Done, 2009; McCulloch et al., 2012; Meron et al., 2011; Pelejero et al., 2005). Atmospheric carbon dioxide is increased by human activities over the years and therefore more carbon dioxide is dissolved in the sea, which results in a more acid marine environment (Meron et al., 2011). Lowered pH values can lead to reduction of calcification rates (Marubini and Atkinson, 1999; Meron et al., 2011). This potentially affects the calcium carbonate structure where corals are made from (Meron et al., 2011). This means that these structures could dissolve over time. A comparison has been made that the calcification rate decrease has larger effects than nutrient value increase on coral health and recovery over time (Marubini & Atkinson, 1999). For pH value fluctuations within an area, currents and flow patterns are among the main causes (Pelejero et al., 2005). Limited flushing likely has influence on coral habitats and for altered PH values, these flow patterns should be mapped (Pelejero et al., 2005).

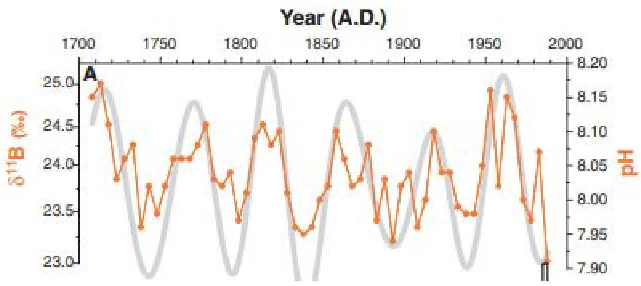

Figure 3.4: Oceanic PH values over the years. Towards present time, a decrease in PH value is observed. This is likely caused by an increase in atmospheric co2 rate (Pelejero et al., 2005)

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Possible actions for altered pH values are (Kennedy et al., 2013):

- Enhance water circulation in the area when low water circulation is observed.
- Local management (fisheries, recreational)

Conclusion - water quality factors
Once again, values that are mentioned above are species dependent and could differ per site specifically. Still, the thresholds found in literature or according to measurements should be taken into account in order to determine if coral species can survive within an area.
All above mentioned abiotic components are values that can be measured. To create a 'baseline', the abiotic components should be measured and examined to not transcend coral thresholds.

The following steps can possibly be taken if one of the thresholds is or will be transcended:

- Local management to minimise stresses, including legal regulation of activities and introduction of e.g. fishing limits, diving limits etc.
- Focus on species which are growing on the location and are healthy and thus are resilient to local circumstances. These species can be used for propagation techniques.

Morphological factors
Within coral ecosystems, morphological factors can also play a role (Spieler et al., 2001). Coastal morphology are processes that influence shapes and structures of coastal regions (C. J. Hein & Ashton, 2020). These processes can trigger baseline abiotic parameters and therefore coral ecosystems. In this subsection, the events that could possibly cause disturbances on coral reefs are discussed.

- Hydrodynamics
- Hurricane risk
- Substrate
- Bathymetry (Depth)

- Hydrodynamics

  The specific location of coral tends to be important for coral development (Spieler et al., 2001; A. Hylkema, personal communication, June 29, 2021). Therefore, also the wave and current interaction should be taken into account (Baynes & Szmant, 1989). Thin and tall formed corals, commonly experience more hindrance from larger wave actions and currents than smaller, rocky corals with few branches (Tunnicliffe, 1982). Tunnicliffe (1982) explains that the inertial and drag forces induced by moving water, can cause stress on coral reefs. Research from Forsman et al. (2012) about water motion on coral farming demonstrates a significant lower overall coral growth rate for a constant water motion of 11 cm/s compared to 4 cm/s. This should not be taken as a threshold, since these numbers are not fully specified.

  In other words, the water motion on reefs tends to have implications on coral growth rates. This statement is supported by laboratory research executed by Riegl et al. (2009). Riegl et al. (2009) refers to metabolic response of corals to water motion changes which alter photosynthesis and calcification rates. The same tends to be the case for the surface area of coral reefs with different flow regimes (Schutter et al., 2010). A test is executed for the coral: *Galaxea fascicularis*, making use of nubbins (Figure 3.5). Increases in buoyant weight and surface area from this coral species is observed during higher flow velocities. However, growth in surface area is not as continuous due to the "burst" type of development. This coral species first forms tissue around the coral, before dilation while skeletal growth is a continuous process. Concluding, the flow rate has been demonstrated to have an impact on coral development.

  Excessive wave stress can cause coral damage but (wave driven) water flows can promote circulation patterns that stimulate water refreshment and maintain lower temperatures, since waves are frequently cleaning corals passively. (J. S. Rogers et al., 2016; Pickering and Whitmarsh, 1997; T. Brink, personal communication, September 15, 2021). Per species the favourable current, wave actions and tidal fluctuations differ and should be investigated individually. Johansen (2014) quantified current velocities in Lizard Island (Great Barrier Reef) on a 'healthy' coral reef. He found out that tidal currents rarely exceed 0.055 m/s, while a tidal current below 0.25 m/s is highly unsuitable for corals according to Erftemeijer et al. (2003) in the Bahrain case. Therefore,

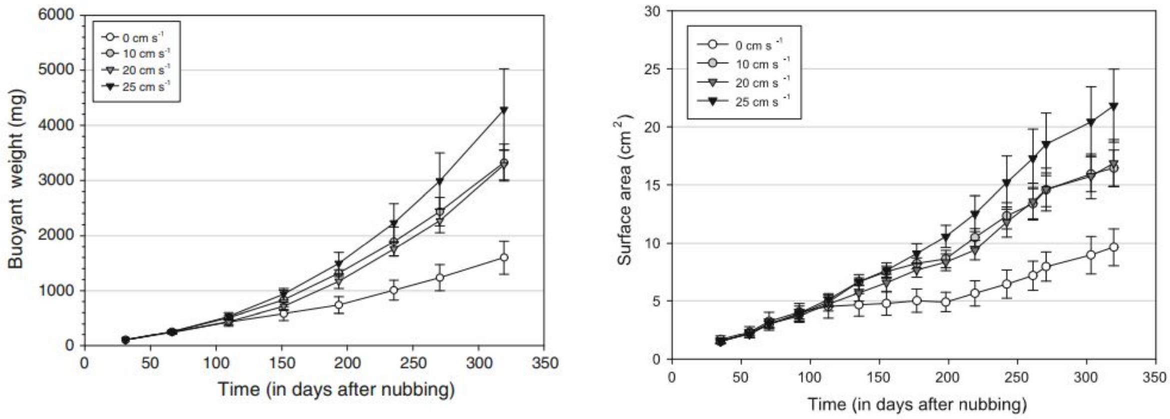

Figure 3.5: flow patterns of coral species Galaxea fascicularis during the experimental period. On the left the buoyant weight and on the right the surface area. This experiment is done with coral nubbins (micro fragments) and is therefore different than for other coral materials as coral colonies, fragments etc. (Schutter et al., 2010).

every coral species type benefit from different current values. However, if the average (tidal) current speed in an area changes, regarding to 'old' (tidal) current speed values in the same area, this could lead to change in coral development. Wave forcing on a stony coral is displayed in the following image:

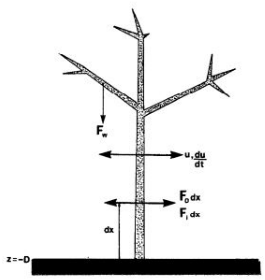

Figure 3.6: Wave interaction on a stony coral. F_w Downward weight force, F_D Drag force, F_1 Intertidal force, U Velocity of water, Z = Depth from water surface, D = Depth (Tunnicliffe, 1982)

.

According to literature, marine infrastructure orientated perpendicular towards the prevailing current direction could be beneficial, due to nutrition supply from organic and planktonic elements (Mathews, 1981). Currents potentially assist in bringing these nutritious elements and larvae towards corals (Pickering & Whitmarsh, 1997) and nourish corals better when flowing perpendicularly towards the axis of the marine infrastructure (Mathews, 1981; Aska, 1981). More investigation on this topic is needed and cannot be fully substantiated with literature. However, literature introduces the waste removal capability, enhancement of recruitment and decreased sedimentation due to steady currents and water circulation in reefs (Baynes and Szmant, 1989; Pickering and Whitmarsh, 1997; Erftemeijer et al., 2004) which can lead to higher species diversity and coral cover (Baynes & Szmant, 1989). Hence, to sustain a healthy coral reef, a steady current should be present for supplying nutrients, CO_2, oxygen and food (Erftemeijer et al., 2004; Pickering and Whitmarsh, 1997). Lower water particle velocities and currents frequently lead to sedimentation and smothering, abrasion and reducing of the functionality of reef systems (Pickering & Whitmarsh, 1997). However, when water velocities are high, probability of: corals detaching from substrate increases, food supply is limited and larval settlement is reduced (Baynes & Szmant, 1989). To sustain a healthy reef, the current velocity should stay ideally underneath 1.5 knots or 0.75 m/s (Tseng et al., 2001; Grigg, 1965; Erftemeijer et al., 2003). Site and species variations are possible but to provide an indication; water currents above 1.5 knots should ideally be specified as relatively strong currents and should be avoided (Grigg, 1965).

Extreme water forces or currents, could be stopped by the implementation of artificial structures. This infrastructure could potentially decrease wave and current actions. It is highly recommended to build an artificial reef according to the approach presented during this study. Monitoring of the hydrological parameters before and after implementation of an infrastructure project, remains necessary. Consider resilience of individual species against strong/weak currents.

- Hurricane risk

  A hurricane risk system is a system that is regularly ravaged by hurricanes. Hurricanes could destroy coral ecosystems through their size, velocity and randomly occurrence (Gardner et al., 2005). Hurricanes are formed due to a certain difference between air and water temperature (Gray, 1979). The warm air from the sea surface moves up due to lower air pressure below. High air pressure replaces the ’old’ air but becomes moist and moves up too. This spinning systems continues in the formation of a hurricane (See Figure 3.7) (Palmen, 1948) with powerful storm waves as a consequence. According to Wilkinson and Souter (2008), powerful storm waves may result in significant coral reef damage. Another note that needs to be made, is that cooling surface waters can be a side effect of the occurrence of a hurricane, which could be a remedy against coral bleaching (Wilkinson & Souter, 2008). Hurricanes are divided into categories 1 to 5, as indicated in Figure 3.8. From category 3, impacts on coral reefs are severe (Wilkinson & Souter, 2008). Therefore, if a category 3-5 hurricane occurs, the region can be labelled as a hurricane risk system.

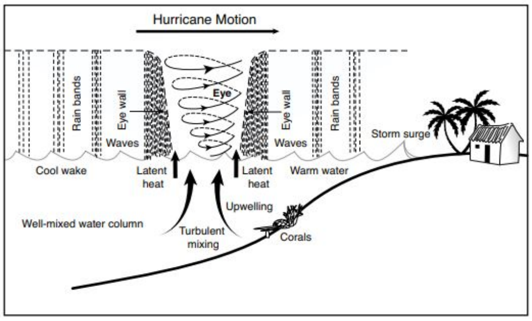

Figure 3.7: The forming of a hurricane (Wilkinson & Souter, 2008)

Hurricane Category	Impacts
1	Wind 64-82 knots, storm surge 1.0-1.6 m, no real damage to building structures, damage to trees
2	Wind 83-95 knots, storm surge 1.7-2.5 m, some roofing and window damage, considerable damage to trees
3	Wind 96-113 knots, storm surge 2.6-3.8 m, some building damage, large trees blown down
4	Wind 114-135 knots, storm surge 3.9-5.5 m, complete removal of some roofs, extensive window damage, most trees blown down
5	Wind 136+ knots, buildings fall over, storm surge 5.6+ m, widespread loss of roofs, some buildings destroyed, all trees blown down

Figure 3.8: Hurricane categories (Wilkinson & Souter, 2008)

Hurricane waves can potentially affect all parts of reefs. Solidly built corals, such as the stony *Porites spp.*, will likely be less vulnerable to hurricane waves than coral that is more fragile (e.g. *Acropora spp.*) (Wilkinson & Souter, 2008). Corals can be dislodged and coral branches can be ripped off by strong wave actions and spread over a larger area, where they sometimes regrow again (Wilkinson & Souter, 2008). In many cases, coral recovers quickly. However, it should be said that these coral reefs typically have little variety in species and ages. In hurricane risk systems, relatively young coral is present which is able to regrow rapidly, restoring the ecosystem values it once had before a hurricane arrived. In deep water areas, hurricanes tend to cause less damage since wave action is lower. Another negative aspect next to damaging coral reefs, is that hurricanes could cause enhanced nutrient runoff from land to sea which causes eutrophication and therefore increased algae growth. (Kimani, personal communication, June 25, 2021)

Hurricanes could possibly reduce invasive algae species that are in space competition with corals (Lapointe et al., 2006). Invasive species are less used to local circumstances compared to native species. A ’reset’ may be beneficial for coral development. However, this is not fully proven and needs more research to verify. For example, hurricane Gilbert in 1988 damaged algae and corals in Jamaica. Algae rapidly developed after the hurricane but corals did not (Talbot & Wilkinson, 2001). Something to keep in mind, is that everything depends on the starting point of human/nature intervention. An unhealthy or degraded reef is less likely to fully restore after a hurricane has passed, while a healthy reef is more likely to recover. Therefore, it should be said that if hurricanes occur, corals should be resilient enough to retain its value.

Possible measure recommendations for a hurricane risk system:

- Implement enough and suitable substrate for faster recovery and use niches for extra protection.
- Use fast growing (native) species for coral propagation techniques.
- Enhance substratum by the use of adding artificial structures.
- Substratum stabilisation

- Substrate

  Rubble and hard substrate areas are possible locations for corals to grow on (Spalding et al., 2001; Vermeij, 2006; Tomascik, 1991; Creed and De Paula, 2007; Harriott and Fisk, 1987; Fitzhardinge and Bailey-Brock, 1989). Sandy soils function less frequently as a substrate since sand is easily moved or disturbed. When sediment transport is a more common phenomenon in an area, zooxanthellae will frequently be covered with sand and will therefore probably not receive enough sunlight to survive. In systems with much substrate, larvae can more easily find a place to settle. The substrate is then able to provide enough shelter and provides a useful base to grow on (Sherman et al., 2002). This can be the result of different factors. Factors which could cause limited substrate or limited recruitment are: the use of explosives for fishing, erosion of areas or just areas where there is not enough hard/rubble substrate (sandy beaches). Usual substrates are skeletons from calcium carbonate, which provide shelter and an efficient base to develop. Artificial reefs can be built from concrete but also jetties, breakwaters and sea-walls made from quarried granite or sandstone are providing coral ecosystems (Silva et al., 2016). In Luckhurst and Luckhurst, 1978 was demonstrated that the rugosity of the substrate has a strong relationship with species richness. It appears that increased surface area and increased base complexity, tends to provide shelter places that results in more diverse marine life present (Luckhurst and Luckhurst, 1978; Sherman et al., 2002). The complexity and surface area have a proportional relationship. An increase in complexity, leads to an increase in surface area (Holmes, 2008). A substrate limited system occurs when no or almost no substrate is present on location. Even though larval supply is abundant, larvae cannot settle since there is no appropriate base. Sandy coastal regions often have limited substrate available.

  Possible recommendations for substrate limited systems:

  - Implement more hard substratum
  - Use niches and varying rough surface
  - Create a large surface for recruitment
  - Make use of natural materials
  - when substrate quantity is low (disallowing larvae to settle), extra substrate needs to be built in the form of artificial reefs, modular structures and rocks etc. Marine infra is an opportunity to enlarge substrate.

- Bathymetry (Depth)

  Reefs are located in different aquatic ecosystem depths. Corals in shallow areas are more frequent reached by sunlight. This generates rapid coral growth. On the other hand, shallow reefs will probably be more affected by disturbances as hurricanes, climate change, human interventions etc. (Pereira et al., 2018). Corals can be found in a wide range of depths. Since the focus lies on nearshore coral reefs, corals appear in the euphotic zone (NOAA, National Oceanic and Atmospheric Administration, 2021c). The euphotic zone is the range in water column depth where photosynthesis is still possible (Lee et al., 2007). This implicates the growth of zooxanthellae and therefore the coral growth zone. The euphotic zone stops at 70 m water depth (NOAA, National Oceanic and Atmospheric Administration, 2021c). Every coral species favours different water depths. One needs more sunlight, while the other benefits from deeper waters, where wave impact is generally lower. The following websites are possibilities to use to check the depth limits per species: www.iucnredlist.org, animaldiversity.org, coraltraits.org. Commonly, > 10 m depth is enhancing coral development (Erftemeijer et al., 2003). A trend has been observed that the depth related to coral settlement (vertical zonation), tends to be more dependent on water quality parameters than on the hydrostatic pressure under water (Mundy and Babcock, 1998; Spieler et al., 2001).

Monitoring of the environment is necessary. Preventive erosion and subsidence measures could be implemented by the construction of marine infrastructure. Depth could also influences the construction type of marine infrastructure. For more shallow waters (<15 m), rubble mount structures are usually more used. For deeper waters, monolithic structures are easier to implement since less material is needed and stability is less an issue for monolithic structures (Research et al., 2007). Further elaboration on this subject, can be found in Chapter 4.

Conclusion - Morphological factors
The morphological factors need recommendations, depending on data of factors. Actions are dependent on flow velocities, chance of > 3 category hurricane's in the area and the availability of substrate in the region. The depth is not something that would hamper coral development since some species thrive in deeper waters while others prefer shallower waters.

3.2.2. Biotic system overview

The other part of the 'natural system' is the biotic side and involves living organisms. Living organisms interact with other living organisms, in forms of producers, consumers and decomposers (BBC, 2021) which maintains the food chain (Levin and Dayton, 2009; Dasgupta, 2021). Regarding coral reefs, biotic components are present in different types and sizes. Plants, fish, bacteria, coral polyps and algae as the zooxanthellea all are biotic components that contribute to coral ecosystems. A simplified version of the food chain, present in coral ecosystems, can be found in appendix Figure D.2.

Tropic levels	Function	Examples
Producers	Production of Energy, Nutrients by photosynthesis/chemosysnthesis	Corraline algae, seagrass, phytoplankton, seaweed
Primary consumers	depend on producers	Zooplankton, coral, sponges, queen conch, sea urchins, crabs, turtles, herbivore fish, invertebrate larvae
Secondary consumers	eat primary consumers	carnivorous fish as lobster, stingray, sea star, squid, whales,
Tertiary consumers	consume other carnivores (secondary consumers)	sharks, barracuda, dolphins, seals
Decomposers	break down of organic material and production of nutrients to close the life cycle	polychaete worm, bacteria, some crabs

Table 3.1: Food chain in coral reef ecosystems (Geographic, 2021)

All species belong to different tropic levels, have their own functions and contribute in a different way to preserve healthy coral ecosystems. The aim is to not disturb corals life cycle, but to enhance coral development together with infrastructure implementation. The list of biotic components is illustrated in Appendix C Figure A.2 and could become infinite. There are plenty of available biotic components which exclude, limit or cause coral development. Examples are coral predators (Rotjan & Lewis, 2008), algae (Venera-Ponton et al., 2011), sponges (Aerts, 1998), coral diseases (Humann & Deloach, 2013) and coral bleaching events (Hoegh-Guldberg, 1999). The focus of this research lies on biotic components and measures which are manageable by project initiators, engineers, managers and superintendents and are in accordance with other perspectives such as from marine biologists, ecologists, marine park rangers, etc. Therefore, the biotic components below are described for selection of inventory status. Underlying biotic components which are causing the main coral biotic events are dealt with in Appendix Section C.1. The main coral biotic components are:

- Coral coverage check
- Connectivity check
- Reef type
- Structure and size
- Coral species check
- Recruitment limited check

- **Coral coverage check**

  Coral coverage is a principle that demonstrates coral existence in an area. This indicates the coral reef health and is executed by a method with observations and/or measurements involved (Jokiel et al., 2015). According to Jokiel et al. (2015), a variety in methods is available and depends on the one requested. Factors that could be included; coral, algae, fish, invertebrates and rugosity (Jokiel et al., 2015). According to Weinberg et al. (1981), two prevailing questions regarding coral coverage should be asked:

  – What is concluded within the local ecosystem?; Species, coverage, density..

– Have occurring species a correlation with abiotic parameters?

The focus lies on mapping corals in a specific area. Other components such as algae and fish abundance could have consequences for coral coverage (J. E. Smith et al., 2006; Feary et al., 2007). However, focusing on coral - infrastructure interaction, tells us that methods with only coral coverage measures can better be included.

A coral coverage check should be performed at the footprint location (green field) and close surroundings. This is needed to exactly map coral health, which reveals if coral growth is observed and therefore possible in the area of interest. If so, this check provides an indication of possibility of coral development after implementation of a marine civil work. Protection measures for infrastructure implementation and coral propagation methods could then be executed.

First, the following methods for the coral coverage check are applicable according to Jokiel et al. (2015) and Weinberg et al. (1981):

1. Quadrat method
2. Random
3. Line transect (Point intercept - PIT)
4. Cramp Rat
5. Video transect
6. Towed diver
7. Photoquad (quadrat method with camera)
8. Estimate
9. NOAA ground truth

Jokiel et al. (2015) provides an extensive analysis of each method. He indicates how each method should be performed and what materials are needed. Assistance and advice for the application and execution for a suitable method should be asked for. Marine biologists, marine ecologists or marine park rangers could assist in this matter.

Quantification of coral coverage is done in and according to the method described in Section 3.4. Another quantification method is if the comparison of coral coverage to historical data in the same area would indicate if coral is degenerating or progressing over time. An undisturbed similar area without human interventions and activities is otherwise a sufficient location to compare the location of interest with to check whether coral in the area of interest is increasing or decreasing. This step is needed, because it indicates the behaviour of a reef and the vulnerability against human interventions and abiotic or biotic components. When coral coverage surpasses 40 per cent, it indicates a healthy coral reef (Gardner et al., 2003; Burke et al., 2011; Jackson et al., 2014).

When degenerating, low or no coral coverage is present, a small nursery is an option to check if the corals survive. This should be done during a period of a year with at the same time measuring and monitoring the abiotic components.

After such a period (year or longer), before the execution of marine infrastructure implementation, results of the testing ground should be gathered. When corals demonstrate positive development and when the anthropogenic system proves that active development of corals is necessary, asexual or sexual propagation methods can be applied. See therefore Section 3.3.2. The goal is to create a self sustaining reef mechanism (Burt et al., 2009; Maya et al., 2016) on or around marine infrastructure.

- **Connectivity check**

  Closely located coral ecosystems protect and have the ability to restore reef biodiversity from impacts generated by human activities and nature (Almany et al., 2009). The connectivity in coral reef ecosystems is also referred to as surrounding coral habitat and its implications. This includes the proximity to nearby reef systems that could act as potential sources for recruitment.

Larvae are transported passively via currents from reef generating coral larval systems towards downstream areas (Roberts, 1997). When the 'connection' between different coral reefs is low, recruitment will less likely be established (Roberts, 1997; Almany et al., 2009). Keep in mind that the larval supply commonly dependents on currents. If predominant currents from spawning reefs aim towards another direction, larvae will less likely reach the receptor site. Roberts (1997) explained that coral reefs with sufficient (upstream) connectivity, experience consequences of alterations occurring at other locations. This has implications on management strategies. If connectivity is strong, providing suitable substrate for coral recruits could be a solution. In this case, corals will passively develop when circumstances are sufficient. Implementing local management strategies for low connectivity areas can become useful. An example is low presence of coral reefs upstream of receptor reefs and therefore low larval supply. Low connectivity and therefore supply limited, is the cause of poor coral recovery (Roberts, 1997). while high connectivity promotes coral development through a larger fragment of total larvae reaching destination. (Almany et al., 2009). The further another reef system is distanced, the lower the connectivity (Almany et al., 2009).

As explained before, the connectivity is vital for coral reef protection, restoration and generation (Roberts, 1997). One of the negative effects of large, distanced coral surrounding habitat, is its low ability to restore from impacts. G. P. Jones et al. (2007) indicates that problems arise when spacing between reefs or reserves is increased. Connectivity decreases and disperse of larvae is less likely to reach another reef (see Figure 3.9. Therefore, passive coral development is not sufficient and coral recovery becomes low, which will lead to mortality of poorly connected coral reefs when no measures are applied (Roberts, 1997; Wagner et al., 2007). See Figure 3.9.

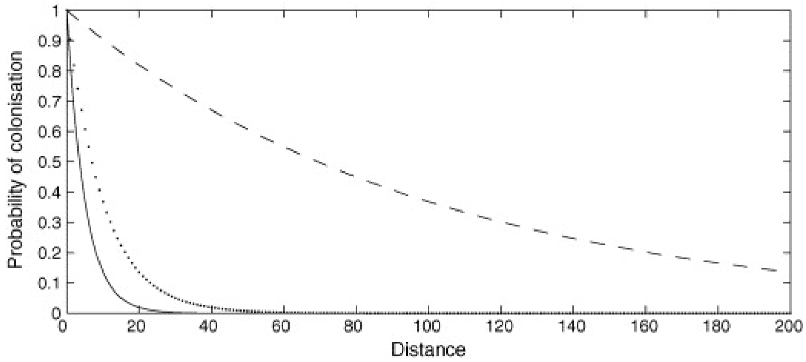

Figure 3.9: A study example of the probability of colonisation as a function of the distance (d) in km. According to: $e^{-\alpha d}$, with α 0.01 (solid), 0.1 (dots), 0.2 (dashed). This graph illustrates a decrease in colonisation probability during distant increase. (Wagner et al., 2007)

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According to Almany et al. (2009) larval recruitment is enhanced because of high connectivity (and larval supply). However, Fernandes et al. (2005) indicates that larger but fewer reefs/reserves are preferred over more and smaller reefs. For relatively large areas, the area can generally be better protected since more coral (larger metapopulation) is available to protect coral species within this network. Moreover, due to elevated metapopulation growth, species diversity frequently is enhanced. Coral species are less able to adapt to alterations in its surroundings when genetic diversity is decreased (Frankham, 2005).

Decreased spacing between reefs, could however lead to low natural variability of this area in terms of species diversity. The populations tend to become more correlated to each other and becomes therefore more susceptible to environmental risks (Almany et al., 2009). In addition, environmental risks occur in specific regions. If more reefs are available in this same region, the probability of impact on all these reefs is higher than if space between reefs would be increased (Almany et al., 2009; Wagner et al., 2007). Environmental risks are hurricanes, diseases, water pollution etc. This should be kept in mind for management implementations for enhancing coral reef surrounding habitats, since the aim will still be to become as connective as possible. In this manner, coral reefs become more resilient and have the ability to overcome disturbances. See Figure 3.10. (Roberts, 1997; Almany et al., 2009; Wagner et al., 2007).

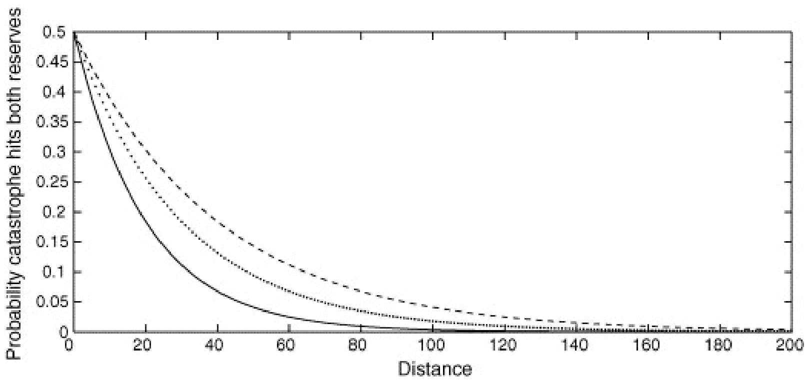

Figure 3.10: A study example of the probability that a lethal environmental effect hits both two reserves over a distance [km], with varying mean values. probability by: $r * e^{-d/\mu}$, μ: 20 (solid), 30 (dots), 40 (dashed) and r = 0.5. This graph illustrates that the probability of hitting two reserves due to an environmental risk, decreases over distance. (Wagner et al., 2007)

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With low connectivity; coral recovery, development and protection are likely to decrease. Low connectivity tends to make it difficult for coral to develop passively, since upstream supply from healthy larvae is needed. On the other hand, high connectivity tends to improve the resilience of coral reefs and can therefore overcome human or nature induced disturbances more easily. The biodiversity is therefore more easily maintained. (Roberts, 1997; Almany et al., 2009)

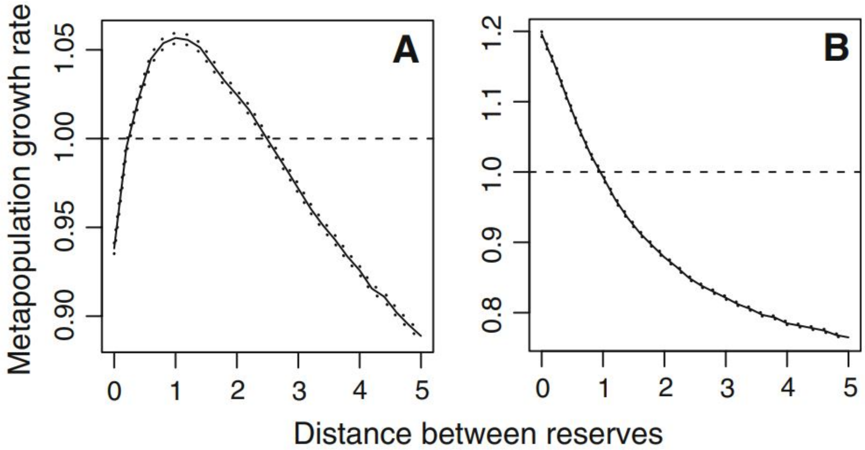

Figure 3.11: The metapopulation growth rate set against the distance between reefs/reserves in km. This figure illustrates spatial population dispersal of similar species within a reserve. Both A and B are in a similar situation. Area A demonstrates that for a shorter distance [km] between its reefs, environmental risks cause lower metapopulation growth. For an increased distance, environmental effects are less correlated but risk spreading stays small. For more distant reefs, the metapopulation declines over time due to low larvae dispersal. Between these two, the metapopulation growth is on its highest point. This is a compromise between environmental impacts and dispersal rate over the distance and is positively influenced by the connectivity. Graph B, illustrates an area where closer distant reefs promote metapopulation growth. The further away, dispersal success becomes less likely. (Almany et al., 2009).

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The conclusion of figure Figure 3.11, is that by comparing two identical spaced coral areas, coral development could differ. Environmental effects could play a role on closely spaced reefs but are for some areas not affecting other reefs spaced over the same distance. Larval dispersal tends to have influence on the distance between reserves (Wagner et al., 2007). A correlation between the two should be searched for.

For an increased connectivity, measures can be applied. Relatively low connectivity means low larval supply, high means sufficient larval supply that generates a self sustaining coral reef. A recruitment limited reef, is a possible example for low connected coral reefs upstream. The overview below includes the possible recommendations to take when connectivity is low or high.

Low

- Get an overview of nearby coral reefs and measure their coral coverage and spawn production (larval dispersal). Location, size and spacing should be based on knowledge and data.
- Measure biodiversity with the help of a spatial analysis, in this way a comparison with the connectivity can be made (Almany et al., 2009).
- Set boundaries for marine protected areas (MPAs). This declines the occurrence of impacts and the consequences for coral health. No mooring zones, reduce fishing activities etc. could be implemented. (Wilkinson et al., 2003)
- Management plans can be set carefully with backing up of the local community. Planning, monitoring and enforcement are important steps in this management approach. (Wilkinson et al., 2003)
- Do not necessarily use labour intensive breeding techniques. A suitable environment should be created for gametes to propagate and larvae to settle.
- Stabilising substrate techniques is also an option.
- Larval supply from upstream should likely be increased to stimulate natural coral development in an area. This can possibly be done by measures mentioned before for the upstream area. Including potential measures as direct transplantation, coral gardening, addition of suitable substrate and substrate manipulation. (M. Y. Hein et al., 2020)
- If coral reefs around the recipient are too far away, destroyed or if there is any other cause why larvae do not reach the recipient location; larval propagation methods could become an option. This can be done by the deployment of inoculated substrate or by larval enhancement (Boström-Einarsson et al., 2020; M. Y. Hein et al., 2020).

high

- Set up a network of MPAs, to monitor and maintain the high connectivity of coral reefs (Wilkinson et al., 2003).
- More widely distributed coral reefs (reserves) tend to achieve better results than more closely spaced reefs/connectivity (Almany et al., 2009). When the connectivity is high, it is important to check if the connectivity network represents the entire area. Therefore, spatial analysis and data on larval dispersal for diversity of coral species should be studied carefully (Almany et al., 2009).
- No intensive breeding techniques are needed.
- Substrate enhancement methods as substratum stabilisation and substrate addition could be beneficial when used correctly (M. Y. Hein et al., 2020).

• **Reef type**

The different reef types that exist are already explained in Section 2.3.3. This however is a step that should not be skipped. The following reef types exist: Fringing reef, Patch reef, Barrier reef, Atoll and a Bank/platform reef. However, loose colonies are also a possibility. Loose colonies on artificial structure, form artificial reefs.

When only separate colonies and not a specific reef is observed, coral coverage is probably low. When a new marine structure is placed, the coral coverage in this area will likely not be enhanced. To promote and protect corals in the area, connectivity should be enhanced, and the following possible recommendations can be applicable:

- Relocation of separate coral colonies before implementation of marine infrastructure, with an in or ex-situ phase. Subsequently, transplanting this back to the recipient cite (marine infrastructure).
- Larval dispersal on newly created substrate
- Assign MPAs in the environment (mainly upstream of predominant current direction)

- **Structure and size corals**

  According to Bak and Meesters (1998); size and structure of corals are indicators of coral species development. The habitat structure varies spatially, dependent on location and water quality parameters. Next to coral coverage (J. Bell and Galzin, 1984; Sano et al., 1984; Bouchon-Navaro and Bouchon, 1989; Chabanet et al., 1997), is the reef complexity offering important resources for marine life (Luckhurst and Luckhurst, 1978; Syms and Jones, 2000; Gratwicke and Speight, 2005; Roberts and Ormond, 1987).

  Habitat structure is a constant customizing environment, reflecting the needs of species preferences in regard to corals, fish and other marine life (Syms & Jones, 2000). The complexity of a coral reef, indicates the health of a reef system and species richness (Syms and Jones, 2000; Gratwicke and Speight, 2005). Characteristics to determine complex reefs are: surface rugosity, variety of coral shapes, and height and number of holes (Luckhurst and Luckhurst, 1978; Gratwicke and Speight, 2005; Roberts and Ormond, 1987). According to Gratwicke and Speight (2005) rugosity and variety of growth form the two important characteristics.

  Measurement of the complexity (rugosity and variety of coral shapes), can be executed by observations in relation to other coral reef areas nearby. If the complexity is high, together with the coral coverage, a healthy reef system can exist including benefits for reef fishes (Komyakova et al., 2013). A relatively low habitat complexity asks for possible recommendations (during the design of marine infrastructure):

  - Substratum addition (marine infrastructure)
  - Roughen substratum
  - add reinforced or heavy weight rubble

- **Coral species check**

  Coral species occurring at the green field of a future footprint or on existing marine infrastructure that will be expanded, should be checked. This is done by making underwater footage of all corals in the area of interest. Subsequently, these species are categorised by making use of coral identification books (Humann & Deloach, 2013), literature and websites. Examples for coral databases are: Goemans (2012), Base (n.d.), Veron et al. (2016), Data (n.d.), NatureServe (n.d.), Myers et al. (n.d.) and IUCN (2021).

  This coral species check is needed to check whether coral species are threatened according to IUCN (2021). These species are threatened and should therefore be protected in order to handle human interventions or environmental changes (Hughes et al., 2003). Therefore, these specific species should be categorised, protected and propagated. The following Red List categories are present:

Figure 3.12: IUCN Red List categorisation (IUCN, 2021)

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When the IUCN Red List categorisation reveals that the specific species belongs to the NE, DD, LC or NT category, nothing happens and no protective measures should be introduced. However, when the categorisation reveals VU, EN, CR or EW; one of the following recommendations can become options:

- Protect by assigning a designated MPA
- Before building: relocate and transplant these species with intermediate gardening phase in or ex situ.
- Collect spawn for coral rearing and/or seeding of these species. Grow developed corals on new marine construction.

• **Recruitment limited check**

An overgrow of algae, for example, tends to cause small availability in substrate, since algae are a space competitor with corals (Humann & Deloach, 2013). Low substratum availability is left for larval settlement. This is one example of a recruitment limited system. Coral larvae attach to a sufficient base by settlements, to develop into larger corals (Edwards & Gomez, 2010). In recruitment limited systems only large or no corals are observed, without the occurrence of small (0,5 – 5 cm) corals (juveniles) (Edwards and Gomez, 2010; Doropoulos et al., 2015). If almost no juvenile corals are found, poor recruitment is a fact. Therefore for recruitment limited systems, negative circumstances to settle prevail. Water flows do probably only contribute to reduced recruitment conditions when exceeding 0.75 m/s (Tseng et al., 2001; Grigg, 1965). Abundance occurrence of macro algae could cause competition for suitable substrate (Venera-Ponton et al., 2011). Larvae needs cues to settle (Meyer et al., 2011; Vermeij et al., 2010). A system with absence of suitable substrate either by low substratum availability or overgrowth of competitive species such as micro algae, will probably not provide these cues. Without cues, larvae are not supported in their settling period and will consequently die. For large supply of larvae, substrate availability is key. When larvae supply is insufficient and low or when almost no juvenile corals are observed on 'suitable' substrate: water quality, hydrodynamic, biotic or anthropogenic factors possibly do not permit coral development. The following recommendations can be applied: (Edwards and Clark, 1999; Clark and Edwards, 1994; Spieler et al., 2001)

- Improve connectivity (when low) with neighbouring reefs to gain on natural reef recovery using natural reef recovery techniques (MPAs) or construct a new 'artificial reef' upstream of the recipient location and close to other reserves.
- Implement appropriate surfaces to settle
- Introduce coral propagation methods (larval supply or coral transplantation)
- Decrease fishing activities in the area
- Improve poor water quality, monitor constantly (check abiotic components).

Conclusion - biotic system

The biotic system encompasses a variety of components, in which the situation of coral habitats is ideally measured according to coral coverage, connectivity, reef type, structure and size, coral species and recruitment. A coral coverage check is needed to check the number of species in an area. The connectivity is needed to find out if larval supply is abundant and if the reef is resilient. The type of reef could include loose colonies on artificial reefs, which need to undergo actions as described. The structure and size have implications on marine life. Coral species could be in the IUCN red list and should then be protected. Concluding, a recruitment limited check is executed to obtain results on the suitability of a location for recruitment of larvae in regard to circumstances, substrate or larval supply. Per component recommendations are described to protect or assist improving coral habitats.

3.2.3. Conclusion

In this section, the abiotic and biotic part of the natural system that could impact corals in any way, is described. All components that are needed to know from a marine infrastructure developer perspective are included. All these data needs to be as reliable as possible, since new projects and research is based on this information. One of the best practices is to generate a baseline of measurements with all abiotic and biotic components involved. To obtain reliable results, measurements on a year-long basis should be performed. After a year, obtained data can be sufficient for data analysis and next steps towards implementing infrastructure in coral reef ecosystems can be executed. The longer a measurement period, the more confident decisions can be made. The importance of certain (a)biotic factors is highlighted and focus is on a goal oriented management approach. How this management approach works and how factors cooperate with one another can be found in Chapter 2.

3.3. Anthropogenic system approach of coral reefs

3.3.1. Usage functions

The upper part of Figure 3.1, indicates the anthropogenic system. This system can also be labelled as a human usage or a socio-economic system.

Humans specify a location for usage functions, such as fisheries, construction activities or tourism. These activities affect coral environment frequently negatively, however could be redirected towards a positive development when correct measures and methods are used due to innovative perspectives and Building with Nature (BwN) implementations (de Vriend et al., 2014).

A study is done by Bunce and Townsley (2000) on how to assess socioeconomic values for coral reefs. This study provides a guideline for managers on how to sustain and conserve coral reefs. If information is needed on this topic, suggested is to make use of this report (Bunce & Townsley, 2000).

Ecosystem services consist of four pillars: supporting-, provisioning-, regulating- and cultural services (Vriend and Koningsveld, 2012; Assessment et al., 2005; Costanza et al., 1997; Laboyrie et al., 2018; De Groot et al., 2002; Daily et al., 1997). Direct and indirect substantiation is not provided within these ecosystem services (K. J. Wallace, 2007; Daw et al., 2011) and is therefore studied by Kittinger et al. (2012). Ecosystem services and the socioeconomic (direct and indirect) impact are illustrated in Figure 3.13.

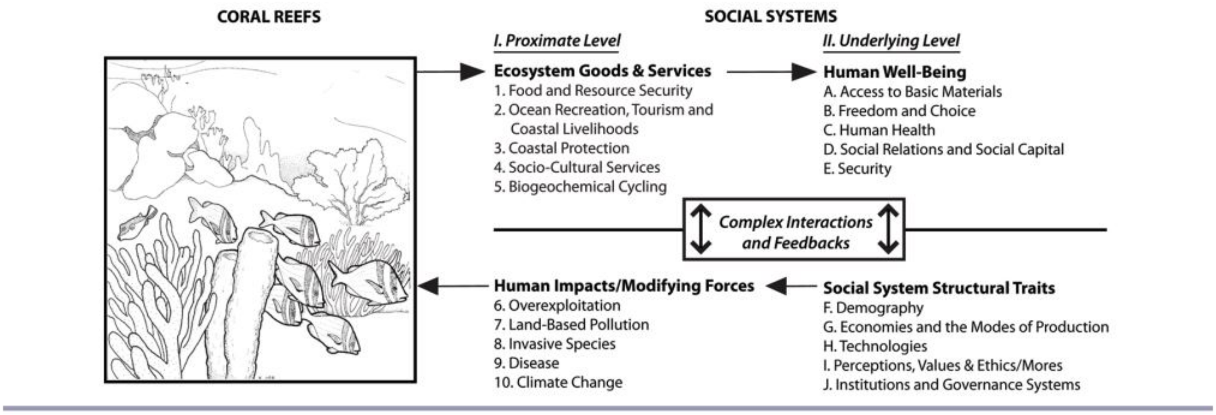


Figure 3.13: Coral reef with human services and benefits. Divided in Ecosystem goods and services, Human well being, impacts on coral reefs and system traits (Kittinger et al., 2012).

Knowledge that is taken from Figure 3.13, is the division in two social system levels. The ecosystem goods and services, together with human impacts are forming the basis for the anthropogenic system.

In coastal regions, areas can be used for different purposes to be beneficial for humans. This can be artificially created areas, created by humans or locations created by nature. For example, areas that are suitable for recreation due to the natural formation of sandy beaches or areas which are used to protect hinterland against storm surges by man made coastal barriers. In this study, the functions where humans could make use of certain 'natural' areas are called: human usage functions. These human usage functions does not necessarily impact coral reefs. Therefore, these usage functions differ from human activities only impacting reefs. The following general usage functions are distinguished (altered from Chen and Nihoul, 2008):

- Recreational (Touristic)
- Food provisioning
- Providing of natural resources
- Coastal Protection

- Environmental protection
- Transportation and navigation
- Storage (Dumping and littering)
- Power generation

Each human usage function potentially has effects on coastal regions with focus on coral habitats (Kittinger et al., 2012; Spurgeon, 1992; Bunce and Townsley, 2000). The explanation per human usage function, the effects on coral reefs, and a possible management approach towards nature-inclusive solutions for marine infrastructure are described below:

- **Food provisioning**

  Thousands of different fish and plant species can be found in the oceans, which provide nourishment for humans (Tibbetts, 2004; Golden et al., 2016; Ferreira et al., 2016). Fish and seafood products contain proteins, minerals, and energy that are consumed all around the world. Seaweed has been used in cuisine for centuries (Hosomi et al., 2012; Cisneros-Montemayor et al., 2016. Fish and other marine animals can find refuge in coral ecosystems (Shulman, 1985). Commercial fishing is frequently the lifeblood of coastal communities (Cisneros-Montemayor et al., 2016). Commercial fishing has become more popular over time. The problem of 'bycatch' has grown, and the extinction of entire fish species has disrupted marine life cycles (Davies et al., 2009).

  One of coral functions is to provide sea food for people. This is due to the enhanced diversity and presence of fish and seafood around coral reefs. Corals function as refugia for fish and other marine species by offering protection with complex structures against predators and currents. The accommodation of diverse marine species in and around reefs, leads to a nutrient rich system. Resulting in a complex food web, which is maintained by the structure of coral reefs. (Cesar, 2000; Syms and Jones, 2000; Komyakova et al., 2013; Hicks and Cinner, 2014; Kittinger et al., 2012; Spurgeon, 1992; J. E. Smith et al., 2006; Feary et al., 2007).

  The following possible recommendations can become applicable if it appears that coral reefs in the area function as important source for food provisioning:

  - Granting of MPAs (Wilkinson et al., 2003). See paragraph 3.3.1 for an explanation of MPAs. Cabral et al. (2020) and Weeks et al. (2014) demonstrate that allocation of MPAs have a direct link with fish multiplication and food production.
  - The introduction of fishing (gear) limits potentially results in an increase in biomass (Campbell et al., 2018). This does not mean that fishing should be completely stopped but fishing limits could assist in the restoration of the fish population. Use biodegradable netting and other fishing gear to reduce the likelihood of coral reef destruction and by catch (Samoilys et al., 2011). For local fisheries, follow the guide provided by Samoilys et al. (2011).
  - Monitoring: The tolerance of fish and fish populations to stress can be assessed by monitoring fish populations (Wedemeyer et al., 1984). This results in better defined fishery systems.
  - Artificial substrates are used to boost the production of fish (Keshavanath et al., 2001; Powers et al., 2003). Implement niches, extra substratum and increase surface for recruitment, to gain net positive effects on fish abundance (Yanovski and Abelson, 2019; Sherman et al., 2002); Hackradt et al., 2011).

- **Recreational**

  Marine life, particularly coral settings, can offer unique marine species for humans to discover all over the world. This can be done from above, on, or below the water's surface (Brander et al., 2007; Wielgus et al., 2003). Recreational human usage includes non-extractive activities such as diving, snorkelling, sailing, swimming, board sports and other activities that take place in marine settings. A coral ecosystem can be classified as a recreational system if one of these activities is routinely performed there (Brander et al., 2007; Wielgus et al., 2003; Reef resillience network, 2021). Humans can also discover the marine recreational world by building resorts and homes in recreational regions. The great barrier reef is an example of a (partly) recreational reef. The Great barrier reef is the world's largest recreational coral reef. Every year, 14 million people visit the Great Barrier Reef to see the aquatic creatures but this has consequences for the reef in terms of coral destruction and bleaching events (Great barrier reef marine park authority, 2021). Littering, direct contact during diving and snorkeling, introduction of alien species, and anchor damage are only a few examples of (human-caused) reef degradation (Reef resillience network, 2021; Great barrier reef marine park authority, 2021).

Coral reefs serve as tourist attraction for recreational activities (Pendleton, 1994). The value per region and activity can be found in Figure D.13. The following measures could be options to implement to increase recreational value in a nature-inclusive manner.

– Establish MPAs
– Improve waste removal and recycling, in order to keep waste out of coral habitats.
– Encourage users of coral regions to engage in conservation minded behaviour (Needham, 2010). To promote ecologically responsible behaviour, use informational and educational seminars (Briggs, 2005). Avoid direct contact with coral reefs, by using education and implement no go zones (MPAs) Consider avoiding areas to minimize direct contact with corals (Lück, 2008).
– Monitor coral reefs
– Add artificial structures (units) for coral development, enhance coral in other area by e.g. transplanting to shift focus from original coral reefs towards newly developed reefs. The original reef will subsequently be less subject to recreational impact.

• **Providing natural resources**

In coastal regions, frequently natural resources are being used. Think of lime, shells and minerals for jewelry or other materials for construction (Kittinger et al., 2012; Howdyshell, 1974). In coral reefs: the pharmaceutical industry could benefit from the extraction of natural marine resources. Sea sponge and urchins are used for the advancement of anti-carcinogenic medicines (Chen and Nihoul, 2008; Spurgeon, 1992). Corals are an excellent source to use for medicinal purposes. Since corals created (chemical) resilience to protect against hazards, the use of coral elements could help in medical treatments (NOAA, National Oceanic and Atmospheric Administration, 2021b). Other usage of corals is for cosmetics and other products used by humans. Moreover, other usage functions exist which not directly link to coral reefs. Think about the extraction of oil and gas (offshore) and transport to coastal zones. The world is dependent on fossil fuels and therefore the marine environment is subject to the extraction of natural resources. However, extraction and transport of oil could have implications for coral habitats by oil spilling. The spill of oil on reefs causes among other things; cell disruption, tissue damage, and lower growth rates (Loya and Rinkevich, 1980; Birkeland et al., 1976; Johannes et al., 1972).

The extraction of coral elements is done through mining and can be used for lime or building material production (Dulvy et al., 1995; Brown and Dunne, 1988; Coughanowr et al., 1995; Berg et al., 1998). Degradation of coral reefs is noted (Rajasuriya et al., 1995; Öhman et al., 1993; Berg et al., 1998; Brown and Dunne, 1988). A few proposals are addressed to diminish the impact of mining for natural resources and to enhance coral development here.

– Establish MPAs
– Monitor activities and impacts from mining/drilling proceedings.
– When transplanting to a location that is prone to mining or drilling with a significant risk of contaminating, use coral that has a high tolerance to these disturbances.
– Relocate coral species (IUCN red list), when they are in danger.

- **Coastal protection**

  Coastal protection systems are (coral) structures, that provide shoreline protection against waves, storm surges and floods both naturally as artificial (Reguero et al., 2018; Kittinger et al., 2012). Because of coastal protection, likelihood of erosion decreases, and communities, beaches and other coastal life and development is protected (Spalding et al., 2014). Different management strategies can be used. Holding the line strategy refers to the use of coastal defences to protect a coastline. Hard and soft engineering can be used. Another option is the managed realignment strategy. This allows an area to be flooded in order to protect hinterland against erosion and sea level rise. (R. K. Turner et al., 2007)

  Developed and healthy coral reefs tend to function accordingly to Gourlay (1994) and Lugo-Fernandez et al. (1998) as coastal protection systems by reducing energy of wind driven waves by 80 per cent. Barrier reefs can play a role in coastal defence if reefs are healthy and developed (Kunkel et al., 2006). Coastal protection of coral reefs is further dependent on amplitude, wavelength, geometry and offshore distance and do not necessarily function as expected in all cases (Kunkel et al., 2006). Removing natural barriers, as was done in the Maldives, is not a great idea. Coral mining activities had taken place and as a result, the 'natural coral protection wall' was vanished. A new protection wall had to be implemented at the cost of $10 million (USD) per km. (Talbot & Wilkinson, 2001)

  This indicated that coral reefs can be important as protection of the hinterland and marine environment against rough hydrodynamic circumstances. Coastal protection by coral reefs includes protection by reducing wave energy by damping of waves, which diminishes coastal erosion (Kittinger et al., 2012; Moberg and Folke, 1999; Beaumont et al., 2007), caused by, for instance; high tides, storms and hurricanes.

  Function: Protection of coastal regions against natural disturbances
  Recommendations:

  – Large blocks/rocks (limestone) can be used as protection, stabilise corals with cement if dislodged (Edwards & Gomez, 2010)
  – Do not remove reefs, certainly not when the reef has a protective function (Talbot & Wilkinson, 2001).
  – Assist or improve coastal protection by building artificial structures with coral friendly materials, implement closely to the reefs.

- **Environmental protection**

  This is protection of the environment that is created by environmental organisations as the protection of marine life against human impacts (Wilkinson et al., 2003). If a protective marine environment is addressed, building of marine infrastructure is not allowed within this area. Commonly, recreational activities and fisheries are also not allowed in these areas.(Wilkinson et al., 2003)

  An environmental system, provides the opportunity for corals and marine sea life to restore. This could improve connectivity to other coral reefs, whereby the region can profit from increased marine biodiversity and coral health by maintaining coral cover (Wilkinson et al., 2003; McClanahan et al., 2006; Selig and Bruno, 2010).

  Humans benefit from environmentally protected areas through a healthy living environment, enhanced food resources, added recreational activities and through the aesthetic value. An example of a marine park is the Parcel de Manuel Luís Marine State Park in Brazil. This marine park protects the largest coral reefs in the South Atlantic (Rocha & Rosa, 2001).

  Functions: Protection of marine life
  Recommendations:

  - Raise awareness through excursions, dive trips, education etc.
  - Monitor (surveillance) with the assistance of marine park rangers

- **Transportation and navigation**

  Since the invention of ships and the advantages of shipping became clear, humankind increased the use of shipping for transport and trading (Fayle, 2013). Historical events were based on securing strategic locations for the transport and trade of goods, resources and people (Harlaftis et al., 2012; Fayle, 2013). Coastal regions are still the economic regions due to harbours and terminals where from and to cargo is shipped (Ducruet, 2009). Ports are still being expanded, and navigation channels are being deepened, e.g. to accommodate larger ships and transport larger quantities (Tsinker, 2004; Laboyrie et al., 2018).

  Coral reefs, especially in coastal regions, encounter threats of the shipping industry. Ship groundings regularly occur, resulting in damaged reefs, turbid waters and rubble (Jaap, 2000). Anchoring damage on coral reefs is another problem, frequently occurring by cruise ships (S. H. Smith, 1988). Ships carry pathogens in ballast water and on hull and introduce these to other areas and coral reefs (Coles & Eldredge, 2002). Humans benefit from shipping by importing and exporting goods and food.

  The following recommendations have a chance to decrease transport and navigation effects on coral reefs:

  - Erect permanent moorings and compel vessels to use these permanent moorings (S. H. Smith, 1988).
  - Without permanent moorings, vessels should stay under power or anchor only when there is enough sand on the bottom (no coral reefs, seagras meadows etc.) (S. H. Smith, 1988).
  - Execute sampling and surveys (BPBM, CRIMP) to minimise effects of transportation of indigenous species (Coles & Eldredge, 2002).

- **Storage (Dumping and littering)**

  This includes plants for waste storage and treatment and sewage discharges. Waste, such as plastics, are promoting disease outbreaks on coral reefs (Lamb et al., 2018). Sewage discharges lead to increase nutrient levels in coral environments (P. Bell et al., 1989). Elevated nutrient values increase algae growth and subsequently decrease coral growth as explained in paragraph 3.2.1.1. However humans use storage as dumping and littering areas frequently to dump their waste.

  Questions that can be addressed with recommendations:

  - Is waste dumped close to the site of interest? Remove waste outlets and use waste treatment.
  - What sort of waste is it? Is it toxic and would it affect corals health? Measure toxicity and other components and check the harmfulness.
  - Check dump regulations, when needed adapt regulations.
  - Map industrial activities in the region.

- **Power generation**

  Various types of power generation on sea are possible; solar, wind, wave and tidal energy renewable resources (Widén et al., 2015). Closer to shore wave and tidal renewable resources are among the options (Gill, 2005). The energy transition requires innovative solutions for and from humans. Improving air quality and stopping climate change, which are possible results from sustainable power generation, are according to Erickson and Jennings (2017) beneficial for the health of humans.

Constructing renewable power sources in coastal areas, should be done by following a systematic method. The following questions and recommendations can be used:

- What is the size of the area that is suitable for power generation?
  A possibility is to use mooring systems that will not harm coral reefs for floating platforms.
- And what is the size and amount of already built power generation platforms?
  Check if corals have a positive or negative effect from shadow from floating constructions.
- What structure is in place and or what is needed?
  Use the same approach for non floating structures; maximise substrate, increase roughness and texture.
- Are there future plans for renewable energy in the marine coastal environment?

3.3.2. Coral enhancing methods

Active or passive coral development

Two substantially different techniques for coral rehabilitation and restoration are used; passive or active techniques (Edwards and Gomez, 2010; Boström-Einarsson et al., 2020; Rinkevich, 2005; Edwards and Gomez, 2007; van Koningsveld et al., 2017). Passive techniques are management actions that affect (biotic) components which influence coral development in a natural way, with minimal human assistance (Rinkevich, 2014; Edwards and Gomez, 2010; van Koningsveld et al., 2017; Epstein et al., 2003). Examples are MPAs, fishing limits and other stress regulating measures. Passive management can be less costly and relatively easy to implement but appears to be ineffective for some projects in stopping reef degeneration or restoration (Edwards and Gomez, 2010; McClanahan, 1999; Rinkevich, 2005; Jameson et al., 2002).

Active management involves the direct implementation of measures by using coral stimulating resources or techniques. Coral transplantation, coral gardening, larval propagation (e.g. the ReefGuard method (van Koningsveld et al., 2017)) are possible active restoration or coral development techniques (Boström-Einarsson et al., 2020; Edwards and Gomez, 2010; Rinkevich, 1995; Rinkevich and Shafir, 2000). In order to succeed with active interventions, mostly passive restoration techniques should also be applied (Edwards & Gomez, 2010).

Active coral enhancing methods

The following active methods can potentially be used: (Edwards and Gomez, 2010; Edwards and Gomez, 2007; Boström-Einarsson et al., 2020; Rinkevich, 2005; Epstein et al., 2003; Boström-Einarsson et al., 2018)

- Transplantation (asexual propagation)
  The placement of corals (fragments) from the donor site towards the recipient site. This could be with a gardening phase (indirect transplantation, explained in the following bullet point) or without an intermediate gardening phase (direct). Transplanting corals, reared in ex-situ tanks towards recipient site is also a possibility. (M. Y. Hein et al., 2020; Boström-Einarsson et al., 2020; Boström-Einarsson et al., 2018; Epstein et al., 2001; Edwards and Clark, 1999)

  The following coral materials for transplantation are used (Epstein et al., 2001):

  - (small) coral colonies
  - Coral fragments/branches
  - Micro fragmentation (Nubbins)
- Coral gardening ex-/in situ ((a)sexual propagation)
  The intermediate nursery phase after transplantation which can be in- or ex situ (Epstein et al., 2001; M. Y. Hein et al., 2020; Edwards and Clark, 1999).
  The following materials originating from corals could be used for gardening (Epstein et al., 2001; Boström-Einarsson et al., 2018):

  - Coral fragments/branches

    - Coral colonies
    - Coral nubbins (micro fragmentation)
    - Coral larvae (ex-situ)

- Larval enhancement/propagation (sexual propagation)
  First the collection of larvae from the donor site (or ex-situ from coral colonies) during coral spawning events. Then; fertilize eggs and sperm (or slick sampling) and rear for settlement in field or laboratory. Subsequently, settle cultured larvae onto substratum (ex or in- situ) for development into corals. Corals can be placed on recipient substrate. (Omori and Iwao, 2014; Rinkevich, 2005; M. Y. Hein et al., 2020; Edwards and Gomez, 2007)

  The following larval propagation techniques are available depending on the number of available larvae and the exact timing of spawning events:

    - Industrial scale (focused on enhancing recruitment): high concentrations pumping of slicks towards tanks for culturing and settlement of larvae in or ex situ (Doropoulos, Vons et al., 2019; Doropoulos, Elzinga et al., 2019). High larvae concentrations and timing of spawning event is evident.
    - Juvenile scale: Relocation of coral colonies to ex-situ tanks, collection of gametes, fertilize eggs and rear larvae (all ex situ). Or collect gametes in-situ and fertilize ex-situ. Offer substrate (in or ex situ) and rear coral until out planting (van Koningsveld et al., 2017). Suitable for lower coral spawn supply and when time of spawning is not exactly known.
    - small scale: direct seeding of obtained larvae from spawning coral colonies to recipient site. intermediate ex-situ rearing phase is possible but larvae will thereafter directly be seeded in-situ on recipient site. (Barton et al., 2017)

- Substrate enhancement
  Encourage natural larval settlement by increasing recruitment opportunities through the provision of suitable substrate (Omori and Iwao, 2014; Rinkevich, 2005; M. Y. Hein et al., 2020; Boström-Einarsson et al., 2020).

    - Substrate addition (Artificial reefs, biorock, ecoreef, reefball etc.)
    - Substrate stabilisation

According to Boström-Einarsson et al. (2020), 70 percent of all restoration projects is covered by transplanting and gardening. Substratum addition and manipulation is done in 10 per cent of active restoration projects and larval propagation is used in 1 per cent of the cases (Boström-Einarsson et al., 2020; M. Y. Hein et al., 2020). However, a combination of techniques could be profitable (M. Y. Hein et al., 2020; Edwards and Clark, 1999). For the exact procedure of active coral enhancing (restoration) methods, one may follow the steps described in Boström-Einarsson et al. (2018).

When production of coral on site (in-situ) is needed and a nursery is chosen as coral propagation measure, the following nursery constructions or applications are possible (Shaish et al., 2008; Edwards and Gomez, 2010; Shafir and Rinkevich, 2008; Edwards and Gomez, 2007):

- Fixed nurseries (see for example Appendix Figure D.10)
- Floating nurseries (see for example Appendix Figure D.11)
- Attach to suitable substrate with epoxy glue or rapid drying cement (Epstein et al., 2001).

For a gardening site, without substrate available, small floating devices (tree shaped) are recommended in frequent cases. See appendix Figure D.12. This is due to the vertical spatial variability which is included to cover influences over the water column (depth). Coral fragments or colonies can also be glued on present substrate (Epstein et al., 2001). Needless to say that this method is dependent on the availability of substrate on location.

Passive coral enhancing methods
(Edwards and Gomez, 2010; Edwards and Gomez, 2007; Meesters et al., 2019; Boström-Einarsson et al., 2020; Rinkevich, 2005; Epstein et al., 2003; SURASWADI and YEEMIN, 2013)

- Improve water quality - waste and water quality management
- Introduce MPAs
- Recover fisheries production
- Mitigate climate change
- Control predators
- Diminish tourism impact
- Diminish sedimentation impacts

3.3.3. Conclusion

Improving usage functions of and by developing infrastructure projects could lead to socio-economic development. Distinction in general usage functions is done by the following : food provisioning, recreational, providing natural resources (mining and drilling), coastal protection, environmental protection, transportation and navigation, storage (dumping and littering) and power generation. This division enlists possible effects on corals and indicate recommendations to map the anthropogenic situation and to become beneficial for the socio-economic and coral reef environment. Furthermore, potential coral enhancing methods are discussed which are divided in active and passive coral development techniques.

3.4. Quantification of coral ecosystems

Quantification of coral ecosystems is needed to define the quality of a coral ecosystem. Due to quantification, the current state of a coral reef can be confirmed by measuring, photographing, counting and observing coral species on a reef (Porter & Meier, 1992). This should then be compared to old data of the same area.

Biodiversity metrics quantify the value which biodiversity has in a coral ecosystem (Skidmore et al., 2015). Quantifying ecosystems keeps being inherently unpredictable due to a variety in methods and ecosystems. However, defining a baseline and trying to predict how this baseline changes over a temporal basis over time are both needed. Coral ecosystem functions are defined in Section 3.2, however extra guidance is hereby provided through quantification metrics. Coral ecosystems are, as discussed before, area specific. Therefore, it is key to use easy to measure quantification indicators to classify a coral ecosystem.

Different types of metrics exist, with each its own indicators that is focused on. The list of metrics from Figure D.3, is composed with the assistance of Ir. G.S. Williams (Van Oord) and can be found below and in more detail in Section 3.4.

- Biodiversity Metric 3.0 (Crosher et al., 2019)
- Habitat Equivalency Analysis (HEA) (NOAA, 2000)
- Uniform Mitigation Assessment (UMA) (of Environmental Protection, 2007)
- Coral Health Index (CHI) (Kaufman et al., 2011)
- Reef Health Index (RHI) (Currently under development) (Initiative, 2008Díaz-Pérez et al., 2016)
- System of Environmental-Economic Accounts - Experimental Ecosystem Accounts (SEEAEEA) (Contributing et al., n.d.)
- MERCI-COR (Pioch et al., 2017)
- Reef trust offset calculator (Maron et al., 2016)

To check the habitat quality, the area, distinctiveness, condition, strategic significance and connectivity can be taken into account. Quality indicators such as fish, algae or microbes can also be included. However, one of the methods can be chosen for reef evaluation depending on the managers decision. From this list, biodiversity metric 3.0 is suitable for all type of coral habitats and includes also a risk component. Every method can be used to study the baseline of a coral reef. An ideal way to obtain a proper baseline is to follow the approach that will be discussed in chapter Chapter 2.

3.5. Conclusion

This chapter, provides the tools to facilitate identification of coral values for persons without knowledge of coral reefs with the aim to identify criteria for coral reef value determination. The reader has to become acquainted with corals and how they function. The influences on corals from the environment and vice versa should become clear. Guidance is provided through the computation of a coral 'system'. This system is divided into a natural system with abiotic components (the water quality and the morphological factors) and biotic components. Especially for the abiotic components, acquiring transparent, reliable data can be a solution to generate knowledge and possibly identify suitability for coral development. Without this baseline being present, it is hard to tailor measures to local conditions. A test nursery can be one of the options for implementation, if local development of corals hamper or is not observed. For hurricane risk systems stable substrate needs to be added to increase the chance for recruitment. Flow velocities are needed for the 'self-cleaning mechanism' of corals. These should however not be too high since high currents will break off corals. The connectivity, together with the predominant current direction and spawning events are key to determine the amount of larval supply. The coral coverage provides insight in the development of a coral reef and can be quantified with the assistance of one of the quantification metrics. The other part of the natural system is the anthropogenic system. The human usage functions of the area indicate the value of a coral ecosystem. Corals are influenced by human activities and nature-induced stresses but active and passive coral recovery methods are in place. Coral propagation techniques, covering some of the active measures, could be labour-intensive and are dependent on water quality, morphological and biotic factors. Passive methods are generally easier and less costly to implement.

Natural System			**Anthropogenic System**
Abiotic system		**Biotic System**	**Usage functions**
Water quality factors	Temperature	Coral coverage	Recreational
	Salinity	Connectivity	Food provisioning
	Suspended Sediment Concentration (SSC)	Reef type	Providing natural resources
	Nutrients	Structure and size	Coastal protection
	PH	Coral species	Environmental protection
Morphological factors	Hydrodynamics	Recruitment (limited)	Transportation and navigation
	Hurricane risk		Storage (Dumping and littering)
	Substrate		Power generation
	Bathymetry		

Table 3.2: Overview table with necessary criteria to investigate possibilities for coral development.

4

Approach for marine infrastructure to use in the systematic method

In this chapter, potential marine infrastructure sources for coral development are studied. The goal is to create nature-inclusive potential for marine structures with the focus on enhancing coral development on/around these structures. In this chapter, elements of infrastructure are assessed to determine suitability of infrastructure designs for coral development. The construction phase of infrastructure is not included in this study. This chapter carries out methodological step 3 in which types of marine infrastructure projects with their elements are analysed and selected to investigate possible effects on the overall coral ecosystem during their functional life. Interviews, literature review and observations were carried out during this study and also during the period of stay on Sint Eustatius.

In order to improve the overview and to keep this chapter readable, it has been decided to narrow the focus in this chapter towards the application of the systematic method in Chapter 5: hard infrastructure. This should improve clarity for creating nature-inclusive infrastructure potential in this case. However, soft engineering remains an equally important element and will therefore be discussed in detail in Appendix B as an approach for use in the systematic method for other cases. During this current chapter, an occasional link is made to Appendix B to briefly explain the situation for soft engineering infrastructure.

4.1. Introduction

Marine infrastructure in tropic regions commonly offer unintended habitats for coral development (Feary et al., 2011; Burt et al., 2011; Wen et al., 2007). According to research conducted by Burt et al. (2011), mature breakwaters offer opportunities for coral development. In this study ((Burt et al., 2011), mature breakwaters even demonstrated larger coral cover than studied natural reefs. This implies that man-made coastal structures might serve as suitable homes for corals. It has been hypothesized that it takes at least ten years for man-made structures to produce ecosystems comparable to natural reefs (Burt et al., 2011; Aseltine-Neilson et al., 1999; Abelson and Shlesinger, 2002; Perkol-Finkel and Benayahu, 2005). However, Burt et al. (2011) state that these structures should be built in an environmentally sustainable manner in order to preserve natural reef ecosystems. Other infrastructure example is the Rigs-to-Reefs program. Rigs-to-Reefs is a program in which non-functional offshore facilities are converted into artificial reefs (Bugnot et al., 2021). These rigs were not built in a nature-inclusive manner, however coral development results look promising. This indicates that certain marine structures, by including adequate components for coral habitat stimulation, might be excellent for coral development (Jagerroos & Krause, 2016).

The expectations of a civil construction include both the utility (usage function) and the durability (life cycle). Corals that seek to grow on marine infra can only develop in line with the marine infrastructure's functional life before decommissioning takes place. The life cycle of 'nonfunctional' rigs2reef constructions for example, is not comparable to that of functional marine infrastructure. When the functional purpose of a 'regular' structure is no longer met, a new construction should be built to meet the functional needs. Consider quay walls, protective dikes, or breakwaters for coastal protection, as well as jetties and piers for mooring. The focus of this research is on nearshore infrastructure during their functional phase. The decommissioning phase is a feature shared by all relevant marine infra. The life cycle determines the length of functional fulfilment and possibilities to coral development. The idea is to encourage as much coral formation as possible on and around infrastructure during its functional life. This study does not include aspects of the construction phase, since this is focused solely on mitigation or ecosystem protection measures (Laboyrie et al., 2018).

4.2. Elements of marine infrastructure

Both soft and hard engineering constructions are to be divided into two different stages: The process stage (construction phase) and project stage (functional life of infra). Elements during the construction of soft and hard marine infrastructure can cause process effects and belong to the process stage. This is during the execution of e.g. beach nourishment or deepening of channels. Element examples that interact or have a one-sided effect on the environment are: turbidity, movements of ships, vessel interactions, underwater noise or other environmental impacts during construction or project preparation (Laboyrie et al., 2018). The other stage is the project stage, which could induce project effects. These effects are the result from marine infrastructure that are already implemented and ready to use (functional life). Social and ecological aspects are important in this category (Laboyrie et al., 2018). Elements from the project stage that could result in project effects, are discussed below.

4.2.1. Hard Engineering

In principle, any hard substrate that is placed/positioned in the marine environment has the potential to offer substrate for (new) coral development (Edwards and Clark, 1999; Oren and Benayahu, 1997; Clark and Edwards, 1994; Spieler et al., 2001; Wen et al., 2007) but its suitability for the successful establishment (settlement) of new coral recruits depends on several parameters. Parameters are environmental factors but also design/composition factors of a structure (Wen et al., 2007, Burt et al., 2011; Ushiama et al., 2016; Erftemeijer et al., 2003; Erftemeijer, personal communication, August 20, 2021). Site selection according to a location analysis is described in Chapter 3. Design and composition of structures will be elaborated in this section.

Piled structures tend to have smaller areal footprints than gravity-based constructions. However, this does not per definition mean that resulting effects (hydrodynamics) cause more severe impacts on corals. Therefore, structural elements should be discussed separately for infrastructure - coral interaction. Distinction is made in:

- Material properties
- Design (size, placement area, orientation etc.)

Material properties

Per hard engineering structure type, construction materials vary. For one structure, rubble or concrete is needed for stabilization while the other structure uses steel piles. For marine applications, materials are divided in metals and non-metal materials (Srinivasan Chandrasekaran, 2016) (See Appendix Figure D.6). Non-metals are divided in plastics, environment, finishes, textiles and woods (man-made and natural). Structural properties of materials, determine the use for marine application and should be used according to site and hydrodynamic specific factors. Environmental loads (e.g. wave interactions) and negative and positive environmental effects of materials on the environment are important considerations. Environmental loads can lead to fatigue, stress, corrosion, biofouling and chemical effects (Srinivasan Chandrasekaran, 2016). Materials need to maintain their function during collisions and during loads exerted on structures. Concrete is a frequently used construction material in marine environments (Baine, 2001; Srinivasan Chandrasekaran, 2016). Options used for artificial structures are: concrete, rock (stones, boulders, gravel etc.), platforms, tyres, plastic, vessels, barges, wood, steel, metal, netting etc. For the whole list, functioning as an example to what is possible in artificial structures, see Figure D.7 (Baine, 2001). For this study, not all artificial structure materials can be used. The materials should be able to be used for construction purposes of hydraulic structures. The construction materials are comprised to a small list, in order to keep construction materials for coral enhancing, manageable.

The list of materials is the following:

- Concrete
- Steel
- Rocks (granite, gabbro, sandstone, basalt)
- Timber

Every material can be subdivided into more material components. Further research is based on these main material properties.

Design
The design is influenced by material properties and by the engineer. Different design choices are to be made. The following list includes possible design elements (Spieler et al., 2001; Grove, 1982; Bohnsack and Sutherland, 1985; Bailey-Brock, 1989).

- Surface
- Complexity
- Texture
- Colour
- Stability
- Orientation
- Size
- Placement area
- Wet surface area

In Appendix Section C.3, the hydraulic structure categories are described. Per structure type, the size, placement area and wet surface area are elaborated, since these factors possibly differ per category. In the following is a short substantiation of these elements.

Size
This will generally determine its overall effectiveness to act as an artificial reef system in the sense of fulfilling significant ecosystem services. The size is functional- and site specific and is compared to other structures that have been constructed in the same area.

Placement area
The area where a construction is placed, the greenfield, is related to size and dimensions of structures. The placement area is exactly where the construction is placed and where coral is affected (negatively) by the weight of the structure.

Wet surface area
What is meant with the wet surface area, is the surface of a structure which is in direct contact with water.

4.3. Potential effects of marine infrastructure on corals

4.3.1. Hard engineering

Design and material properties with composition of hard substrate, structural complexity, surface texture, size and dimension, placement area and surface orientation are all elements addressed by certain positive and negative effects.

As described in Section 2.4, any hard substrate that is placed in the marine environment has the potential to offer a substrate for coral development. Successful settlement of new coral recruits tend to depend on various abiotic parameters (see: Section 3.2.1) and on design and material composition.

Design and material composition effects on coral ecosystems are discussed in this section.

Alternatively, the construction and placement of artificial structures proved to also have negative impacts on existing coral reefs by altering hydrodynamics and sediment dynamics, and (in some occasions) leaching of contaminants/toxic compounds (Ushiama et al., 2016; Tseng et al., 2001; Erftemeijer et al., 2004; Arunvivek et al., 2016). The negative and positive effects are addressed below:

Material properties
Hard substrate that is directly linked to artificial structures, could be composed of concrete, steel, timber and rock as explained before (Srinivasan Chandrasekaran, 2016).

- **Concrete** is made from portland cement and originally contains limestone, which contains the same original building block as coral reefs. This 'natural building material' is called calcium carbonate (Subcommittees et al., 2004). Concrete is frequently used for marine infrastructure construction. Coral seems to thrive on concrete subsoil, due to this natural building block (Xu et al., 2019; Kaufman, 2006). Therefore, coral would be suitable as construction material. But there are also some negative effects due to the use of concrete as construction material.

  Negative effects:

  - The use of recycled concrete components could lead to intoxication of marine environments (Subcommittees et al., 2004).
  - It is not entirely sure if marine infrastructure made of concrete is able to provide a similar developed natural habitat as 'natural reefs' (Ido & Shimrit, 2015).
  - The carbon footprint of concrete is high (Purnell, 2013; Flatt et al., 2012).
  - Concrete has low tensile strength. This becomes a problem when tensile forces on a concrete construction are applied. Due to little toughness, brittle failure of concrete occurs relatively soon (Beeby, 1997).
  - Due to the heavy weight of concrete, transport can be costly and chances on bottom subsidence increase (Subcommittees et al., 2004).
  - The high PH values of lime (alkalinity: 10-11), make surfaces toxic for invertebrate organisms for the first 3-12 months (overall > 6 months) of concrete implementation in marine environments (Arunvivek et al., 2016; Xu et al., 2019; Subcommittees et al., 2004). Leaching and sulfate attack due to the alkali carbonate reaction, prevents biofouling (W. Baker et al., 1995). This reduces the likelihood of larvae settling for the first months after implementation (Xu et al., 2019).
  - During the last years the price of concrete has increased due to limited availability of natural resources for concrete (from rivers or quarries) (Xu et al., 2019).

  Positive effects:

  - Concrete can easily be combined with other (local available) materials to come up with a suitable construction. For example, the combination of concrete with other materials as quarry rock and vessels is used to construct functional artificial reefs (Baine, 2001).
  - The diverse structural complexity of concrete (and cement) leads to target specific applications. For example, the use of complex antifers (armour units), could lead to more 'complex' structures, where organisms and coral have sufficient places to shelter and to develop. Since concrete can be built in any shape: blocks, pipes, cubes and pyramid forms, coral develops easily due to these complex structural elements. (Subcommittees et al., 2004; Baine, 2001).
  - Coralline algae has a proportionate relationship with coral health. Study indicates that coralline algae thrive on eco antifers with larger coverage as a result compared to standard antifers. This is also the case for diversity and coverage of fish and other organisms. Invasive species occur to a lesser extent on these eco antifers compared to the 'regular' antifers. (Ido & Shimrit, 2015)
  - Concrete gains compressive strength due to hydration of cement on a molecular level (Subcommittees et al., 2004).
  - Material is durable in sea water, stable and easy to produce (Stark, 1995; Fitzhardinge and Bailey-Brock, 1989).

- Concrete is relatively cheap and widely available (Jonkers, 2007).
- Application is possible in many different forms, such as construction blocks or reef balls (Hylkema et al., 2021).
- Rough surface texture tends to improve larval recruitment (Fitzhardinge and Bailey-Brock, 1989; Burt et al., 2009; Al-Horani and Khalaf, 2013; Hylkema et al., 2021).
- Marine/artificial structures from concrete can potentially attract and distribute fish (Baine, 2001).
- Concrete material is often used in structures for the protection of coasts and habitats (Subcommittees et al., 2004).
- Concrete promotes epifaunal colonisation (Baine, 2001; Hylkema et al., 2021).
- With small concrete artificial structures, habitat rehabilitation and restoration are possible (Hylkema et al., 2021).

• **Metal/Steel** is another often used material. Negative and positive effects are listed in bullet points below.

Negative effects:

- The upper layer on vertical steel walls frequently peals of due to corrosion, which is accelerated by sea water. Coral decays due to this mechanism. Steel corrosion can lead to loss of epibenthic animals (Subcommittees et al., 2004; Zhang et al., 2020; Hylkema et al., 2021; A. Hylkema, personal communication, June 29, 2021)
- Recycled steel from vessels, airplanes etc. could contain contaminants and other toxic components (Subcommittees et al., 2004; Aguilera et al., 2016; Johnston et al., 2003).
- Metals encourage biofouling which eventually favours algal and bacterial growth which hampers coral development (Hylkema et al., 2021; Greenberg and Itzhak, 2005).
- To stop corrosion, anti corrosion applications are frequently used like polyaniline or epoxy coatings. No research is done to investigate the effects of coatings on coral development. The coating functions as a protection layer to prevent biofouling etc. Therefore, coral development is also less plausible (Talo et al., 1997).
- Corrosion attacks happen faster on rough surfaces than on smooth surfaces (Pradhan et al., 2018).
- Costs of steel for constructions is high. This is for the construction but also for the maintenance (community, 2020).
- Steel mostly has a lesser quantity of epibenthos invertebrates (e.g. corals) than other materials. Some species types demonstrate other results but in general metal or steel is less suited for the creation of epibenthic community compared to other materials. This could be due to lower food availability on steel materials (Ushiama et al., 2016; Anderson and Underwood, 1994).

Positive effects:

- The use of steel vessels for artificial reefs for recreational diving is often beneficial for fish and tourism and could be cheaper than scrapping (Subcommittees et al., 2004).
- Metal is lighter than other materials. This possibly results in lower transport costs, easier to handle during construction, subsidence is less likely (community, 2020;Lima et al., 2019)
- Vertical (metal) surfaces provide current alterations that can be attractive for fish and coral species.
- Steel has high tensile strength and is a relatively ductile material. Therefore, this material is widely used in offshore construction (Srinivasan Chandrasekaran, 2016).
- Sinking vessels from steel/metal, could lead to driving away of fishermen from natural reefs, in this way, natural coral reefs are possibly protected against over-fishing, fish net damage, anchoring damage and ship groundings. (Subcommittees et al., 2004).
- Steel can be created in different shapes, it is easily fabricated. Adding complexity by complex steel structures could favour coral development and is a possibility (Mercader et al., 2017; Scarcella et al., 2015; Herbig and Szedlmayer, 2016).
- Steel potentially increases epifaunal colonisation probability (Baine, 2001).

- Steel potentially enhances fisheries due to increase in epifaunal colonisation (Baine, 2001).

- **Rock** comes natural in different sizes and types. Examples are granite, gabbro, sandstone, basalt, volcanic rock etc. (Burt et al., 2009).

  Negative effects:

  - Rocks are not optimal to create high complex structures, which decreases its value to support ecosystem functions as juvenile coral protection and development (Kawasaki et al., 2003).
  - Smaller rock sizes could be buried underneath sand layers in sediment-rich areas.
  - In extreme weather circumstances, boulders could roll off from structures or displace and damage surrounding environment, decreasing its functionality. (Shadwell, 1930)
  - Durability depends on the type of rock, longevity cannot always be guaranteed if local quarry rock is used (Olivier, 1979).
  - Transport costs are higher for heavy large materials like rocks. It is more difficult to transport large stones to site than prefab concrete shapes or steel beams of equal sizes. Moreover, heavy equipment is needed. (Subcommittees et al., 2004)
  - Texture depends on the type of rock and cannot be guaranteed to always be sufficient for recruitment.
  - Usage of rocks makes it difficult create stable and complex habitats, especially for larger depths (Feary et al., 2011).

  Positive effects:

  - Different rock types look to be suitable for the recruitment of larvae. These types are granite, sandstone, gabbro and terra cotta (Burt et al., 2009). Gabbro is widely available and contains grained structures (Sen, 2001). But also the other materials could function as suitable substratum, especially when it is a dominant occurring rock in an area (Bulleri, 2005; Creed and De Paula, 2007; Moschella et al., 2005).
  - Coarse grained sedimentary rocks, entail low costs and have low impact on marine environment (Baine, 2001).
  - Widespread availability (Sen, 2001).
  - Fish attraction and distribution occurs due to material properties of natural stones (Baine, 2001).
  - Habitat rehabilitation and restoration are possibilities with natural rocks (Fox et al., 2005).
  - Coastal and habitat protection are offered by the use of natural rock in diverse breakwaters and coastal protection works (Schoonees et al., 2019).
  - Epifaunal colonisation is possible (Burt et al., 2009).
  - When local situated rock is used, it is cheaper and readily available.
  - Quarry rock is dense, stable and durable (Subcommittees et al., 2004; Hameed and Sekar, 2009).
  - More different species are mostly observed on natural reefs consisting of ingenious rocks compared to concrete reef blocks (Risk, 1981; Hylkema et al., 2020).
  - Varying sizes and shapes could create a complex structure and interlocking of these different rock sizes could provide resistance against storms.
  - Low environmental impact. Local rocks are compatible with the environment, since these rocks occur naturally in the environment and will therefore likely cause less disturbances (Klemm & Wiggins, 2016).
  - Limited scour and sedimentation for reefs consisting of rock. Other reef materials tend to experience more scour and sedimentation (C. H. Turner et al., 1969).
  - Piles made of rock, are relatively cheap and easy to use for construction purposes with a moderate complexity for recruits to shelter. (Hylkema et al., 2020)

- **Wood/timber** is the last much used construction material in marine engineering.

Negative effects:

- Relatively short life span when in contact with the marine environment. Deterioration of wood, results in spreading of wood rubble in the environment (Subcommittees et al., 2004).
- Wood is relatively light. Much weight is needed to keep the construction stable (Subcommittees et al., 2004).
- Timber used in constructions usually goes with anti rotting components that can be toxic or are probably not sufficient for coral development (Subcommittees et al., 2004).
- Boring by microbial organisms in wood occurs (A. C. Oliver & Brown, 1974).
- Wood has difficulties in withstanding mechanical forces (crushing, war, tear) (A. C. Oliver & Brown, 1974).
- Fungal decay above the waterline is possible (A. C. Oliver & Brown, 1974).

Positive Effects:

- Wood is largely available (Subcommittees et al., 2004).
- Possible fish attraction and fishery enhancement (Baine, 2001)
- Epifaunal colonisation is possible (Baine, 2001) and coral grows on wood and on wooden debris. (Mantelatto et al., 2020).
- Riddling effect of worms in wood likely increases habitat complexity (Subcommittees et al., 2004), this could improve complexity for coral recruitment.
- Wood is light, low transportation costs and easy to handle (A. C. Oliver & Brown, 1974).
- Wood is mostly strong in withstanding shock loads (bending) (A. C. Oliver & Brown, 1974).
- Structural adaptability (in situ) is easy and replacement of wooden components is relatively easily done (A. C. Oliver & Brown, 1974).

Material	Recruitment	Reef substrate	Information	Reference
Concrete	- -	++	Due to leaching not suitable for recruitment for the first months after deployment.	Subcommittees et al., 2004; Arunvivek et al., 2016; Xu et al., 2019; Jo et al., 2007; Neo et al., 2009; Burt et al., 2009; Fitzhardinge and Bailey-Brock, 1989)
Rock	++	+	Natural occurring rock both suited for recruitment and reef substrate.	Moschella et al., 2005; Creed and De Paula, 2007; Bulleri, 2005; Burt et al., 2009; Fox et al., 2005; Subcommittees et al., 2004; Klemm and Wiggins, 2016; Hylkema et al., 2020
Steel	+	0	Corrosion can lead to material disintegration (peeling off), the reef stays within the colonisation phase (younger reef). Transition towards a natural reef is less likely.	Fitzhardinge and Bailey-Brock, 1989; Hylkema et al., 2021; Zhang et al., 2020; Pradhan et al., 2018; Baine, 2001; Creed and De Paula, 2007
Wood	+	- -	Shorter longevity	Subcommittees et al., 2004; A. C. Oliver and Brown, 1974; Baine, 2001; Ushiama et al., 2016

Table 4.1: Material comparison with recruitment suitability vs suitability as (developed) reef substratum. For this comparison, the natural (environmental) values, anthropogenic influences and design component (orientation, rugosity etc.) values are assumed constant. Indications are provided with: perfectly suitable (++), high suitability (+), neutral (0), low suitability (-) not suitable (- -).

Recruitment suitability indicates the successful settlement of larvae on the material. Suitability as reef substratum, indicates the effectiveness of the material to function as substratum for further development of corals into coral reefs. Table 4.1 illustrates that concrete and rock are both suitable materials for enhanced coral development.

Design

The design of marine structures is dependent on different factors. Marine structures are artificial reefs deployed in the marine environment with extra functions such as protection, transport etc. Literature states that artificial reef designs could involve in and improve ecosystems dependent on some of these factors, which are described below (Spieler et al., 2001; Grove, 1982; Bohnsack and Sutherland, 1985; Bailey-Brock, 1989).

- Surface
  The first factor is the surface. This is the design component on which larvae settle. Every material type has other surface characteristics determined by the texture, complexity and colour (Spieler et al., 2001). These factors can determine the settling preferences.

- Complexity
  For artificial reefs, the complexity determines the biotic assemblage (G. B. Smith et al., 1979; Loke et al., 2015; Loke et al., 2014; Sherman et al., 2002; Shulman, 1984; Helvey and Smith, 1985, Gorham and Alevizon, 1989; Hixon and Beets, 1989; Bohnsack, 1991; Charbonnel et al., 2002; Moschella et al., 2005). This includes the amount of openings, voids and surface irregularities (Bohnsack & Sutherland, 1985). Increased structural complexity, tends to enhance settlement of coral larvae (Carleton & Sammarco, 1987). Due to complex structures, shelter can be provided and could therefore protect corals. In shallow marine areas, coral recruitment frequently favours shaded areas which could be provided by a high complexity in structures (C. Wallace, 1985; Maida et al., 1994). Complexity of habitats could also be provided by installing caissons, blocks or rocks of different heights, shapes etc. It is believed that uneven (modified) surfaces can improve coral abundance (Maekouchi et al., 2008; Foster et al., 2010).

- Texture
  Surfaces with rougher texture are favourable for, in any case, stony corals according to some literature (Carleton and Sammarco, 1987; Harriott and Fisk, 1987; Tomascik, 1991; Spieler et al., 2001). The recruitment dependence by texture is still species specific (C. Wallace, 1985;). Soft corals in general have other settlement properties and could prefer rims and corners and less exposed parts but also rough texture possibly combined with turf or coralline algae (Benayahu and Loya, 1984; Benayahu and Loya, 1987). Abrasions and grooves offer possibilities for enhanced coral recruitment (Maekouchi et al., 2008; Akakura, 2005)

- Colour
  Not much research has been executed on the influence of colour on recruitment and development of corals. Settlement preference tends to be towards darker and shaded areas in less deep waters (C. Wallace, 1985). This could indicate that darker colours in shallow waters, promote larval settlement. This is not investigated any further and is an assumption.

- Stability
  The flow of water around a structure is one of the main causes of unstable structures (Grove et al., 1991; Kim et al., 2016). Extreme weather circumstances could be the basis of higher turbid water streams, which result in more and different flow patterns around marine structures (Greenough et al., 2001). And if structures have not been appropriately stabilised or fixed to the seabed, they can possibly damage nearby reefs by rolling around over the corals (doing more damage than good), e.g. during storms (Ceccarelli et al., 2020; Johns et al., 2018; Fox and Caldwell, 2006; Cameron et al., 2016). Examples of this are reef balls and car tyre reefs (Hylkema et al., 2021). Unconsolidated materials commonly have implications on coral recruitment by decreasing the survival rate of corals (Viehman et al., 2018; Fox et al., 2003; Fox and Caldwell, 2006; Yadav et al., 2016). Unstable substrate, increases the probability of hydrodynamic alteration on the substrate (Viehman et al., 2018). Without appropriate measures to stabilise substratum, the mobility threshold of loose material remains low and coral colonisation is less likely (Viehman et al., 2018).

- Orientation
  Since environmental factors as currents have impact on the stability of substrate by marine con-

struction, the orientation of substratum or the structure in general should be accounted for. The orientation of a structure, depends on its main functions and is site specific. A study proposed to orientate structures functioning as reefs, perpendicular to current directions (Nakamura, 1982; Bohnsack and Sutherland, 1985). More research is needed to figure out if this is the case. In addition, marine infrastructures are being constructed to fulfil a certain function. This could be the breaking of waves or mooring of vessels for example. Orientation of these structures should be done according to the functionality of breaking waves or mooring vessels in combination with growing coral reefs, unless proven otherwise in future research. However, research already indicated that substratum orientation in the vertical direction is promising for coral colonisation. Horizontal substrate that is faced upwards, creates space and opportunities for species development that are competitive with coral (e.g. algae). For this reason, downward facing (underside) and sloping or vertical orientation of constructions/plates/elements could be more suitable for coral development. Enhanced light and food availability for competitors are possible causes for space competition and overgrowth. (Ushiama et al., 2016; Vermeij, 2006; Akakura, 2005; Tomascik, 1991; Carleton and Sammarco, 1987; Harriott and Fisk, 1987).

- Size
  A small marine structure, offers little room for coral to develop. The larger the structure, the more 'suitable' substrate for benthic organisms and especially for coral reefs can be created. Smaller constructions probably have less impact on the environment, since less material is used and therefore the ecological footprint is smaller. On the other hand, a larger construction creates a larger footprint/placement area, with negative consequences for the environment. The construction and maintenance requires more work with increased possible damages for coral habitats. But large amount of substrate offers more space for coral recruits, since the probability of settlement increases when suitable substrate increases.

- Placement area
  Without devise and execution of measures, existing corals underneath future marine constructions, will probably be destroyed due to the weight of the construction. The difference between a small and a larger placement area, is that larger placement areas logically entails a larger area where corals can be destroyed. When the placement area within a relatively small reef, is large, coral could simply not have the capacity to re-grow naturally in the same area. This could be the case when a reef is threatened by climate change and therefore has low resilience. Additional factors such as low connectivity and small coral coverage would probably not encourage coral development here. For smaller placement areas (relative to the entire coral ecosystem), less coral will be destroyed and regrowth will probably happen faster without human interventions. A positive effect could be that due to a relatively larger placement area, this area is rearranged to take into account coral health, coral coverage, predators, invasive species etc. This 'reset' is an opportunity to create an ecosystem that is more resilient and healthier than before the intervention. To that end, certain measures should be in place.

- Wet surface area
  The type and also the availability of substrate, could influence settlement of corals by sending more cues (Ritson-Williams et al., 2009). Other factors such as larval availability, post settlement survival and development should be positive (Ritson-Williams et al., 2009). When the wet surface area increases and when the substrate is in principle suitable for coral recruitment, the chance for larvae to settle and attach to the substrate and develop into well functioning corals, also increases. Substrate suitability for coral recruitment, can be found in the material properties per material. The wet surface area can be orientated vertically, horizontally or inclined. This depends on the material, type of structure and purposes. Research confirmed by own observations, revealed that inclined and vertical elements in structures are typically more beneficial for coral growth than horizontal elements, since settlement rates for horizontal elements are lower (Tomascik, 1991; Carleton and Sammarco, 1987; Harriott and Fisk, 1987). Additionally, corals frequently prefer to settle on complex substrate surface areas due to the effects of sheltering (Spieler et al., 2001).

4.3.2. Conclusion

The hard engineering but also soft engineering effects (Appendix B on coral environment and on possible coral stimulation are diverse. Soft Engineering elements, mainly induce negative effects on the environment. Therefore the Soft Engineering management methods on corals will be focused on mitigation and protection interventions. For Hard Engineering, literature and observations indicate that hard substrate when properly implemented, could lead to enhanced coral value. Concrete if applied sufficient, looks to be sufficient for transitioning into a natural reef. Wood and steel tend to enhance recruitment but functioning as reef substrate is less suitable. However, all steps should be followed as indicated in chapter Chapter 2 in order to create added value for corals.

4.4. Potential measures for coral-inclusive marine infrastructure

4.4.1. Hard Engineering

Possible recommended measures for hard engineering structures with different components are explained in this section.

Material properties

Concrete

- Apply concrete in the marine environment months for coral spawning events, to leach before larvae can settle on concrete substrates.
- Eco concrete reduces its carbon footprint compared to regular portland composite concrete. This is done by implementing supplementary cementitious materials (SCMs) (Flatt et al., 2012). Less portland cement is needed and together with the use of SCMs, eco-concrete is made more durable and sustainable. Calcium carbonate based pozzolan material is used as SCMs. Another material that is used to reduce its concrete carbon footprint, is the use of slag cement instead of portland cement.
- Use a mix design of recycled coral based material, which improves the recruitment of corals on this concrete type. A positive effect is the high performance and service life of this concrete and lower environmental impact compared to regular concrete. An example is Ultra-High Performance Concrete (UHPC) (X. Wang et al., 2017).
- Use plasticizers to lower the water to cement ratio. This decreases the permeability and increases the longevity of concrete (Rai et al., 2012; Nagrockiene et al., 2013).
- Use pozzolanic materials instead of cement. It reduces the ordinary portland cement production which decreases the amount of carbon dioxide released in the atmosphere. Pozzolanic material is also used to create better bonding between aggregates and makes the material stronger over the longer term (Franke and Sisomphon, 2004; Massazza, 1993). One of the ideal pozzolanic materials is fly ash. Concrete with fly ash, requires less water for the same workability. Furthermore, it reduces the permeability and costs (Nath & Sarker, 2011).
- Use as much recycled concrete for the construction of 'new' marine infrastructures. However, check recycled concrete of undesirable components before application.
- Use molds to create complex 3D structures and components.
- Use non-solid armour units. without smooth interlocking, preferably irregular armour units with different sizes that interlock due to their size differences. This creates a habitat/substrate where the surface structure differs over the distance, which creates a more suitable place for coral recruitment (Nozawa et al., 2011).
- Roughen concrete texture/surface by adding coarse sand to the mixture which can be shaped to the exact design specifications (Fitzhardinge and Bailey-Brock, 1989; Brock et al., 1985).
- Use reinforced concrete for structures when tensile forces are present. Corrosion of steel within this structure could become a problem. Use one of the corrosion monitoring system as addressed by Song (Song & Saraswathy, 2007).
- Use concrete armour blocks with surface processing techniques as gutters on the surface (Akakura, 2005). See Appendix Figure D.15 as example.

- The use of Sulpho aluminate cement together with the use of sea water and marine sand decreases costs, Co2 and PH values. The low PH values are enhancing environmental conditions and makes concrete faster attractive for marine life (Xu et al., 2019).

Metal (steel)

- Use corrosion inhibiting admixtures to increase corrosion thresholds but watch out for negative effects for coral development. Anti corrosion applicants could hinder corals attaching to metal. (Subcommittees et al., 2004)
- Monitor corrosion development of the metal structure. This can be done by taking regular observations.
- Addition of horizontal hard substrate. This is a measure that should be implemented if the structure consists of solely vertical components and no suitable substrate is present on the horizontal bottom. Corals, that fall off steel walls, will end up on the new substrate and could try to regrow again, preferably by the help of humans. Attachment of loose colonies on substrate probably results in less mortality than without attaching corals (A. Hylkema, personal communication, November 17, 2021). This can be the result of unstable and moving coral fragments due to the swell. Colonies can be attached and stabilised with polythene strings to the sea bed (Lindahl, 1998 Lindahl, 2000). However, horizontal substrate could end below the sediment. An artificial reef could also be an option.
- Angle vertical steel components in the design. Add horizontal or angled components to prevent corals from falling off.
- Aluminium alloys may exhibit greater corrosion resistance than carbon steel (Reboul & Baroux, 2011).

Rock

- Monitor the structure and environment constantly.
- Study rock availability in the area, which suits to the needs in terms of durability, strength, texture, amount and the suitability of substrate for coral development.
- Especially for smaller rocks, apply substrate stabilisation and eventually small modular structures as reef balls, EcoReefs or other 3D frames (Hylkema et al., 2020; Geoblock, n.d.) to increase the complexity of the structure (Ceccarelli et al., 2020). Natural stabilisation can be achieved for low hydrodynamic circumstances and when the rocks interlock (Ceccarelli et al., 2020). Netting or mesh could help in active stabilisation when natural stabilisation is not possible. Reinforcement bars through rocks is also a solution; putting larger rocks on top of the unstable ones and grout injecting (Ceccarelli et al., 2020).
- Implement scour protection to minimise scour around the structure.
- Minimise the placement area if coral is present at the location.

Wood (timber)

- Use heartwood to lengthen the life span
- Use protective/chemical materials against fire and abrasion but do not use materials which affect the marine environment and coral development (Subcommittees et al., 2004).
- Use turpentine wood as resistance to marine borers (Cookson & Barnacle, 1987).
- To overcome buoyancy, drive wooden piles with light hammers and large drops.
- Use fenders to protect against mechanical forces.
- Roughen wood by sanding to create a rougher texture.
- Try to construct as much ex situ as possible, to minimize damage to the environment.
- Use regional sustainable wood and try to recycle as much as possible.

Design

Size

Small

- When the structure is small and when recruitment is low due to low larval supply, inoculated substrate becomes an option. This is pre-conditioned substrate with coral larvae (M. Y. Hein et al., 2020). The new substrate can be deployed with marine infra, to try to develop coral ecosystems. For larger structures, releasing of larvae at the marine infra is probably a better option, since inoculated substrate will not cover the entire site and the labour intensity is high (M. Y. Hein et al., 2020).

- Check the wet surface area. if small, apply small artificial coral stimulating structures (Reefball, EcoReef, Biorock, Mars spiders etc.) (Boström-Einarsson et al., 2020).
- Focus on ridges, material properties with texture and complexity to increase usability of micro-structures for coral development.

Large

- Try to maximise wet surface area and minimise the placement area by making use of 'hollow' constructions or other placement area minimizing concepts. This decreases material use, which reduces costs and maintenance.
- The use of the right construction material, will be expressed in a habitat that transmits sufficient cues to larvae, to stimulate recruitment (Ritson-Williams et al., 2009; Meyer et al., 2009). Therefore, it is important that for a large structure the right construction materials are chosen. Check therefore the material properties.
- Increase the roughness of the outer layer and try to maximize surface irregularities by adding blocks. Do not use labour intensive techniques.

Placement area

Small

- Study of the coral species types in the placement area. Relocate low resistant and endangered coral species, before construction takes place. Finally relocate these species to the original location in combination with the structure if substrate is sufficient. This can be done with the assistance of an intermediate nursery phase in situ or ex situ. (Boström-Einarsson et al., 2020; M. Y. Hein et al., 2020) Only in situ gardening should be executed when environmental and hydrodynamic factors do not exceed coral species threshold values (Boström-Einarsson et al., 2020). See chapter Section 3.2.1. Keep in mind that the costs for ex situ culturing is higher than in situ culturing (Edwards & Gomez, 2007).
- To stimulate re-growth, small labour intensive breeding techniques are an option. Think of selective breeding, ex situ nursery tanks and in situ nurseries. As an example: stocking (reseeding) of larvae on substrate is a possibility. Bundle the collection of eggs and sperm for fertilization or sample slicks. Then rear the larvae and reseed these on the substrate.

Large

- Avoid labour intensive coral relocation techniques if the majority of corals that occur in the placement area, also occurs in the nearby areas and if they are not endangered (Red list) and are resilient (natural system). For these coral species, conduct the same measures as for small placement areas: transplant with the intermediate nursery phase.
- Focus on increasing connectivity with other reefs (use MPA's).
- Make use of sexual propagation methods when passive techniques do not work: larval enhancement and asexual propagation methods: direct transplantation and coral gardening with an intermediate nursery phase (ex situ or in situ), transplantation phase and micro-fragmentation. Advised is to use an intermediate (ex situ) nursery phase such as the reefguard (van Koningsveld et al., 2017), to avoid undesirable external factors during nursery (for in situ). This is however totally dependent on the location and should only be executed if larval supply to the location is low.

Wet surface area

Small

- Use substrate enhancing methods as addition of substrate by the use of artificial reefs or micro structures (Bio rock, ecoreef, reefball etc.) (Boström-Einarsson et al., 2020).

- Another substrate enhancing method: stabilisation of current substrate when substrate or parts of substrate are mobile. Different options are available. This can be done by the use of mesh or nets over mobile rubble parts (Lindahl, 2003), driving of reinforcement bars through rubble (Fox et al., 2005), putting extra weight by large rocks on top of loose rocks (Fox et al., 2019) use natural fibre bags to collect all loose rubble and place these in closed bags or in baskets on the reef or inject grout to stabilise mobile parts (RRAP, n.d.).(Ceccarelli et al., 2020)
- Try to use as many inclined elements in the design as possible. Sloping walls are a useful alternative due to the enlargement of the wet surface area. This enlarges the wet surface area by creating shallow flats. Think of step structures and sloping structures.
- Placing stones outside construction to create more shallow flats around structure.
- Uneven processing on vertical walls (caissons) by making protrusions (Akakura, 2005).
- For vertical piles, increase the wet surface area by enlarging the pile diameter and let the pile slope at an angle.
- Focus on increasing of ridges, texture and roughness.

Large
- Do not use labour intensive techniques.
- Stabilise substrate by using large nets or putting extra weight on top of loose rubble (Ceccarelli et al., 2020).
- Increase the connectivity (MPAs) to increase the probability of success for recruitment.
- Include large scale larval enhancement techniques.
- Enhance mass culture of juvenile corals in a nursery followed by outplanting juveniles. The coral engines would be an option such as the reefguard (van Koningsveld et al., 2017).

Texture, Stability, Orientation, Complexity
These components contribute to coral enhancement according to literature (Section 4.3.1). Complex texture, stable substratum and non-horizontal construction components could enhance potential coral development. Keep the following recommendations in sight:

- Allowing space between elements (caissons, stones) causes better circulation of sea water and is therefore positive for coral development.
- Place blocks/caissons unevenly (with varying heights etc.).
- Apply surface processing on concrete structures or rocks.
- Use vertical wall processing techniques. The software tool CASU, is conceived to create and visualise habitat complexity. The CASU focus was on creating complex moulds for concrete units. This software can now also be applied for other materials. (Loke et al., 2014)

4.4.2. Conclusion
Different actions or applications can be executed to create coral-inclusive infrastructure as indicated above. One of the important recommendations is to us ‘natural‘ substrate or substrate that is closely related to natural occurring coral substratum. The material properties can be adjusted to enhance coral development on these materials. Think also of design components such as texture, stability, orientation and complexity which can change coral development.

4.5. Conclusion
In this chapter, the possible hard- and in Appendix B, the soft-engineering elements were investigated in order to create coral-inclusive potential for area’s allowing coral development. Sufficient hard substrates could lead to the generation of a coral-stimulating environment. This means that if coral development is required and the natural system allows coral development, hard marine structures are possible solutions to enhance coral development. Meanwhile, soft engineering does not initially lead towards a coral-stimulating environment. Sand is not a preferred substrate for coral development. Mitigating measures should be in place. Hard engineering of hydraulic structures or artificial structures could lead towards the choice of coral-enhancing environments due to the addition of suitable substratum. The material properties, concrete and rock, occur to be suitable coral-developing substrata.

However, there is still much to be gained on material properties regarding nature inclusivity (carbon footprint, production, transport etc.). Texture, roughness, the wet surface area and stable structures could be decisive for coral development and should be focused on. Creating ridges, transform slopes, decreasing the use of material and placement area are actions favouring corals. Together with coral propagation methods dependent on the effort (structure size) and costs, coral growth could be stimulated.

5

Application of the systematic method

This chapter elaborates more on step 4, named in methodological Section 1.4.2. The goal of this chapter is to evaluate whether the systematic method works. This will become apparent from the application of the systematic method to the case study according methodological step 4. This can show whether the method is suitable for providing guidance to stakeholders who want to build nature-inclusively. Or in other words, this chapter is used to verify if the method works optimally in practice by application of the systematic method. Observations, literature, interviews and measurements are providing the information that is needed.

5.1. Introduction

A case study with an actual implementation goal would corroborate the approach towards implementing marine infrastructure in coral habitats. A clear construction purpose is needed to concretize the project. In addition, access to the site should be possible for measurements and observations. Opportunities for stakeholder interviews should be made available. One of the places where nature is under pressure and where the intention is to develop marine infrastructure for socio-economic development, is Sint Eustatius. Subsequently, Rijkswaterstaat (Netherlands Ministry of Infrastructure and Watermanagement) offers opportunities to conduct research on Sint Eustatius. For these reasons, this location and specific case study was chosen.

5.2. Step 1 - Project Description

5.2.1. Location description

The area of interest depicted for the case study is Sint Eustatius (locally known as Statia). Sint Eustatius is one of the Dutch Caribbean islands, located in the northern part of the Caribbean islands, also referred to as the 'Lesser Antilles'. The island of Sint Eustatius is 21 km^2 in size (De Freitas et al., 2012), is populated by roughly 3200 inhabitants and is a 'special municipality' within the Kingdom of the Netherlands (government, 2020). St. Eustatius marine environment is home to rich diversity of coral community (30 km^2) on lava subsoil (Bak, 1975; Bak, 1977; Meesters et al., 2019).

One of the largest employers of the island is the oil terminal: GTI Statia (Debrot et al., 2014; De Freitas et al., 2012). Additionally, the population on the island is completely dependent on the import of goods and food, which has increased over the last period (Meesters et al., 2019, LNV and IenW, 2020). The island has a small harbour on the Southwest of the island (see Figure 5.1) and an airport. The island's rich history as a trading location in the 17th and 18th centuries is still visible and appealing to visitors. The tourism industry receives 10.250 visitors per year (before COVID-19) (Cado van der Lely et al., 2014; Kateman and Bos, 2010). According to Tieskens et al. (2014), the coral reef area is important to the economy of St Eustatius, since the tourism sector belongs to the main economic drivers of the island. Two marine reserves where no anchoring and fishery is allowed are located on the north and south of the island (see: Figure 5.1).

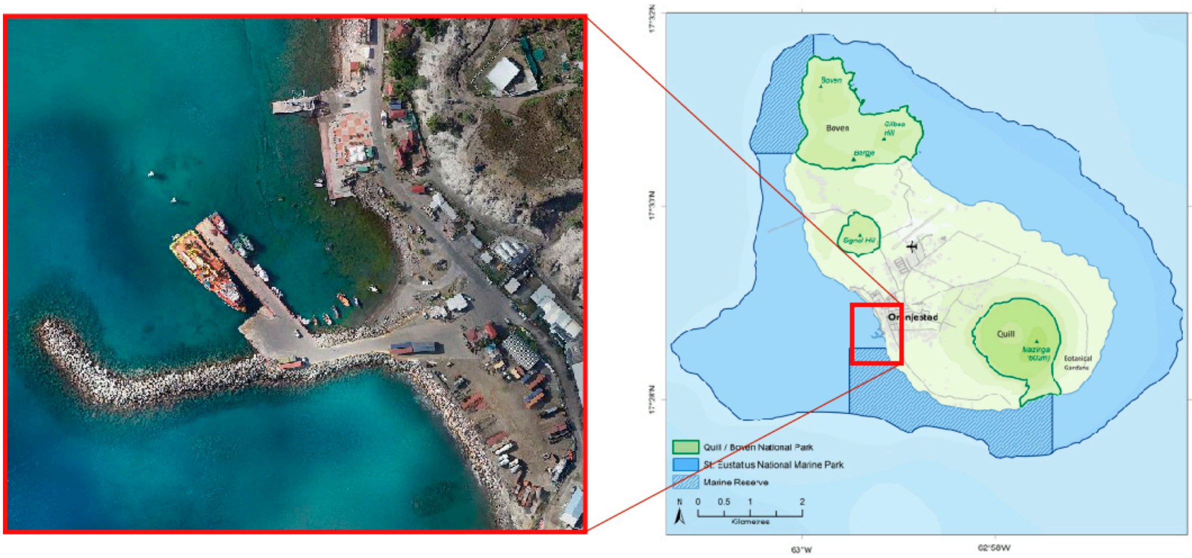


Figure 5.1: On the left the top view of the harbour (taken from QGIS). Right figure: Map of the island St. Eustatius (van Andel et al., 2016).

The average, seasonally influenced yearly rainfall is 986 mm and hurricanes frequently sweep across the island (Debrot et al., 2014). Other threats raised by Cado van der Lely et al. (2014) are invasive species, sand mining, littering, overfishing, construction and oil spills (Fenkl et al., 2014).

5.2.2. Problem analysis/definition

Harbour activities, excluding the oil terminal, includes shipping of goods and food (LNV & IenW, 2020). According to conversations with M. Ruijter of Rijkswaterstaat (Ruijter M., personal communication) and interview(s) with the harbour master of Sint Eustatius, G. Maduro and the commercial manager transport of Sint Eustatius, V. Oedjaghir (Maduro G., Oedjaghir V., personal communication, June 29, 2021), St. Eustatius needs to expand its port facility. This is due to two reasons: (Ruijter M., personal communication; Maduro G., Oedjaghir V., personal communication, June 29, 2021):

- In the seaport, a relatively strong surge has been noted (Slijkerman et al., 2011), resulting in disturbed seas for berthing, loading, and unloading. As a result, ships frequently depart the port after loading/unloading to anchor offshore where the sea is calmer. Port expansion with breakwater protection will probably diminish swell and create calmer waters inside the harbour (van der Leer et al., 2018). Instead of mooring offshore, ships can stay inside the harbour.
- Nowadays, relatively small ships and only one ship at a time may berth in the harbour. (Kateman & Bos, 2010). See Appendix Figure D.17 for vessel types, capacity, frequency and duration of stay. Expansion of the port will create space for larger sized ships and additional mooring places (van der Leer et al., 2018). Yacht berthing and small cruise ship berthing may become more viable options.

Another problem is the decline in coral coverage from an average of 22% in the region (Klomp and Kooistra, 2003) towards an average of 5% coverage measured on 20 different locations around St Eustatius in 2015/2016 (de Graaf et al., 2015; Piontek, 2016). According to LNV and IenW (2020); unfavorable conditions, diseases, algae overgrowth, climate change, eutrophication, coastal development and overfishing are considered as possible causes for coral degradation around St Eustatius. Furthermore, the marine reserves do not include all valuable coral reefs inside their boundaries. This includes the area around the harbour. For example, one valuable reef is partly located in the anchoring zone (Figure 5.9).

The final problem is the difference in stakeholder perspectives on the approach to make socio-economic progress or to choose for ecosystem protection. Rijkswaterstaat and the port authorities are of the opinion that the port facility needs to be expanded due to earlier mentioned reasons to gain socio-economic progress (Ruijter M., Maduro G., personal communication). The environmental organization on the island (Stenapa) and the research institute (CNSI) do not deny this, but believe that focus should be on ecosystem protection at all times. According to them, direct adverse effects on (healthy) coral reefs should preferably be excluded or kept to a minimum (Stapel J., Boman E., personal communication).

5.2.3. Design definition

The original design objective is to expand the harbour in order to create space for larger and more vessels and calmer waters for (un)loading activities.

The design requirements are subdivided into categories (Molenaar & Voorendt, 2020), which are described below:

- Functional requirements:
  - Enlarge berthing capacity
  - Creating calm conditions within the harbour
- Structural requirements:
  - Construct-ability: should be relatively easy to construct without influencing harbour activities.
  - Stability: should be stable during all weather circumstances.
  - Strength: withstand large wave impacts from storms and hurricanes
  - Maintainability: maintenance on the structure should be executed relatively easy

Witteveen+Bos (W+B) designed the harbour (breakwater) expansion for the Ministry of Infrastructure and Water Management (IenW). The design goal was to create a future-proof, hurricane-resistant harbour (van der Leer et al., 2018). W+B investigated alternatives in regard to area usability, navigability, wave penetration, hurricane resistance and costs. The following alternative breakwater lay outs were assessed:

Figure 5.2: Three lay-out alternatives studied in detail by W+B (van der Leer et al., 2018).

The following findings emerged from the W+B report (van der Leer et al., 2018): None of the layouts are large enough to provide shelter from all wave directions. The design on the right has been revealed to an effective solution at creating a calmer wave environment in the harbour. For this layout, frequent areas used for berthing purposes are sheltered and is therefore chosen to be the optimal lay-out. Furthermore, various cross section alternatives were investigated. The preferred option is to use Accropode 10 m^3 with a design return period for hydraulic conditions of 100 years. This option resulted in slightly higher costs but improved storm resistance.
W+B defines the following 'starting points' for the development of the current breakwater into a nature (coral) inclusive solution based on the preceding information (van der Leer et al., 2018):

- An expansion of the current breakwater

- similar dimensions as current breakwater
- Rubble mount structure

The last stage within the design definition are the boundary conditions. This is divided into three categories:

- Natural boundary conditions
  - **Hydraulic:**
    Near St. Eustatius, a mixed diurnal micro tidal range of 10 to 20 cm exists (Kjerfve, 1981). However, a semi-diurnal area is located west of Statia. Kjerfve (1981) believes that a mixed semi-diurnal tide is also plausible.
    Swell is generally coming from SE (55%), 23% from SSE and 10% from the North according to van der Leer et al. (2018). Waves coming from W/NW (30 % of the time) are not stopped by the breakwater and enter the harbour with wave heights between 0.3 and 0.8 m (van der Leer et al., 2018).
    Wave heights up to 5-6 m could occur during storms (Slijkerman et al., 2011) but for 95% mean significant wave height (H_s) is below 0.55 m (van der Leer et al., 2018). Hurricanes can induce large storm waves. However, H_s (and T_p) is seasonal fluctuating as can be seen in Appendix Figure D.23 and Figure D.24 (van der Leer et al., 2018). High waves occur generally in the winter and summer periods. Low wave periods are frequently occurring during summer periods (van der Leer et al., 2018).
    There is a lack of current (flow velocity) information due to the absence of realistic measurements and documentation. Near the harbour, the plausible estimate is: 10 cm/s (directed Northward) (Slijkerman et al., 2011). This, however, is an estimate and should not be taken for granted. However, currents look likely to be wave driven (van der Leer et al., 2018).
  - **Meteorological:**
    Wind on St. Eustatius primarily comes from the northeast to the east, with gusts ranging from 2 to 3 Beaforts (Kateman & Bos, 2010). Because the harbour lies on the leeward side, the harbour is less influenced by severe winds (Slijkerman et al., 2011).
  - **Geo-technical:**
    Soil consists of volcanic rock, sometimes topped with sand (Slijkerman et al., 2011). According to van der Leer et al. (2018); more research on soil consistency should be executed since it is not exactly clear of what the layers exactly consist.
- Artificial boundary conditions
  - Decrease swell inside the harbour. The maximum H_s according to H. Verhagen and van den Bos (2017) at berth should be for fishing vessels: 0.4 m, for General cargo: 1.00 - 1.25 m and for passenger vessels: 0.7 m.
  - Reduce the likelihood of waves entering the harbour.
- Legal boundary conditions
  - The project should meet the legal conditions for a license from Rijkswaterstaat Noordzee (the Netherlands) (Slijkerman et al., 2011).

5.2.4. Design of original infrastructure (if present)

As discussed before, a breakwater is already present and will be extended to create a larger breakwater. According to A. van Heijningen (Economy Infrastructure director of Statia), the current breakwater was built between 1993 and 1995 (van der Leer et al., 2018; van Heijningen, A., Personal Communication, August 9, 2021).

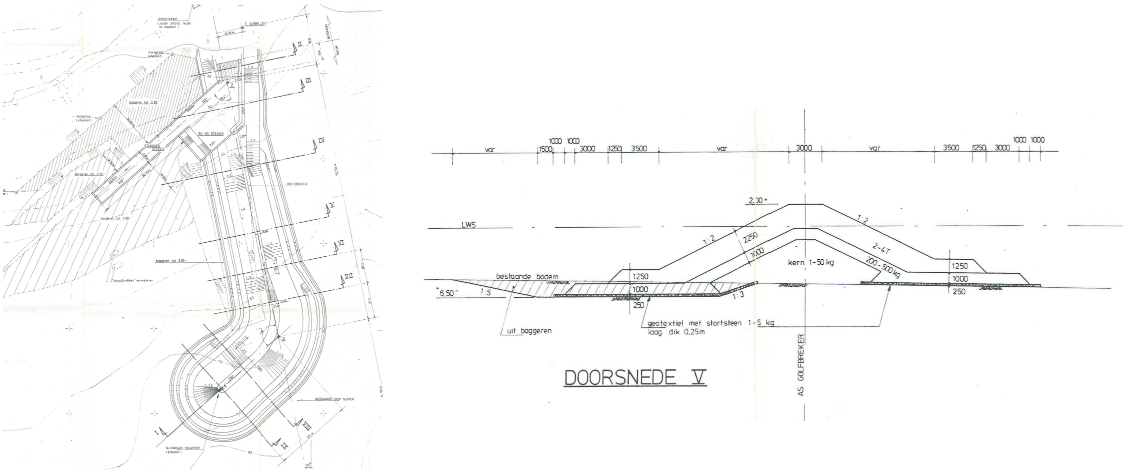


Figure 5.3: Current breakwater design with one of the cross-sections, acquired from D (1992). For detailed version with all cross-section, see Appendix figures **??** and D.19

Different grades of limestone rock have been used for the construction of the original breakwater on top of a fascine mattresses and was build from sea side in 3 project phases. The limestone rock came out of Europe. The breakwater covers a total crest length of 197.50 m (according to Figure 5.3). The stones of the top layer were placed one by one (as closely as possible) and the outer stone layer (top layer) consists of at least two layers of boulders with weight classes of 9-12 tons and 7-10 tons. The weight class depends on the location of placement (see appendix figure D.19). The core consists of 1-50 kg stones. The second layer between the top layer and the core consist of 500-2000 kg stones. (D, 1992; van Heijningen, A., Personal Communication, August 9, 2021).

5.2.5. New initial design

The initial concept is to expand the breakwater in a similar way as done before (Maduro G., Oedjaghir V., personal communication, June 29, 2021). In Figure 5.4, the initial concept, designed by W+B (van der Leer et al., 2018) is displayed. The design will be an extension of the current breakwater.

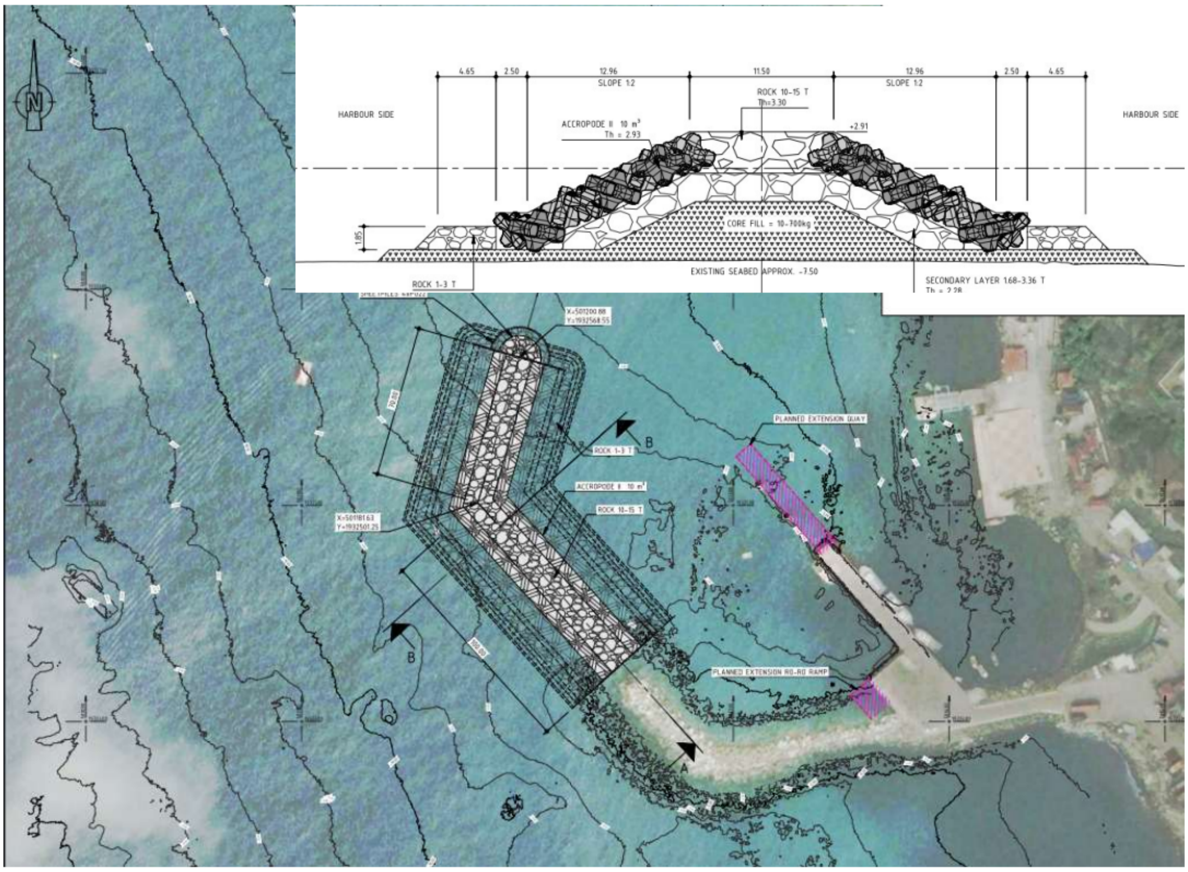


Figure 5.4: According to W+B, this is an ideal layout and cross section in terms of usability, navigability, wave penetration, hurricane resistance, and cost (van der Leer et al., 2018).

5.3. Step 2 - Location analysis

5.3.1. Natural system

On the existing breakwater, several coral colonies are present. Apart from the present breakwater, no coral is visible on the greenfield. However, coral colonies observed on the current breakwater are loose coral spots without a developed coral reef structure. Examples can be found in the appendix: Figure D.16.

When proper substrate is present and the natural system allows coral growth, the location is most likely suited for some coral development. The breakwater was completed in 1995 (van Heijningen, A. Personal communication, August 9), although minimal coral development has been recorded. For a suitable substrate and coral-friendly circumstances, coral development would have been predicted to be greater than what is now observed after a period of 25 years. The goal is to create enhanced coral development on the old and especially new part of the breakwater. Factors hampering coral development are investigated by going through the natural scheme: Figure A.2.

What species are growing on the current breakwater and what are the threshold values for abiotic water quality parameters per species?

Water quality factors

species	Temp (C)	Salinity (ppt)	SSC	Nutrients	PH
Siderastrea siderea (Massive starlet coral)	<30.5	High <42	Tolerance to high siltation and high turbidity values	Low and balanced supply (order 0.1 - 0.15)	7.7 - 8.4
Pseudodiploria strigosa (Symmetrical brain coral)	25 - 29	High <55	Water clarity preference but also found in turbid waters	Low and balanced supply (order 0.1 - 0.15)	7.7 - 8.4
Porites astreoides (shouldard hill coral)	<32	High	Water clarity pref. but common in areas with high sedimentation and turbididy	Low and balanced supply (order 0.1 - 0.15)	7.7 - 8.4
Diploria Labyrinthiformis (Grooved brain coral)	25 - 29	High <55	Little resistance to sedimentation	Low and balanced supply (order 0.1 - 0.15)	7.7 - 8.4
Acropora palmata (Elkhorn coral)	<35.8	Lower 18 - 40	Extremely susceptible to sedimentation (<200 mg/cm2) - clear well circulated water is required	Low and balanced supply (order 0.1 - 0.15)	7.7 - 8.4
Porites furcata (Branched finger coral)	22 - 32	lower 15 - 40	Resistant to sedimentation, preferred water clarity environment	Low and balanced supply (order 0.1 - 0.15)	7.7 - 8.4
Poritis divaricata (Thin finger coral)	22 - 32	Lower 15 - 40	Resistant to sedimentation	Low and balanced supply (order 0.1 - 0.15)	7.7 - 8.4
Siderastrea radians (Lesser starlet coral)	<32	High <45	Sedimentation tolerance	Low and balanced supply (order 0.1 - 0.15)	7.7 - 8.4
Pseudodiploria clivosa (Knobby brain coral)	25 - 29	High <55	Turbid waters but prefer clean waters	Low and balanced supply (order 0.1 - 0.15)	7.7 - 8.4
Millepora complanata (Blade fire coral)	<32	High	Tolerance for high turbidity	Low and balanced supply (order 0.1 - 0.15)	7.7 - 8.4

Table 5.1: Water quality parameters of species occurring on the 'old' breakwater. Made use of the databases in Section 2.7.2.1. Specific Temperature, Salinity and SSC values were obtained. For Nutrients and PH, exact values lack. Therefore general coral threshold values are acquired via literature.
(Humann and Deloach, 2013; S. Smith et al., 2013; Banks and Foster, 2016; Muthiga and Szmant, 1987; Soto-Santiago et al., 2017 C. S. Rogers, 1983; Aronson and Precht, 2016; Lirman and Manzello, 2009; T. F. Goreau and Wells, 1967; Fitt, 2012)

Local water quality parameters will now be checked by literature and from obtained data in the area.

	Values from literature	Information	Certainty	Ref
Temperature	26 - 29 C	from buoy Stenapa (Figure D.20)	Certain, measured over longer period of time.	https://aqualink.org/sites/978 Debrot et al., 2014; Rahn, 2017
Salinity	No information	35.99 ppt was measured but for short period (May - June)	Not certain (short measurement period) Only found in one report.	Kitson-Walters et al., n.d.
SSC	High	Sedimentation by runoff from land, erosion, turbidity from volcanic silt, sometimes heavy swell waves	Not sure, no specific values	citeDebrot et al., 2014; Slijkerman et al., 2011; Meesters et al., 2019; LNV and IenW, 2020
Nutrient	High	more import of material and food, no waste processing Increased nutrient runoff Land based pollution No wastewater treatment	Not sure, no specific values. literature indicates high nutrient values.	Meesters et al., 2019; Debrot et al., 2014; Kitson-Walters, 2020; Lindeboom, 2017; Slijkerman et al., 2011; Debrot et al., 2018
PH	No information	Appears to be sufficient since coral development is observed	Not sure	-

Table 5.2: Local water quality values from literature with certainty/uncertainty taken from the following literature: (Debrot and Sybesma, 2000; Debrot et al., 2018; Slijkerman et al., 2011; Meesters et al., 2019; Kitson-Walters, 2020; Lindeboom, 2017; LNV and IenW, 2020; Gardner et al., 2003)

Water quality parameters on site are not all measured consequently. The following can be done:

- Measure all water quality parameters to get exact values for the harbour of St Eustatius (yearly measurements)
- Measure SSC values, they are probably high. To decrease these levels, the following measures could be implemented:
  - Use coral species occurring in the area that are well developing under local circumstances (resilient, resistant) for coral propagation methods, if needed.
  - If SSC concentrations are elevated through dredging works, tackle the source as described in Laboyrie et al. (2018).
  - When SSC values are not constant and fluctuating find the source and implement erosion mitigation measures; enhance vegetation, fence stray cattle, etc. (Meesters et al., 2019)
- Nutrient levels are also not measured and are probably high according to literature. Still real data is needed to verify this. The following solution can be executed when nutrients are indeed at a high level:

  - Waste management
  - Water storage capacity increase. This can be done by building catchments, reforestation projects, digging channels etc.
  - Stimulate a more circular economy by localising food production end other circular ideas.
  - Decrease the likelihood of erosion and sedimentation (e.g. Replant vegetation)
  - Restore or build ecosystem relations. Mangrove forests could stop e.g. nutrients due to their filtration capacity.
  - Construct dams to hinder water runoff.
  - Reduce sewage dumping in coral areas.
  - A long term policy, focused on sustainability, should be realised.
  - Improve regulations and enforcement.
  - Raise awareness through education.

- Another action is the implementation of placing coral nurseries on the old part and on the greenfield of the breakwater. Gardening should be done for at least a year. Following that, it is possible to determine whether or not coral formation has occurred by observations. This test is performed to see if coral formation is possible regardless of the substrate, based on abiotic (water quality) parameters.

An Acoustic Doppler Current Profiler (ADCP) is used to measure parameters as the water temperature. The temperature is measured from June to August. Temperature values can be seen in the following figure.

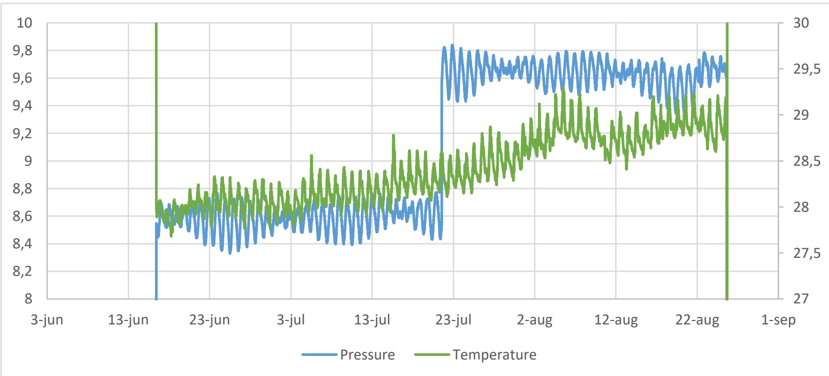


Figure 5.5: Temperature measurements executed from June to August near Statia harbour with an aquadopp profiler (ADCP)

According to figure Figure 5.5, the temperature is increasing from 28 C in June towards 29 C in August. This corresponds to literature (Debrot et al., 2014; Rahn, 2017). To be exactly sure, additional temperature measurements were executed by means of a buoy on the SW side of Statia. See Appendix Figure D.20. The sea temperature during the year is fluctuating between 26 and 29 °C.

Morphological factors
The same application as for the water quality parameters is done but now for the Morphological factors: the hydrodynamics, bathymetry, hurricane risk and substratum availability on location. The location is the harbour of Statia.

species	Hydrodynamics	Bathymetry	Substratum
Siderastrea siderea (Massive starlet coral)	Strong to heavy wave actions are possible	Shallow reef environments Depth: 0 - 70 m	hard substrates
Pseudodiploria strigosa (Symmetrical brain coral)	Prefers hydrodynamic exposure environment	Shallow slopes and lagoons 0.5 - 55 m (mainly <10 m)	hard substrates
Porites astreoides (shouldard hill coral)	wave exposure preference	0.5 - 35 m (1 - 15 m mainly)	rocky substrates and seagrass beds
Diploria Labyrinthiformis (Grooved brain coral)	broad wave exposure preference	1 - 43 m Lagoons	hard substrates
Acropora palmata (Elkhorn coral)	well circulated water is required, wave actions	0.1 - 5 m Shallow tropical reef ecosystems. Can also occur to 40 m depth	hard substrates
Porites furcata (Branched finger coral)	broad wave exposure preference	0.2 - 50 m (mainly 1-15 m) mid slope reef environments and shallow seagrass habitats	hard substrates
Poritis divaricata (Thin finger coral)	Resistance to wave impacts	0.5 - 3 but 0.1 - 35 m also possible. Shallow back reef environments (sea grass beds)	hard substrates
Siderastrea radians (Lesser starlet coral)	broad wave exposure	0 - 3 m tidal flats, seagrass beds, shallow reef environments	hard bottom, rubble fields
Pseudodiploria clivosa (Knobby brain coral)	Wave exposure	0 - 15 m (mostly 0.5 - 3 m) back reefs	hard substrates
Millepora complanata (Blade fire coral)	Water movements with surge, strong to heavy wave action	0 - 15 m breaker zones, shallow water reef tops	hard substrates

Table 5.3: Morphological factors of corals occuring on the 'old' breakwater. Made use of the databases in Section 2.7.2.1 (Tseng et al., 2001; Grigg, 1965)

In general, currents should not exceed 0.75 m/s in order to not damage these corals due to large flow velocities (Tseng et al., 2001; Grigg, 1965).

Morphological factors	Values from literature	Certainty	Ref
Hydrodynamics	Outside harbour: Waves 3-4 m (sometimes 5). Period: 10-20 s New design: only W/NW (30 %) waves enter harbour Hs of W/NW waves: 0.3 - 0.8 m Flow velocities +- 10 cm/s Micro tidal range (10 - 20 cm) Flow velocities during storms: 1 - 1.5 m/s	Measurements are done but exact duration and details are not provided. Flow velocities and directions are not certain at all and should be investigated by extra studies.	Kateman and Bos, 2010 van der Leer et al., 2018 Slijkerman et al., 2011 https://aqualink.org/sites/978 https://obscape.com
Bathymetry	The deepest point of the breakwater extension lies at 8.5 m depth. Towards the coast, the depth is gradually increasing. Erosion is observed in the area (NW) Subsidence is not observed	Sure about bathymetry. Erosion of NW beach is observed but no exact certainty about the origin of this problem. Construction of the harbour is one of the indicated causes. But more measurements should be done to be certain about the cause.	van der Leer et al., 2018 Meesters et al., 2019 Kateman and Bos, 2010 Lindeboom, 2017
Hurricane risk	Category 3-5 hurricanes Occur every 10 years	Certain	Slijkerman et al., 2011 van der Leer et al., 2018 Kateman and Bos, 2010
Substratum availability	In direct area: Low. Vulcanic rock layer with sand on top. Only real available substratum is the breakwater itself.	Certain. Own observations.	Slijkerman et al., 2011 van der Leer et al., 2018

Table 5.4: Morphological factors of harbour together with the certainty and references (Slijkerman et al., 2011; Kateman and Bos, 2010; van der Leer et al., 2018).

Flow velocities on the inside after construction of the extension, look to be sufficient (< 0.75 m/s). The other part of the breakwater will probably experience larger flow velocities, The question arises if these flow velocities would hamper coral development. The same goes for the average flow direction in the area, since larval supply is dependent on the current direction. Since no reliable data is available, only suggestions of hampering of coral development on the breakwater can be opposed.

The breakwater is an area with high wave action, which could potentially limit the type of coral that will grow on these "shallow", highly hydrodynamic areas. Only a few species like to be in shallow, high wave energy areas. Additionally, due to currents, larval supply is not necessarily constant. Ocean currents take the larvae somewhere else and bring them rarely to the breakwater. The Significant wave height is measured on the SW side of Statia by a buoy from Stenapa and NW from the harbour by a buoy from rijkswaterstaat. This data indeed correspond with an average significant wave height between 0.2 and 0.8 m, with occasionaly outliers towards 1 m. See appendix figures D.21 and D.22.
Also hurricanes occur and substratum availability in the area is low. Therefore, the following measures can be implemented:

- Flow velocities are not exactly known around the harbour, therefore the following actions can be taken:
  - Implement coral nurseries to check whether coral development would be possible.
  - Measure flow velocities and directions on outer and inner part of (future) breakwater.
  - Water circulation inside the harbour should be promoted. Monitoring activities and flow measurements should check circulation patterns.

- This area is labeled as a hurricane risk system (3-5 category). Therefore the following actions can be implemented:
  - Implement enough and suitable substrate for faster recovery use niches.
  - Nurse species that grow fast,
  - Enhance substratum by the use of adding artificial structures.
  - If larvae supply is limited, larval enhancement could become an option.
  - Use substratum stabilisation methods
- Substratum availability is relatively low. Therefore the following are possibilities:
  - Implement additional hard substratum (this is already the case for the breakwater extension).
  - Use niches and varying rough surface.
  - Create a large surface for recruitment.
  - Make use of natural materials as substrate.

Current velocities and directions were measured by the ADCP during a three month period (June - August) and can be found in Appendix Figure D.26. Flow velocities were measured on different altitudes above the ADCP. Lower water depth correlates with greater current velocities according to the figures. A current directional shift towards 100 degree (ESE), appears to be underpinning increased water flows towards 0.2 m/s above in the water column and 0.15 m/s near the sea bottom.

The ADCP data depicts data in an unprotected area outside the harbour. It indicates the predicted flow velocity values and directions during the examined time period. To be certain, more ADCP measurements should be taken throughout the year.

Biotic components
The biotic side of the natural system is being carried out (Section 3.2). As previously stated, coral develops on the existing barrier. The information is grouped in a table and looks like this:

Biotic components	Values	Information	Certainty	Ref
Coral coverage check	on breakwater: 5.32 % overall Statia: 2.82 %	Line transect (Point intercept) + literature (photoquad method)	Small, only 1 side of breakwater on the same depth is executed Certainty of literature is high (2020)	Kitson-Walters, 2017
Connectivity	High	On the harbour side of the island, plenty of coral reefs are found (marine park).	Certain. Reefs are used for recreation and education.	Cado van der Lely et al., 2014 Tieskens et al., 2014 Kitson-Walters, 2017 Debrot et al., 2014
Type of reef	Loose colonies	On the breakwater, loose coral colonies (coral spots). Not a developed reef system	Certain (own observations)	
Structure and sizes of corals	Small	Except for two *Acropora palmata*; no large complex coral structures	Certain. Own observations	
Coral species check (IUCN Red List)	1 species	*Acropora palmata*: CR (critically endangered) Other species are stable: LC (least concern)	Certain. According to IUCN Red List	IUCN, 2021
Recruitment limited check	Low recruitment	Current breakwater does not have juvenile corals (0.5 - 5 cm), despite the fact that substrate appears to be adequate.	Certain for period between June - Sep (own observations) Other period uncertain but probability is high for a recruitment limited breakwater during the year.	

Table 5.5: Biotic components on location

The biotic components highlight the fact that, according to the Reef Health Index, coral coverage on the present breakwater looks to be low/poor (5.32 %). The coral coverage on the 'old' breakwater, has to be re-evaluated since the line transect was poorly executed. However, coral coverage looks to be low. Small separate colonies are found on the breakwater and the system appears to be recruitment limited. The outcome is contradictory, because the connectivity is high, since this area is surrounded by coral reefs and current substrate (breakwater) is present and looks suitable. In favourable conditions, it would take at least ten years to produce a reef comparable to a natural reef (Section 4.1). The current breakwater was constructed 25 years ago. After 25 years, an enhanced reef would have been expected. This is however not the case and could be the consequence of poor water quality, hydrodynamic circumstances and/or biotic components. Low recruitment of larvae could be a consequence of negative biotic impacts on corals. The following measures can possibly be included:

- Connectivity is high so recommendations are:
  - Set up a network of MPAs, to monitor and maintain the high connectivity of coral reefs (Wilkinson et al., 2003).

  - More widely distributed coral reefs (reserves) tend to achieve better results than more closely spaced reefs/connectivity (Almany et al., 2009). When the connectivity is high, it is important to check if the connectivity network represents the entire area. Therefore, spatial analysis and data on larval dispersal for diversity of coral species should be studied carefully (Almany et al., 2009).
  - No intensive breeding techniques are needed.
  - Substrate enhancement methods as substratum stabilisation and substrate addition could be beneficial when used correctly (M. Y. Hein et al., 2020).
- The reef is not well developed. Especially separate colonies are present:
  - Relocate of separate coral colonies before implementation of marine infrastructure, with an in or ex-situ phase. Transplant this back to the recipient cite (marine infrastructure).
  - Larval dispersal on newly created substrate
  - Assign MPAs in the environment (mainly upstream of predominant current direction)
- Corals do not have complex large structures:
  - Substratum addition (marine infrastructure)
  - Roughen substratum
  - Add reinforced or heavy weight rubble for substratum stabilisation
- 1 IUCN Red List species is present (2 corals):
  - Protect by assigning a designated marine protected area (MPA)
  - Before building: relocate and transplant these species with intermediate gardening phase in or ex situ.
  - Collect spawn for coral rearing of these species. Grow developed corals on new marine construction.
- The system looks to be recruitment limited:
  - Improvement of connectivity is not necessary, since the connectivity looks to be sufficient.
  - Implement appropriate surfaces to settle
  - Transplant coral
  - Decrease fishing activities
  - Improve poor water quality, monitor constantly (check abiotic components).

In addition, a look at Section C.1 could lead to additional actions. Possible actions that could be used are target fishing of lionfish and the introduction of grazers that consume coral competitors such as algae. This last method is already investigated in Saba with the introduction of sea urchins (Diadema antillarum) in tropical waters for coral restoration (Hylkema, 2021; Altemühl and Vink, 2019). Lionfishing is already done in Statia waters but will not be a long-term solution. This is because lionfish will most likely not fully disappear. Introduction of sea urchins looks more promising if sea urchins could survive and reproduce under local circumstances. However, this requires more research.

5.3.2. Anthropogenic system

Background information

The number of inhabitants is 3100-3200 (LNV and IenW, 2020; government, 2020). Kateman and Bos (2010) state that the population is continuously growing and roughly correlates with the amount of households. However, exact information on the number of households lacks (Fenkl et al., 2014). Immigrants are coming from different countries, including the USA and Europe (Kateman & Bos, 2010). Because Statia was a commercial centre in the nineteenth century, the island is littered with ruins (Kateman & Bos, 2010). This historic aspect is reflecting the ethnicity of the local Statian population. Ethnic groups are: Dutch, Latin American, American and a small percentage of other ethnicitie (Gilmore III, 2005).

Gender and age distribution research on the island is executed by Fenkl et al. (2014). Interviews illustrated a small over population of women over men and a majority of inhabitants are between 30 and 50 years old. Highest followed education by maturity of population is the vocational school/MBO (31.8 %), followed by high school/vmbo and a bachelors (HBO)/college (Fenkl et al., 2014).

Economic situation
In 2019, the Gross Domestic Product (GDP) of St Eustatius was set at 120 million US dollars (CBS, 2021). Particularly the oil industry and the public sector but also the tourism sector have implications on the GDP (Van de Kerkhof et al., 2014). The fishing industry is conservative and small compared to the other industries (DLG, 2011). This is also the case for the agriculture sector but improvement is possible with sustainable initiatives according to DLG (2011). Statia is a non-self-sustaining island that relies significantly on food, products, and resources imported from other countries. The issue is the high expense of local manufacture. Importing products is less expensive since local production is modest and innovation is used sparingly. (DLG, 2011)

Jobs related to coral reefs
There are various work fields related to coral reefs: Fishermen are making use of coral reefs regions for fishing. Fish is commonly exported to other island and countries (LNV & IenW, 2020). However, the fishing sector has only a small number of employees (towards 15) (Cado van der Lely et al., 2014).
Another work sector related to coral reefs is the tourism sector. In this sector, tourists visit Statia especially for marine life around reefs (Van de Kerkhof et al., 2014). 60% is visiting St Eustatius for diving on coral reefs (LNV & IenW, 2020). Dive guides from dive schools Scubaqua and Golden Rock are guiding dive tours through these marine parks.
Marine park rangers from Stenapa (St. Eustatius National Parks Foundation) maintain and monitor marine parks around Statia. Research on and around reefs is done by Stenapa and CNSI (Caribbean Netherlands Science Institute).

Coral reef regulation
Because St. Eustatius is one of the Netherlands 'special municipalities'; nature legislation comes directly under the Ministry of Agriculture, Nature and Food Quality (LNV) (Debrot et al., 2018). This entails national and international obligations as can be found in Figure 5.6.

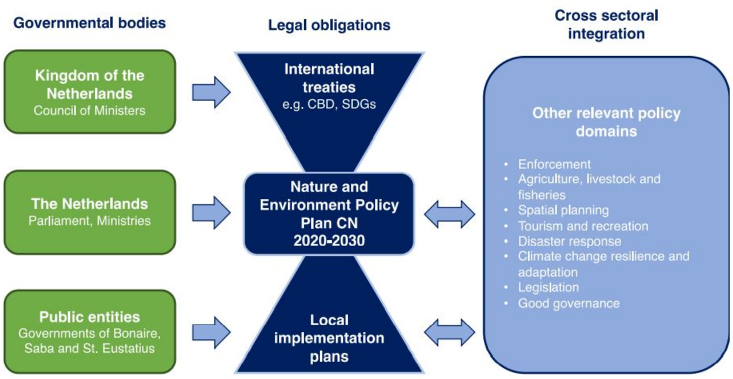


Figure 5.6: Legal obligations for the special municipalities of the Netherlands (e.g. Statia) on behalf of nature conservation (LNV & IenW, 2020)

The following environmental, spatial and other legislation is of interest. For more information about the exact content of these regulations, check LNV and IenW (2020) and Debrot et al. (2018).

Legislation	Name	Info
Environmental	VROM BES	Environmental policy plan
Spatial planning	Wet grondslagen ruimtelijke ontwikkelingsplaning BES	Realizing policy integration
Protected areas	SPAW, Ramsar, CBD	islands are free to decide which areas are designated as protected
Fishery	Visserijwet BES	Fishery policy and management
Others	Wet Elektriciteit en drinkwater BES, De Wet Maritiem Beheer BES	

Table 5.6: Legislation on Statia on behalf of coral reefs according to (LNV & IenW, 2020)

Stakeholders
Conservation and enhancement of (marine) ecosystems as coral reefs, is of importance for all stakeholders on the island according to Debrot et al. (2018). Dutch ministries involved in developing all

components of St. Eustatius are; Infrastructuur en Waterstaat (IW), Binnenlandse zaken en koninkrijksrelaties (BZK), Economische zaken en klimaat (EZK) and Landbouw, Natuur en Voedselkwaliteit (LNV) (LNV & IenW, 2020).
Examples of other stakeholders involved are:

- Marine park management: STENAPA, CNSI
- Local government: Statia government
- Rijkswaterstaat
- Local population of Statia
- NGOs
- Dive schools

5.3.3. Ecosystem services

Ecosystem services of coral in the area (Van de Kerkhof et al., 2014) relate to recreational activities: diving, snorkeling, fishing, aesthetic appreciation. Threats are water sports, overfishing, oil spill, anchoring, invasive species, climate change, erosion, nitrification and littering. Filling in the Anthropogenic system, looks the following:

Human usage functions	Coral dependent (0 - 4)	Info	Coral influence (0 - 4)	Info	Tot	ref
Food provisioning	2	Imports are the primary source of food supply. Fisheries that export fish or employ fish for local consumption rely on coral reefs since the majority of fish occurs here.	3	The reef disruption is not severe but disturbances are increasing. Influenced by anchoring damage, fishing nets etc.	5	Cado van der Lely et al., 2014 Debrot et al., 2018 DLG, 2011
Recreational	4	Diving is one of the most appreciated water based activity and is fully dependent on coral reefs. Coral reef decline is correlated with a decline in dive tourism when coral reef degenerates.	1	Dive related activities are not causing severe effects on corals.Pressures are witnessed but due to dive guides these effects are frequently mitigated	5	Tieskens et al., 2014 Van de Kerkhof et al., 2014
Natural resources	0	Mining of natural resources is not marked as a threat close to coral reefs surrounding St Eustatius (according to literature and interviews)	0	Not influenced, since mining does not take place	0	
Coastal protection	2	A part of marine environment includes developed coral reefs which possibly break waves and assist in natural coastal protection. This is not defined by literature.	3	Building artificial reefs or coral-inclusive coastal protection, could influence coral development (neg and pos). This case-study is a useful example.	5	
Environmental protection	4	The MPAs are fully dependent and relying on coral reefs and visa versa. Because coral reefs have the need to be protected, MPAs are implemented	4	Stenapa monitors and maintains the MPAs around Statia and have observed positive coral development due to MPAs.	8	Piontek, 2016 Debrot et al., 2018
Transport and navigation	0	Ships are frequently sailing to the harbour and the oil terminal. These ships have no coral dependency.	3	Anchoring damage, ship groundings on reefs, pollution (sewage) are all possible dangers to coral reefs. Anchoring damage is a problem for coral reefs near Statia.	3	Tieskens et al., 2014 Debrot et al., 2018
Storage (dumping, littering)	0	Waste storage is not dependent on coral reefs	4	No rubbish waste treatment plant is present on the island. Littering and untreated waste water discharge have negative effects on coral reefs near Statia. Next to the harbour, a energy firm that discharges hypersaline water into the sea.	4	Lindeboom, 2017
Power generation	0	No power generation on marine waters of Statia	0	No power generation on marine waters of Statia	0	

Table 5.7: Anthropogenic usage factors scored regarding coral dependency and influence on corals.

Human usage functions with the highest overall score are food provisioning (5), recreational (5), coastal protection (5), environmental Protection (MPAs) (8) and storage/treatment plants. These factors are relying on and/or have impacts on coral reefs in this area. Threats by ship groundings and waste water discharge are also issues regarding coral reefs. The actions described in Section 3.3 are to be executed to maximise human usage functions and minimise coral loss. Start with the highest score (most important) and follow up towards necessary actions for lower scores.
However, one of the causes for low coral development in the area could be the discharge of hypersaline waters from an energy plant next to the harbour. The discharge should be relocated or another solution for this problem needs to be found.

Furthermore, the following question is asked: is passive or active development of corals necessary according to human usage functions? This question is answered by checking if one of the four enlisted ecosystem services is answered with yes.

- Food provisioning: NO
  Fishing activities are not allowed in and around the harbour according to legislation (visserijwet BES).
- Recreational: NO
  The structure will probably not be available for recreational purposes since it is forbidden to snorkel or dive in the harbour without permission.

- Natural resources: NO
  The area is not used at the moment to mine natural resources for the benefit of humans. This will probably not be done in the future.
- Coastal protection: NO
  Coral development on the breakwater will not enhance coastal development since these corals will not create a fully developed reef which can break waves.
- Cultural services: NO
  No extra cultural service through developed coral on this breakwater will be obtained.
- Biochemical cycling: NO
  Developed coral will not create water refreshment or other water processes on the breakwater.

Humans do not yet benefit from the ecosystem services indicated above in support of coral development on the breakwater. Potentially, a coral-inclusive breakwater could enhance fish in the area and therefore enhances food availability. However, Fishing activities will most likely not be permitted. Coral enhancement could increase recreational value but only when scuba diving and snorkeling around the breakwater is permitted which is not the case. This indicates that the amount of work required to obtain coral development could be maintained to a minimum. Techniques that require less effort could be used. The focus is on passive coral stimulating techniques, in combination with low effort active techniques.

5.3.4. Conclusion

Water quality parameters are not measured to their full extend. 'Poor' water quality could be one of the causes of low coral development. Nutrient and SSC values are missing completely. Furthermore, more insight is given in the hydrodynamics of the area with indications of 0.2 - 0.15 m/s as flow velocities in the water column. However, long term data (>1 year) is needed to have reliable and consistent data. A hurricane risk system is present and biotic components highlight the low coral coverage on the breakwater. High connectivity is observed nearby the breakwater. 1 red list precies (*Acropora palmata*) is present at the old breakwater. Poor water quality, high hydrodynamic circumstances and/or low larval supply could be factors contributing to low recruitment and low coral coverage. The connectivity of nearby coral reefs look to be sufficient. More research is needed to investigate if larvae is transported towards other directions than the breakwater (via ocean currents). Substrate is plenty available and is not likely to be a limiting factor. However the shallow, high hydrodynamic area could be of influence in hampering recruitment.

5.4. Step 3 - Development of marine infrastructure design applications

5.4.1. Detailed design of new infrastructure

The sort of maritime construction that will be constructed is an enlargement of Statia's current breakwater. This maritime structure falls under the category of hard engineering.

The layout of the new breakwater is displayed in figures 5.4 and 5.7. The elements of this breakwater are shortly described according to the initial design plan of van der Leer et al. (2018). The breakwater will be extended with 175 m extra breakwater length.
Armour protection on both sides of the breakwater (van der Leer et al., 2018):

- 1:2 Slope
- Armour layer: 10 m^3 Accropode II units (2.93 m thick)
- Secondary layer: 1.68-3.36 T rock (2.28 m thick)
- Core fill and base layer: 10-700 kg Rock.

Crest:

- Level of crest: 2.91 m MSL
- Rock armour grading 10-15 T (3.30 m thick)
- Crest width: 11.5 m

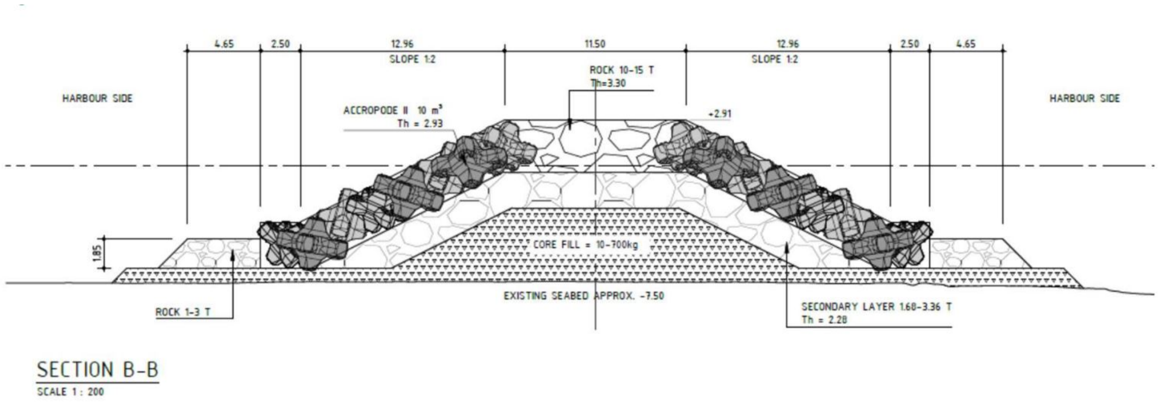


Figure 5.7: Cross section of the breakwater design according to van der Leer et al. (2018).

Toe construction:

- Armour grading: 1-3T rock
- Size toe: 1.85 m thick, 4.65 m wide.
- Toe is on top of bottom level

Relative mass density of concrete used for accropode II:

$$\Delta = \frac{p_r}{p_w} - 1 = 1.3529 \tag{5.1}$$

where	p_r	Mass density concrete	[2400 kg/m^3]
	p_w	Mass density sea water	[1020 kg/m^3]

Stability calculation:

$$\frac{H}{\Delta D} = 2.06 \tag{5.2}$$

where	H	Wave height	[towards 6 m]
	Δ	Relative mass density concrete Accropode	[1.3529 kg/m^3]
	D	Diameter of Accropode	[2.15 m]

Making use of Concrete layer innovations (2012) as a design guide for above values.
2.06 m falls between 1 and 4 m as stability factor and is therefore in the stability category: rubble mound structures.

Type of structure?	Rubble mound	The type of structure is a conventional rubble mound structure. The structure has the aim to protect backwaters. The armour layer encompasses the largest coverage of the structure and is placed randomly, covering one layer (see Figure C.4).
Construction material	Concrete, (rock)	Rock and concrete materials are used as construction material. Rock is used as core fill, the secondary layer is also rock but larger sized. The outer layer and hence the layer of interest for the interaction between the marine work and marine life (corals), consists of rocky materials on the crest and of Accropode II units on both slopes of the breakwater. These Accropode II units are made of concrete (C30/C35). Grading of the core is based on the breakwater of Saba (10-700 kg). Material in the core of the current breakwater is 1-50 kg but is to small to use underneath the filter layer. The crest of the breakwater is above sea water surface and is therefore less suited for coral development. Especially the concrete Accropode units are in contact with marine life.
Size	Large	Comparing this extension of 175 m in length with other marine constructions nearby, provides us only with two similar projects: The current breakwater and the jetty of the oil terminal. The overall size of this breakwater extension is large since the entire volume over 175 m length should be filled with rocks and topped with concrete units or rock (crest). The crest height of the breakwater extension, will be 0.4 m higher than the 'old' breakwater due to steeper slopes. Probably, the height of the current breakwater is declined and needs elevation and reinforcement.
Placement area	Large	A slope of 1:2 leads to a width of 53.72 m. Together with a length of 175 m, this leads to a placement area of 9401 m2. This will be the largest placement area of a marine construction around Statia. The oil terminal is a piled construction and therefore requires less space on the bottom. However, coral coverage underneath the future extension is small or negligible.
Wet surface area	Medium	Wet surface area of the extended structure will be relative large due to its inclining sides. Moreover, the armour units provide more wet surface area due to the irregularities and enlargement of area that is in contact with water. However, the slope of the new breakwater is steeper than the slope of the existing breakwater and therefore has a relative smaller wet surface area per m length than the existing breakwater.

Table 5.8: Hard Engineering structure defined according to the design analysis. (Kateman and Bos, 2010; van der Leer et al., 2018; Concrete layer innovations, 2012)

The information from above leads to potential measures described in Section 4.4.1. Measures for concrete materials should be implemented, since this part is in constant contact with water and marine life.

Furthermore, the use of materials (rock) needed for the breakwater, should be studied. Local production of rock for the fill and sub layers need to be stimulated.

Actions for large sized structures and large placement areas can be followed up. Since the wet surface area is 'medium', suitable measures from both large and small wet surface areas should be selected. All these actions can be found in Section 4.4.1.

5.5. Step 4 - Inventory and ranking of potential measures

Following steps as indicated in Chapter 2, specify the possible actions for a specific case (In this case: Sint Eustatius). In chapters 3 and 4, a list of possible actions and measures are described. Measures have to be specified in more detail according to the inventory and ranking of potential measures approach used in Section 2.9. First, measures are selected based on their relevance to the Statia case. Thereafter, feasibility and effectiveness are assessed per action.

Section	Measures	Feasibility					Effectiveness	Overall	Info
		T	O	Ec	En	Av	+/0/-	G/O/R	
Water quality	More knowledge on water quality is required. Possible high SSC, Nutrients, therefore:								
	Measure all water quality parameters to get exact values for the harbour of Statia: Temperature, Salinity, SSC, Nutrients, PH.	1	1	1	1	1	+	G	Effectiveness: +, because this baseline is needed and effective for future projects.
	Use coral species for development on structure with resilience to high SSC values.	1	0	0	1	0.25	0	O	Effectivity would probably be higher when Environmental conditions are improved
	If ssc concentrations are elevated through dredging works, tackle the source	0	1	-1	1	0.25	0	O	Lower SSC is possible by tackling the source, but is difficult.
	Water storage capacity increase; build catchments, reforestation, digging channels, dams	1	1	1	1	1	+	G	Simple to construct and to operate, run-off is reduced
	Stimulate a more circular economy by localise food production and other circular ideas.	1	-1	1	0	0.5	0	O	Due to populist resistance, it is difficult for St Eustatius to localize food production.
	Erosion and sedimentation measures: e.g. replant vegetation or fence stray cattle	1	0	1	1	0.75	+	G	Replanting cost lots of effort, but will be helpful to decrease erosion, effecting nutrient and ssc values in the harbour.
	Restore or build ecosystem relations. Mangrove forests could stop e.g. nutrients due to their filtration capacity.	-1	-1	-1	1	-0.5	+	O	Effectiveness would be positive, but the creation of ecosystem relations is to difficult for now.
	Reduce sewage dumping in coral areas. (harbour area)	1	1	-1	0	0.25	+	G	Would be helpful for coral development in the harbour, but chance is that the problem will be shifted to other area
	A long term policy, focused on sustainability, must be realised.	-1	-1	1	1	0	+	O	Would be effective, but follow up is not feasible. First enhance education and regulations
	Coral nurserie placement on site, to check whether coral (in general) can develop under present abiotic factors.	1	0	0	1	0.5	+	G	This would indicate if coral would develop on/around the breakwater, without conducting measurements.
Morpholog-ical	More knowledge on flow velocities is required:								
	Since overall flow (current) velocities are not exactly known, flow velocity must be measured on both sides of the harbour (>1 year).	1	1	1	1	1	+	G	More knowledge is needed. This would lead to better adapt a structure or methods to coral growth opportunitites.
	Water circulation on the inside of the harbour should be promoted when water flow velocities are low. Monitor and gather data constantly the flow patterns.	0	-1	-1	0	-0.5	0	R	Too much effort to constantly monitor currents. One year measurements would be enough after construction.
	Due to occurence of hurricanes (3-5 cat), implement more substrate for faster recovery	1	1	1	1	1	+	G	The extension of the breakwater is already implementation of more substratum.
	Nurse species that grow fast	1	-1	0	1	0.25	0	O	Measure would be feasible, but measures which increase coral development naturally are preferred.
	Adding artificial structures	1	-1	-1	1	0	0	O	Would be effective, but since a new artificial reef will be build, no extra artificial structures are needed.
	Larval enhancement if larvae supply is limited	0	0	-1	1	0	+	G	Larval supply is possibly limited, thus could be effective
	Make use of natural materials to use as substrate	0	0	0	1	0.25	0	O	Suitable natural materials are hard to implement in designed breakwater. Finding natural alternatives for concrete with similar characteristics is difficult. Only vulcanic rock can be found in and near Sint Eustatius.
Biotic	Larval supply seems to be limited but high connectivity. Coral propagation actions are within the possibilities.								
	Coral coverage check on breakwater	1	1	1	1	1	+	G	Allowance should be asked for operation in harbour
	Check if the connectivity network represents the entire area. Therefore, spatial analysis and data on larval dispersal for diversity of coral species should be studied carefully	0	0	0	1	0.25	+	G	Difficult to achieve, but would indicate if extra protected area's are needed
	Larval dispersal on newly created substrate	0	0	-1	1	0	0	O	Could be a solution because larval supply is probably limited. High costs and not certain if coral will develop.
	Assign marine protected area's in the environment (mainly upstream of predominant current direction)	1	0	0	1	0.5	+	G	Effective measure, but plans for monitoring and operations are needed due to the presence of an anchoring zone.
	Roughen substratum	1	1	0	1	0.75	+	G	Feasible and effective, needs to be done during design and construction process
	add reinforced or heavy weight rubble for substratum stabilisation	1	1	-1	0	0.25	-	R	No unconsolidated rubble is present around and on current breakwater
	Before building: relocate (2 IUCN Red list species) with intermediate gardening phase in or ex situ. Subsequently transplant back on new breakwater	1	0	0	1	0.5	+	G	Neccesary for protection of Red list species and for develop-ing more species on new breakwater.
	Collect gametes/spawn of species occuring on the breakwater for coral rearing. Grow developed corals on new marine construction.	1	0	-1	1	0.25	+	G	Would be significant step towards establishing corals on new breakwater which survive under existing local conditions
	Implement appropriate surfaces to settle	1	1	-1	1	0.75	0	O	Should not be focused on, since additional substrate via breakwater extension will be provided
	Decrease fishing activities around the harbour	1	-1	1	0	0.25	0	O	Bad for social component, good for fish abundance. Fishing in harbour is not permitted but is still done.
	Target fishing by fishing on lionfish	1	0	1	1	0.75	-	R	Will not be very effective, since not all lionfish will be killed. However, could still be done on recreational basis.
	Introducing sea urchins (Diadema antillarum) in/around breakwater to decrease algae cover	0	-1	0	1	0	0	O	Takes much time, is not a proven concept but if done for research purposes it is an option.
Anthropog-enic	Low effort methods should be preferred: focus on passive techniques								
	Raise awareness through excursions, dive trips, education etc.	1	1	1	1	1	0	O	Very feasible, but the concern is wheter students will follow up.
	Monitor corals on breakwater with the help of marine park rangers, to see the develop-ment of corals and effectivity of measures and actions.	1	1	1	1	1	+	G	This is needed to check whether measurs and actions are functioning and keeps an eye on possible threats.
	Stabilise corals. Use e.g. limestone boulders or cement	1	1	1	-1	0.5	0	O	If coral loss by currents and impact of waves is observed, this is a solution. However, effectiveness is nog guaranteerd and it decreases natural development of a reef system (natural reset)
	Assist or improve coastal protection by building artificial structures with coral friendly materials, implement close to reefs for better connectivity.	0	-1	-1	1	-0.25	+	O	Very costly. Additional reef will already be build by break-water extension. However, add substrate improves probability to coral recruitment and therefore increases effectiveness.
	Improve waste removal and recycling, in order to keep waste out of coral habitats.	1	-1	-1	1	0	+	G	Costly and difficult to operate but would be effective, since water quality must be improved
	The introduction of sustainable fishing gear and fishing limits (use fishing gear as biodegradable netting to reduce the likelihood of coral reef distruction and by catch).	1	-1	0	1	0.25	0	O	Hard to keep under control, Fishing gear improvement can be done by providing fisheries with these tools.
	Erect permanent moorings and compel vessels to use these permanent moorings	1	-1	0	1	0.25	+	G	Corals are often distroyed by vessel anchors around Statia. This would be effective to ensure better connectivity
	Without permanent moorings, vessels must stay under power or anchor only when there is enough sand on the bottom (no coral reefs, see grass madows etc.)	1	-1	1	1	0.5	+	G	Same as above, but include less costs. Difficult to keep manageble without official anchoring zone
Design	Material properaties: Consider possible construction materials:								
Concrete	Use Eco concrete to reduce the carbon footprint and stimulates natural development of marine life.	-1	0	0	1	0	0	O	Does lower carbon footprint. However, it does not influence coral recruitment on this concrete. Thus nog effective.
	Use a concrete mix based on recycled coral material. (Ultra High Performance Concrete or Econcrete are examples).	0	0	-1	1	0	+	G	Would be effective, but is not tested on large scales in constructions. Would be a possible solution.
	Use plasticizers to lower the water to cement ratio. This decreases the permeability and increases the longevity of concrete	-1	0	-1	0	-0.25	-	R	Not effective as a coral developing strategy
	Use pozzolanic materials instead of cement (fly ash)	0	0	1	1	0.5	0	O	Not effective for coral recruitment, but is a way to minimize carbon footprint.
	Use as much recycled concrete for the construction of 'new' marine works. But check recycled concrete of undesirable components before application.	-1	-1	0	1	-0.25	0	R	Use as rubble would be an option, but to reprocess for construction is difficult and not performed on large scale.
	Use molds to create complex 3D structures and components.	1	1	1	0	0.75	+	G	This is the case for the armour units and will increase the complexity of the units.
	Use non solid armour units. without smooth interlocking, but preferably irregular armour units with different sizes that interlock due to their size differences.	1	0	-1	0	0	+	G	Cheaper to construct units with similar sizes, would increase the complexity of structure.
	Make the substrate as irregular as possible. (Roughen concrete texture/surface by adding coarse sand to mixture which can be shaped to the exact design specifications)	1	0	1	0	0.5	+	G	An easy measure to apply. Would enhance roughness and therefore increase the probability of coral recruitment
	Apply surface processing techniques (e.g. gutters)	1	1	1	0	0.75	+	G	Easy to apply if all molds are adapted to form gutters.
	The use of Sulphoaluminate cement together with the use of Sea water and marine sand decreases costs, Co2 and PH values. The low PH values are enhancing environmental conditions	1	1	1	1	1	+	G	Positive effects on recruitment since PH values are lowered.
Rock	Study rock availability in area, which suits to the needs in terms of durability, strength, texture, amount and the suitability of substrate for coral development.	1	1	1	1	1	+	G	Would be an effective measure in terms of local production. Rock/aggregates must be strong enough.
	Especially for smaller rocks, apply substrate stabilisation and eventually small modular structures as Reef balls, EcoReefs or other 3D frames	0	-1	-1	0	-0.5	0	R	Substrate addition is already executed by new breakwater. Thus no extra labour intensive artificial units are needed.
	Netting or mesh could help in active stabilisation when natural stabilisation is not possible.	1	0	-1	0	0	-	R	Breakwater will such be designed that it does not need sub-strate stabilisation.
	Implement scour protection to minimise scour around the structure.	1	0	-1	0	0	-	R	Not neccesary, since the design is already covering this issue
Design others	Minimise the placement area if coral is present on the location.	-1	0	-1	1	-0.25	-	R	Not neccesary, no coral is present on green field.
	Maximise wet surface area in the design by altering the slope or by adding 'steps'.	1	0	0	0	0.25	+	G	More substrate in an affordable way, increases coral settling possibility.
	Minimise the placement area by making use of 'hollow' constructions or other placement area minimizing concepts. This decreases material use, which help reduces costs and maintenance.	-1	0	-1	1	-0.25	-	R	Not effective and technically difficult since the breakwater needs to be strong enough to withstand large impacts from waves and hurricanes.
	Increase the roughness of the outer layer and try to maximize surface irregularities by adding blocks. Don't use labour intensive techniques since structure is large.	1	0	1	1	0.75	+	G	Extra blocks around structure will not be costly and easy to implement and effective due to more substratum.
	Apply industrial scale coral harvesting and culturing spawn slicks, when coral spawn supply is large and time of spawning is known. Seeding needs to be done after construction.	-1	-1	-1	1	-0.5	0	R	Not widely proven and timing of spawning events is not fully known
	When coral spawn supply is low and/or time of spawning is not exactly known, reproduce corals by spawn collection. This can be done in situ/ex situ. Gametes thereafter can be reared ex-situ (reefguard). This needs to be executed before construction takes place.	0	-1	-1	1	-0.25	+	O	Not per definition neccesary, however the collection of gametes from resistent species could be helpful to rear tolerant species for coral development on new breakwater.
	For loose rubble: use bags (e.g. natural fiber) to collect loose rubble and place these closed bags or in baskets on the reef.	1	0	0	0	0.25	-	R	Will not be effective, since no unconsolidated rubble will be present.
	Allowing space between elements (caissons, stones) causes better circulation of sea water and therefore is positive for coral development.	-1	0	1	1	0.25	-	R	Technical not feasible, since the breakwater must be closed without gaps for water refreshment.
	Place blocks/caissons unevenly (with varying heights etc.).	1	1	1	1	1	+	G	Easy to implement, low effort, use different sizes of stones

Table 5.9: Measures for a coral-inclusive solution for the harbour extension in Sint Eustatius. For explanation see Section 2.9. G = Green, O = Orange, R = Red. Feasibility: T = Technical, O = Operational, Ec = Economic, En = Environmental. Effectiveness: Positive (+), Neutral (0), Negative (-).

Measures			Feasibility					Effectiveness	Overall	Info
			T	O	Ec	En	Av	+/0/-	G/O/R	
Active propagation/outplacement of corals										
Transplantation/ Relocattion	Direct transplantation/ relocation	In-situ	1	1	1	0	0.75	+	G	For areas subjected to frequent disasters (hurricanes) or construction interventions towards other area. The other way: after construction, transplant species only from degradating reefs to new breakwater. Fast growth rate (colonies >branches), lower than through gardening, lower survival rate
	Transplant with intermediate nursery phase (gardening)	In-situ	1	1	1	1	1	+	G	(red-list) species can be relocated from the breakwater through an in-situ gardening phase and transplanted back on the new breakwater. Fast growth rate, medium survival rate
		Ex-situ	0	0	1	1	0.5	+	G	Same as above but then ex-situ, this increases the chance of survival but is more costly Fast growth rate, higher survival rate
	Transplantation through micro fragmentation (Nubbins)	Ex-situ	-1	-1	-1	1	-0.5	-	R	Process ex-situ, followed by in-situ placement. Takes much time and is expensive
Larval propagation	Industrial scale	In-situ	0	-1	-1	1	-0.25	-	R	Time of spawning is not exactly known, so this is not an option.
		Ex-situ	-1	-1	-1	1	-0.5	-	R	Time of spawning is not exactly known, so not a viable option.
	Juvenile scale	Ex-situ	0	0	1	1	0.5	+	G	With ex-situ gamete collection, since time of spawning is not exactly known. Overall an expensive method, but high survival rate and low costs per colony. If larval supply is low but (test) nursery shows that coral development is possible then an useful option.
	Small scale	In-situ	1	1	1	1	1	-	O	Only collecting and seeding will not be effective, since time of spawning is not exactly known.

Table 5.10: Active re/outplacement techniques for coral development on the breakwater. Overall score: G = Green, O = Orange, R = Red.

All measures resulting in an overall G (green) score, are recommendations to taken into account for the final design.

5.6. Step 5 - Summary of sustainable design recommendations

New sustainable design recommendations consist of stimulating measures for coral development and mitigation measures to coral threats. A list of possible recommendations is composed from tabel 5.9 and 5.10 and is presented below:

Water Quality

- Gather data (measuring) of all water quality parameters to obtain exact values for the harbour of Statia: Temperature, Salinity, SSC (acidity), Nutrients and PH. This is needed to obtain reliable information in order to act upon. According to literature (Table 5.2) SSC and Nutrient values in the harbour area are probably high and therefore the following measures apply:
- Species with low tolerance to SSC and Nutrients should be relocated (*Acropora palmata*).
- Water storage capacity increase: build catchments, reforestation, digging channels, dams.
- Implement anti-erosion measures: Example, Replant vegetation to decrease the likelihood of erosion and sedimentation.
- Check if brine outlet affects coral in this area. If so remove or reduce.
- Coral nursery placement on site, to check whether coral (in general) can develop under present abiotic factors. An example is illustrated in Figure 5.8.

Morphological

- Value certainty is poor for flow velocities in and around the harbour. Studies have been executed but more certainty on velocities on both side of the current breakwater is needed. Therefore, measure flow velocities for (>1 year) on both sides of the breakwater (Figure 5.8).
- Due to occurrence of hurricanes (3-5 cat), implement more substrate for faster recovery of corals. This is already covered with the implementation of the breakwater extension.

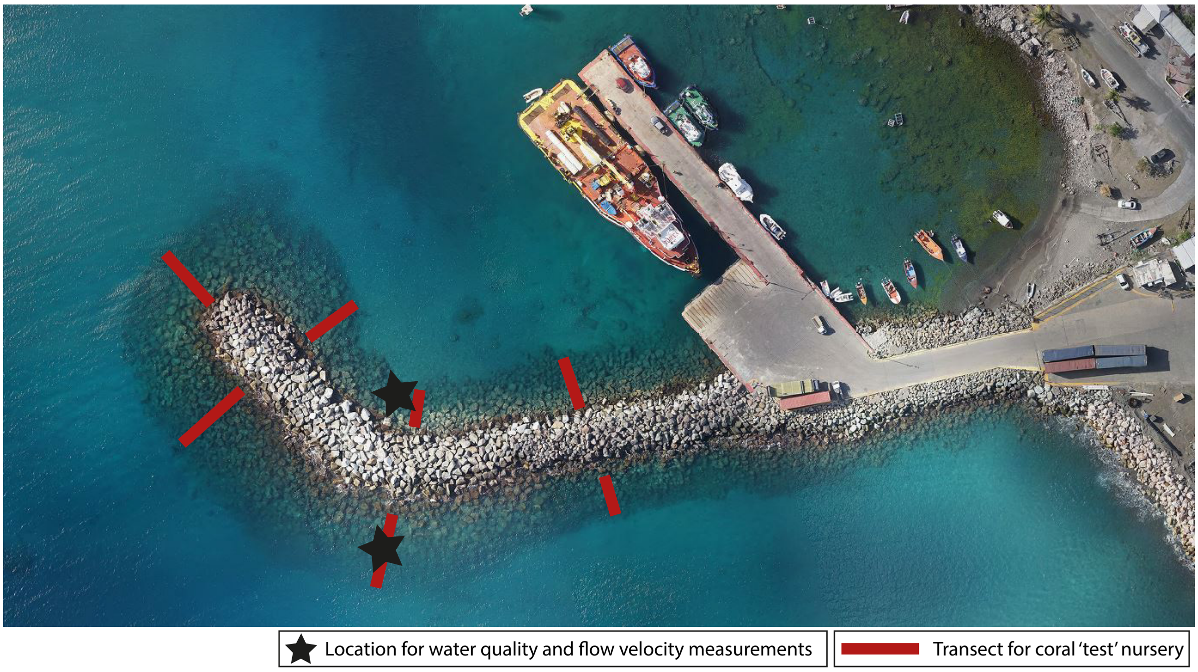


Figure 5.8: The breakwater of St. Eustatius with in red possible transects for the coral reef 'test' nursery. Coral fragments or colonies can be glued on specific depths along the transects. Another option would be the placement of floating or fixed nurseries on specified depths. Monitor coral growth during the execution of the 'test' nursery.

Biotic

- Connectivity is high but larval supply is not per definition abundant. Therefore low effort coral propagation techniques become options.
- Perform a coral coverage check on the current breakwater.
- Assign marine protected areas in the environment (upstream of predominant current direction)
- Before building; relocate 2 IUCN Red List colonies (*Acropora palmata*) with intermediate gardening phase in or ex situ. Subsequently transplant back on new breakwater.
- Collect gametes/spawn of species occurring on the breakwater for coral rearing. Grow developed corals on new marine construction.

Anthropogenic

- The focus should be on passive techniques, since coral development on the breakwater is not per definition needed for ecosystem services/benefits.
- Monitor corals on breakwater with the help of marine park rangers, to see the development of corals and effectivity of measures and actions.
- Improve waste removal and recycling, in order to keep waste out of coral habitats. This implies the discharge of saline water from the power plant (STUCO).
- Take measures against ships damaging coral reefs: Erect permanent moorings and compel vessels to use these permanent moorings. Relocate the current anchoring zone towards a zone where enough sand is present. In figure 5.9 the location of the anchoring zone is illustrated. Without permanent moorings, vessels should stay under power or anchor only when there is enough sand on the bottom.

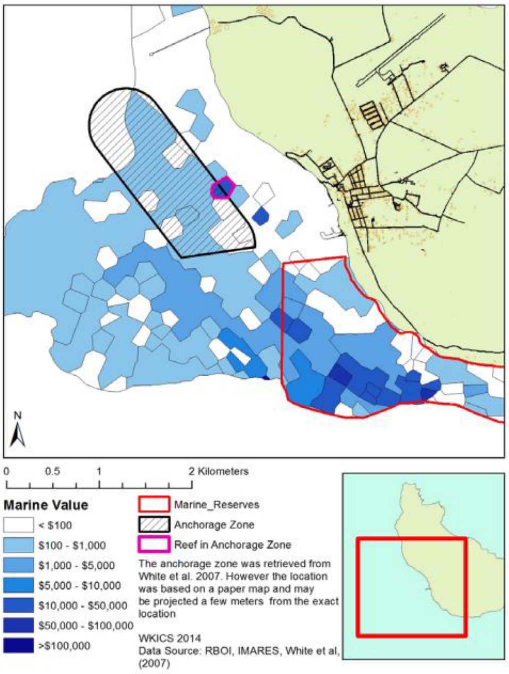


Figure 5.9: Map of the harbour side of Sint Eustatius, retrieved from Tieskens et al. (2014). Coral reefs are located in the anchoring zone. The anchoring zone should be relocated further offshore where the possibility of disturbance to reefs and other ecosystems is minimised.

Material properties and design

- Use a concrete mix based on recycled coral material. Examples are: Ultra high performance concrete or Econcrete).
- Molds are already used to create concrete units (Accropode II). Try to make these molds as irregular as possible and use different sizes to obtain more variability dimensions.
- Roughen concrete texture/surface by adding coarse sand to mixture which can be shaped to the exact design specifications.
- Apply surface processing techniques (e.g. gutters see Figure D.15).
- Use sulphoaluminate cement together with sea water and marine sand. This decreases costs, co2 distribution and PH values. Lowered PH values enhance coral recruitment during the first stage after placement of the hydraulic structure.
- Study the rock availability in the area. If available, check their strength, texture, amount and suitability to function as substrate. A example would be the use of volcanic fine material which is abundantly available on statia. However more studies are needed to prove the effectiveness of using volcanic fine materials in concrete mixtures (see Section 7.2.3).
- Maximise wet surface area by altering the slope.
- Increase the roughness of the outer layer and try to maximize surface irregularities by adding blocks. Do not use labour intensive techniques since the structure is large.
- Build the construction > 6 months before spawning events of local coral reefs.

Active coral enhancement/outplacement techniques

- First check (as explained in the abiotic measures) if coral development is possible by the implementation of coral nurseries around the breakwater.
- Relocate *Acropora palmata* to another reef, or through an in-situ/ex-situ gardening phase to the new breakwater.
- If coral development appears to be possible due to the test nursery check, introduce larvae and seeding on juvenile scale. Since timing of spawning events is not exactly known, this needs to be performed by ex-situ gamete collection of coral colonies living on the breakwater.

5.7. Conclusion

The application of the 'systematic method' was evaluated by conducting a case study about the extension of the breakwater in St. Eustatius. Following the steps of the systematic method, a representation of the coral status at location is assembled, together with the initial design plan and factors that could contribute to coral development or mitigation measures. The method application highlights the fact that reliable and consistent data is needed to substantiate findings. This is substantiated by the fact that a system with high coral reef connectivity and low coral coverage is perceived after a period of 25 years, but no specific cause can be identified. Reliable and long term (>1 year) data is lacking. Therefore, a possible theory that could explain low coral development after several years is synthesized and presented. One assumption that is made is that high wave action on the breakwater limits the type of coral that will grow on these shallow, highly hydrodynamic areas. In addition, larval supply is probably not constant due to ocean currents transporting larvae in other directions. Both factors would decrease the probability of coral development on the breakwater. Poor water quality could still be a part of the problem which also needs to be investigated by baseline data. Data is insufficient for the St. Eustatius case and therefore the initiation of a 'new' baseline in terms of abiotic and biotic data is needed. Implementing a (test) nursery for areas such as the harbour, where low coral coverage or coral degeneration is observed, can be a useful option since this could indicate the possibility of local coral development and together with the baseline, this will create specified measures to enhance coral value. The 'anthropogenic system' lists the importance of social components and examines if active coral development from a social perspective is adding value. For this breakwater extension however, this does not seem to be the case. If coral development is possible (investigated by baseline and test nursery), relatively low cost active coral propagation is an option. For propagation on a juvenile scale (see Section 3.3.2.2, it is not necessary to be sure of the timing of spawning events and could therefore be used. A revised design of the breakwater extension leading to new design recommendations can have a positive impact on coral development.

The main outcomes to which this systematic method contributes are:

- Providing an overview/structure of the steps needed and recommendations to create coral-inclusive infrastructure. This is done by following all the steps (1-5) of the systematic method.
- Instigation of investigation to the status or possibility of coral development in an area. This is executed by step 2: the project location analysis and done by mapping relevant factors that could affect corals.
- Helping the ecologist and engineer to structure the discussion on coral-inclusiveness, by considering most directly impacting factors on coral, coral quantification measures and division into design components. This is done in step 2: the location analysis and in step 3: the development of marine infrastructure design applications. Structuring the discussion is also done by providing a selection-method to execute evaluation and selection effectively (step 4: inventory and ranking of potential measures).
- Increasing the chance that the new design philosophies (BwN) are applied in a good way and most likely lowers the barrier to use these strategies. This is achieved by following selection criteria to come up with feasible and effective coral stimulating solutions. Ranking of potential measures is done in step 4 of the systematic method.
- Potentially offering the realisation that other sides and perspectives (ecological, social, technical) also provide a role in the same project to care about. This realisation can be made due to following step 1 (project description), steps 2 (location analysis) and step 3 (marine infra design applications). During these steps, a general but also environmental, social and technical aspects are discussed.
- The creation of an environmental baseline (abiotic/biotic) can be costly and requires knowledge and time. This should be considered in the project schedule and costs and is made clear in step 4 of the systematic method: inventory and ranking of potential measures.
- By this method, coral growth can be stimulated and negative effects on coral ecosystems can be decreased. The natural system, anthropogenic system, design applications and sustainable design recommendations could contribute to this. This can be done by following all systematic steps (1-5) in the method.

6 Discussion

This chapter discusses the methods used and results obtained in this research. Section 6.1 reflects on the research, 6.2 shows the research limitations and 6.3 is carried out by answering methodological step 5: "How can this method be globally implemented?". This is done by checking shortcomings or possible misfunctions in order to assure to use the method anywhere in the world according to knowledge obtained during this research.

6.1. Reflection and synthesis

The developed systematic method functions as a tool to develop potential for nature-inclusive infrastructure. However, the perspectives and opinions of ecologists and engineers regarding nature-inclusive development of marine infrastructure differ more than initially expected. Ecologists experience difficulties presented by infrastructure in coral habitats. This is because perspectives of ecologists tend to prefer to let nature take its course without performing interventions that could potentially cause disruptions in nature. Whereas engineers prefer to create infrastructure that actually intervenes with nature to create socio-economic benefits. If the systematic method, as derived in this thesis, proves to work for more projects, ecologists and marine biologists have a useful method that is substantiated by these other projects and therefore becomes a useful, widely applicable and reliable tool. However, the dilemma could remain difficult to counteract in one method since diverse perspectives could still cause difficulties in the nature-inclusive approach of new infrastructure.

The expectation to change marine infrastructure towards a coral enhancing system by altering the design, was not fully met, as the local environment did not provide the right conditions for coral development. This shows that the local environment and the exact location where marine infrastructure will be built is more important than the suitability of the coral enhancing properties of the marine infrastructure itself. So the method indicated that all natural and anthropogenic factors should be favourable and taken into account in the design of new marine infrastructure. Consistent long term environmental data is needed, but was not fully available for the breakwater environment of Sint Eustatius.

In support of the expectations, results are similar for marine infrastructure designs as for artificial reefs. Material components and the design should be similar to the natural habitat of coral reefs and could then consequently function as potential coral habitats. The method provides recommendations for solutions that are both effective and feasible as evidenced in literature and previous studies. However, some recommendations supported by literature are not per definition viable solutions since these findings are not always tested on a large scale or findings promote only a limited picture through biased information. This made recommendations of possible improvement measures harder. Biorock, for example, used for the formation of limestone as substrate by electrical currents (T. J. Goreau & Hilbertz, 2005). This is not a widely proven concept and its technical application and operation seems to be difficult. However, this concept is presented as an effective solution to create coral reefs based on literature (T. J. Goreau & Hilbertz, 2005). Therefore, more research is needed to check the applicability of biorock on large scale. This is an example showing the difficulty of literature interpretation.

The systematic method resulting from this research is a tool to aid current generic methods for building hydraulic structures towards coral-inclusive potential. An example of a generic hydraulic engineering design method is the 'basic engineering cycle' (Molenaar & Voorendt, 2020). The method developed in this current study is not a new approach in which current steps of the basic engineering cycle are replaced by other steps. It rather acts as a focus on the (in this case) basic engineering cycle towards coral-inclusiveness. The step: "Verification of concepts" has been expanded with a tool to include nature-inclusivity. Also the step: "evaluation of alternatives and selection" is made easier to perform for coral-inclusive infrastructure through the use of a new selection method. Therefore, the new method is a tool that helps structuring the discussions in order to create potential for coral-inclusive infrastructure and not to create a new general building method.

6.2. Research limitations

6.2.1. Over-simplification of coral ecosystems

Using this systematic method without considering all coral-affecting factors on location, could lead to over-simplification of a coral ecosystem. Every location has its own factors that could affect corals. The abiotic and biotic factors are the 'baseline' that is used to determine the value of a coral ecosystem by checking the relevance of (a)biotic factors on location. This provides information about the quality of a local coral reef, which contributes to the possibility of implementing a strategy for coral-inclusive marine infrastructure. Simplification of factors is needed to globally check if factors are useful. Over-simplification could possibly result in missing nuances by ignoring aspects that are considered 'less important', such as coral predators or development of coral competitors as algae. If any of these factors are considered as coral threats in an area, coral protective methodologies should be implemented. This requires knowledge of marine biologists and cannot simply be covered by stakeholders without knowledge of the matter. By using their knowledge and following the steps indicated in the systematic method, an approach is provided. Unique coral threats per location should be considered in order to not over-simplify a coral ecosystem.

6.2.2. Over-simplification for material comparison

For the comparison between the material components: wood, steel, concrete and rock; the natural factors, anthropogenic influences and design components are assumed constant. According to the results of this study; natural, anthropogenic and design components could influence coral development. However, keeping these 'influences' constant for comparison between these materials is unlikely due to a continuously changing environment and varying material factors. Environmental changes can be caused by, for example, human influences, weather fluctuations, biotic adaptations, food chain alterations and diseases. Another factor that makes material comparison difficult are the varying surfaces per material or different material compositions. Furthermore, coral species' preferences for suitable substrates tend to differ per type of species (Ushiama et al., 2016). The same trends in species' preferences, tend to include design components, such as the orientation of the specific substratum (Vermeij, 2006).

The aforementioned indicates that keeping external factors constant is difficult. However, (over-)simplification demonstrates global differences between materials for coral development and therefore provide an indication to use in coral-inclusive projects. On the other hand, over-simplification could possibly result in less accurate predictions of coral development over time on concerning materials.

6.2.3. Justification of construction in coral reefs

The systematic method can provide reasoned arguments and justifications to build a structure in a marine coral environment. However, this method is not functioning as a 'license' to build in coral ecosystems. The construction plans should comply with local legislation and environmental requirements. A problem that could occur is that this method is not being used correctly and is only used to justify construction of marine infrastructure, without aiming at real coral stimulation. The overall goal should be to create coral-inclusive infrastructure. Therefore, stakeholders from different disciplines should follow the steps demonstrated in the systematic method.

6.2.4. Feasibility baseline

The application of the systematic method indicates that the abiotic and biotic parameters are equally important for the further development of corals in the area. This is recognised in the model with the requirement for a 'baseline', consisting of data. Substantiated findings or the implementation of a strategy, could be based on this data. If data does not exist already, creating data can be a time-consuming process since data should be reliable ready to use and cover all seasons and situations. Without data-gathering devices available or as an additional measure, a test nursery is a possible option. However, a nursery also requires knowledge of the execution and monitoring can be expensive. Therefore part of the cost (and planning) of a project should be estimated taking data-gathering into account.

6.2.5. Differences in following the systematic method

Every stakeholder should be able to use this method for the area and project of interest. However, the possibility could be that people from differing backgrounds implement the methodology differently, resulting in different sustainable design recommendations. An example is the difference in quantification of a coral ecosystem through defining the quality of a coral reef with other biodiversity metrics. However, the likelihood that the steps of the systematic method are followed sequentially is seen as high - this is important for the outcome.

6.2.6. Larval supply

If there is high connectivity of coral reefs in an area, it should not be assumed automatically that larval supply is abundant. The larval supply also depends on the current direction and speed and on the time of spawning. The combination of factors should be considered when the question of sufficient larval supply is asked.

6.2.7. Perspectives

A point of discussion remains the difference in understanding between ecologists and civil engineers about ecosystem protection and coral improvement measures. Ecologists aim and prefer to change as little as possible in ecosystems by focusing on protection and natural resilience. Civil engineers seem to value ecosystems differently in that they seem to place more value on the functionality of an infrastructure to be built on the basis of human needs. As a result, the civil engineer's view on e.g. Building with Nature tends to be different than that of ecologists. While an ecologist would like to let nature take its course with as few interruptions as possible, a civil engineer apparently sees it differently.

Stimulation in coral development could potentially be facilitated through the implementation of nature-inclusive building methods as BwN. However, building in a coral-rich environment is likely to cause consternation from an ecological perspective, as the natural environment is interrupted by non-natural processes. However, this method can help foster constructive collaboration between ecologists and civil engineers. Recommended solutions will certainly not deliver solutions that all stakeholders easily agree on. This depends on the parties involved, personalities, conditions etc.. However, guidance by the systematic method is provided to help structure the discussion.

6.2.8. Literature applicability

Using literature for coral-inclusive solutions can be a potential pitfall for users of the systematic method. Literature is full of possibilities for and functions of coral development. It is not necessarily the case that literature is incorrect, but obtained knowledge or solutions from literature do not always apply to every situation.

For instance, it is indicated that coral reefs provide protection against wave impacts and is of increased value for the anthropogenic system (Harris et al., 2018). However, not every developed reef has the potential to function as a natural breakwater. This also has to do with factors such as location, depth, wave impacts, current, species and amount of colonies to examine coral development. Another example is the fact that the use of (the aforementioned) bio-rock is applicable for the cultivation of coral reefs according to T. J. Goreau et al. (2004). However, due to the technology used and the need for electricity supply, this is questionable. Although literature could potentially be right, it should be checked on site whether this measure is feasible. In addition, it must be proven that measures can be applied on a large scale. This means that all measures, recommendations and knowledge cannot simply be taken for granted from the literature.

6.2.9. Experimentation

Following on from the previous point, experimenting with innovative techniques is not necessarily a bad idea. Now mainly conventional techniques or techniques that prove to work arise from the systematic method. Innovative ideas that have been proposed or are not yet known, such as the 'test nursery', may also offer nature-inclusive solutions. For the development of innovations it is important that experiments keep being carried out.

6.3. How can this method be globally implemented?

The aim of this section is to check whether the systematic method can potentially be used for coral-inclusive infrastructure in other locations across the world. As the application of the systematic method is tested through the case study in St Eustatius, the developed systematic method can possibly be shifted towards solutions for the specific St Eustatius case. The possibilities towards a global approach are therefore discussed by going through the systematic method considering other circumstances and locations.

6.3.1. Step 1: The project description

Diverse projects can be conceived in different locations, however the generic information only covers the problem definition, the design definition and the initial concept. The insight is that the project description step will be generally applicable for other projects and areas.

6.3.2. Step 2: The location analysis

Differing natural and anthropogenic factors could make the application of this systematic method difficult to apply in random cases. To deal with cases where other circumstances are observed, here follow some recommendations:
Firstly, water quality thresholds of species and data on location have to be obtained to gain information on the vulnerability of coral species in the specific area. The five water quality factors: temperature, salinity, SSC, nutrients and PH values are prevalent all over the world. Secondly, the morphological factors are checked specifically per area: hydrodynamics (currents), bathymetry, hurricane risk and substrate quantity. The problem could lay in the interpretation of the substrate quantity. Thirdly, going further into the biotic components could possibly lead to other results. The biotic factors that arise if problems occur in an area, are specified on direct coral influencing components. However, other (in-direct) biotic factors could also hamper coral development which are not directly mentioned in the systematic method. The approach is similar but the resulting actions can be different than described in the systematic method. Furthermore, differences in interpretation of components can be possible but the overall main biotic components are highlighted in this research. For the anthropogenic approach, the usage functions together with the dependence on coral reefs and coral influences will be specified per specific location and will probably not differ much. However, the influence of stakeholders can be different and tend to depend on e.g. the degree of democracy (Moriarty, 2014).

6.3.3. Step 3: Development of marine infrastructure design applications

Elements of the infrastructure can be diverse, such as the structures of pillars in a coral reef area or the use of floating structures for solar panels. Per location, other structures prevail due to different circumstances. However, all conceivable infrastructure types are covered by this study.

6.3.4. Step 4: Inventory and ranking of potential measures

Depending on the location, different recommendations of measures can be applied. For example the feasibility of a measure may depend on the specific location. Technical skills, the economic and environmental situation are other examples that differ per project site and should be taken into account for the inventory and ranking of potential measures. However, the procedure to select recommendations remains the same but the outcomes could be different.

6.3.5. Step 5: Summary of sustainable design recommendations

The creation of new sustainable design recommendations for coral-inclusive potential seems possible. However, recommendations can differ slightly due to different outcomes of the steps before. This will probably not lead to less suitable design recommendations since indicated systematic steps are followed in correct order. However, the discussion still exists if the systematic method is applicable everywhere in the world and might therefore benefit from more research.

7 Conclusions and recommendations

This chapter covers the main conclusions and recommendations of this research. The main- and sub-research questions are evaluated. Recommendations for the application of the systematic method, the sint Eustatius case and ideas for further research are covered. The main objective of this research was to systematically explore nature-inclusive potential for new marine infrastructure.

7.1. Conclusions

Starting with the main research question:

How can marine infrastructure projects be assessed and developed, considering local coral ecosystem values?

Included is economic development through the construction of new infrastructure projects. Possible solutions are emerging such as nature-inclusive construction to optimally support the local coral ecosystem. However, guidance is needed for stakeholders to be able to build nature-inclusively. The solution lies in structuring the necessary discussion while recognizing social, ecological, economic and technical perspectives. The overlap of ecological and technological knowledge needs to be considered at all times to achieve the optimum approach towards nature-inclusive solutions. The aim is to transform a traditional project design into a sustainable design, focusing on coral habitats. This is achieved by using a systematic method, that was developed in this research.

The systematic method consists of 5 steps providing guidance through necessary steps to create coral-inclusive infrastructure.

1. project description, outlining the basic challenge at hand
2. project location analysis, involving a systematic assessment of the relevant 'natural system' as well as the 'anthropogenic system'
3. development of marine infrastructure design applications, involving an inventory of project elements that can have negative or positive effects on the overall system
4. inventory and ranking of potential measures, objectively outlining feasibility and potential effectiveness of measures and design modifications given the overall system
5. summary of sustainable design recommendations, leading to a systematic ranking of potential measures proposed to support further decision making.

The systematic method was tested on a breakwater extension case in Sint Eustatius. From this case, we can conclude that the method works well by providing locally feasible and effective sustainable design recommendations. The main improvements which resulted from using the systematic method are:

- Providing an overview of the steps required to create coral-inclusive infrastructure (steps 1 - 5).

- Instigating the investigation of the status or the possibility of coral development in an area (step: 2).
- Helping the ecologist and engineer to structure the discussion on coral-inclusiveness, by considering most direct impacting factors on coral, coral quantification measures and division into design components (steps 2, 3) and by providing a selection-method to execute evaluation and selection effectively (step 4).
- Increasing the chance that the new design philosophies are applied in a good way and most likely lowering the barrier to use these strategies (step 4).
- Potentially offering the realization that other views and ecological-, social-, and technical-perspectives provide a role in the same project to care about (steps 1, 2, 3).
- Realizing that the creation of an (a)biotic environmental baseline can be costly and requires knowledge and time (step 4).
- Stimulating coral development and decreasing negative effects on coral ecosystems. Taking into account the natural system, anthropogenic system, and design applications (steps 1 - 5).

The contributions from above are only possible when the methodological steps are followed in indicated order. Reliable and consistent data should be used to further analyse coral regions and possibilities for coral-inclusive marine infrastructure. This could provide new sustainable design recommendations to concretize the discussion between stakeholders towards nature-inclusivity. It is essential that the methodology involves stakeholders with different perspectives. This creates optimal solutions for society and marine life. However, to fully substantiate the fact that the method works for every location and all circumstances, the method should be applied in more cases. However, the systematic approach, as derived in this thesis, has shown itself to be able to support diverse stakeholders in assessing the nature-inclusive potential of marine infrastructure.

7.2. Recommendations

7.2.1. Recommendations for the application of the systematic method

- Early involvement of stakeholders (with diverse backgrounds) in the design process is recommended. The better understanding between stakeholders and more value for natural, social and economic aspects can be created due to integrated knowledge.
- Ensure that data used is reliable and spans a longer period of time. In this way, a better assumption can be made about possibilities for creating or preserving coral value.
- Do not always take information from literature for granted. Every coral species and location is unique. This indicates that results from literature are not applicable for every location and circumstances. Therefore, this information should be verified accordingly.

7.2.2. Recommendation for the Sint Eustatius case

- Use as many natural materials as possible when deploying in areas where coral could develop. In addition, use mitigation measures and coral improvement methods as indicated in this study.
- Measure and keep measuring water quality parameters (temperature, salinity, SSC, nutrients, pH) for a longer period of time and measure flow velocities around the breakwater.
- Relocate the threatened *Acropora Palmata* species before starting with the construction phase, implement anti-erosion and sedimentation measures, and reduce or relocate the brine water outflow in the area.
- Start with low effort (passive) coral propagation techniques.
- Relocate the current anchoring zone towards a sand dominated bottom area.
- Apply surface processing techniques as niches and varying rough surfaces on armour blocks to enhance larval recruitment.
- Use a concrete mix based on recycled (coral) material and use sulphoaluminate cement with sea water and marine sand.
- Investigate the use of volcanic fine materials in concrete mixtures and if strength and durability is guaranteed use fine volcanic materials in the concrete mixture.
- Maximise the wet surface area of marine infrastructure.

- Deploy concrete > 6 months before spawning events and active coral propagation techniques take place.
- Make a 'test' site by conducting measurements and implementing the 'test' nurseries to check if coral development is possible.
- If coral development is possible and active measures are required, introduce larvae and seeding on juvenile scale. Use ex-situ gamete collection of coral colonies living on the breakwater (originally and from 'test' nurseries).

7.2.3. Recommendations for further research

- The first recommendation is to spend more effort and time in applying and evaluating the systematic method from this research in other locations with different circumstances. This is needed to evaluate whether the systematic method suffices for world wide implementation in order to potentially enhance coral ecosystems world wide.
- More research on the differences of coral development on the four material types: wood, steel, rock and concrete is recommended. Contemporary studies are mainly focused on materials for artificial reefs, while the coral-inclusive constructions involve limited types of materials. Including design components and altering environmental factors may provide information for enhanced coral value around marine construction implementation. In addition, study and splitting up main material components as rock in basalt, granite etc., additional information will be generated that can be used to design nature-inclusive infrastructure more efficiently.
- Studies that include coral development on materials tend to focus on the settlement, recruitment and the first stage of development. Longer term studies of coral development (10 years) on the four construction materials are recommended to provide an even better picture of coral development over time. The following relations can be studied: benthic community structure, species richness, live coral cover, diversity and the amount of invasive species related to native species.
- Orientation of substratum has potential effects on recruitment and growth of benthic organisms. More research is recommended about the orientation versus the (coral) colonisation and development. This potentially creates more knowledge to orientate and therefore design elements of marine infrastructure in such a way that coral value can be optimised.
- This study focused on coral ecosystems. The marine environment consists of many more relevant ecosystems. For example, mangroves and seagrass are ecosystems that also require plans of action to stimulate their natural and social value by creating nature-inclusive potential for marine infrastructure. An approach for other ecosystems can be designed similarly as this study shows in order to implement steps needed for ecosystem enhancement.
- It is recommended to investigate the relationship between benthic organisms (diatoms, calcareous or crustose algae, turf algae, bryozoans, turnicates, ascidians, barnacles, sponges, corals etc.) more thoroughly. Next to the fact that development of one of these benthic organisms depends on the type of substratum, design (orientation etc) and natural factors such as water quality, they also depend on the colonisation and competition of other benthic organism types. Studying this relation into more detail, will likely improve knowledge on the suitability for specific benthic species on substratum to potentially create more effective nature based predictions and solutions.
- This study focuses on 'coastal regions'. Although the idea for offshore projects would be similar, methods and interventions could turn out to be different. As an example, a study can be done on other regions with coral development. Think of deep- or cold-water corals and offshore infrastructure with tropical corals. Involving more regions in future studies could lead to better integrate other infrastructure in diverse marine ecosystems.
- In literature, innovative solutions are suggested, such as: biorock, removing algae, introducing clouds to decrease solar radiation etc. Research can be useful but has to be proven in terms of feasibility and effectiveness on a large scale. By this way, innovative solutions can contribute to improve coral in the world.
- Ethical questions should also belong to the recommendations for further research. An example is the following: transplanting high thermo-tolerant species from the red sea towards reefs which undergo mass bleaching due to low thermo-tolerance of coral species like the Great Barrier reef in Australia. The question arises whether the introduction of a 'new' species can be ethically

justified? Can the introduction of alien species be justified? Will this work at all? A feasibility study can be carried out to investigate this matter to make active coral propagation techniques and human interventions social, environmental and economical acceptable.

References

Abebe, A. & Smith, I. G. (2005). Pile foundation design: A student guide. *School of Built Environment, Napier University, Edinburgh*.

Abelson, A. & Shlesinger, Y. (2002). Comparison of the development of coral and fish communities on rock-aggregated artificial reefs in eilat, red sea. *ICES Journal of Marine Science*, *59*(suppl), S122–S126.

Aerts, L. (1998). Sponge/coral interactions in caribbean reefs: Analysis of overgrowth patterns in relation to species identity and cover. *Marine Ecology Progress Series*, *175*, 241–249.

Aguilera, M. A., Broitman, B. R. & Thiel, M. (2016). Artificial breakwaters as garbage bins: Structural complexity enhances anthropogenic litter accumulation in marine intertidal habitats. *Environmental pollution*, *214*, 737–747.

Akakura, Y. (2005). Various contrivances for restoration of coral assemblages in harbor development projects: A report. *Proc. 10^< th> Int. Coral Reef Symp. Naha, 2005*.

Al-Horani, F. A. & Khalaf, M. A. (2013). Developing artificial reefs for the mitigation of man-made coral reef damages in the gulf of aqaba, red sea: Coral recruitment after 3.5 years of deployment. *Marine Biology Research*, *9*(8), 749–757.

Allen, S. & Moore, G. (2016). Construction methodologies and challenges for marine concrete structures. *Marine concrete structures* (pp. 115–133). Elsevier.

Almany, G., Connolly, S., Heath, D., Hogan, J., Jones, G. P., McCook, L., Mills, M., Pressey, R. & Williamson, D. (2009). Connectivity, biodiversity conservation and the design of marine reserve networks for coral reefs. *Coral reefs*, *28*(2), 339–351.

Altemühl, D. & Vink, D. (2019). *Optimization of the culture of the long-spined sea urchin (diadema antillarum) in order to maximize the larvae survival* (Doctoral dissertation). Van Hall Larenstein.

Anderson, M. & Underwood, A. (1994). Effects of substratum on the recruitment and development of an intertidal estuarine fouling assemblage. *Journal of Experimental Marine Biology and Ecology*, *184*(2), 217–236.

Andréfouët, S. & Cabioch, G. (2011). Barrier reef (ribbon reef). In D. Hopley (Ed.), *Encyclopedia of modern coral reefs: Structure, form and process* (pp. 102–107). Springer Netherlands. https://doi.org/10.1007/978-90-481-2639-2_43

Anthony, K. R. & Hoegh-Guldberg, O. (2003). Kinetics of photoacclimation in corals. *Oecologia*, *134*(1), 23–31.

Anton, A., Simpson, M. S. & Vu, I. (2014). Environmental and biotic correlates to lionfish invasion success in bahamian coral reefs. *PloS one*, *9*(9), e106229.

Aronson, R. B. & Precht, W. F. (2016). Physical and biological drivers of coral-reef dynamics. *Coral reefs at the crossroads* (pp. 261–275). Springer.

Arunvivek, G., Maheswaran, G. & Kumar, S. S. (2016). Study on mitigating the impacts of highly alkaline hazardous washout water on marine environment by reutilization in concrete for geo-marine pollution control.

Aseltine-Neilson, D. A., Bernstein, B. B., Palmer-Zwahlen, M. L., Riege, L. E. & Smith, R. W. (1999). Comparisons of turf communities from pendleton artificial reef, torrey pines artificial reef, and a natural reef using multivariate techniques. *Bulletin of Marine Science*, *65*(1), 37–57.

Aska, D. (1981). Artificial reefs: Conference proceedings. *Daytona Beach, Fla. Univ. Fla. Sea Grant Coll. Rep*, (41), 229.

Assessment, M. E. et al. (2005). *Ecosystems and human well-being* (Vol. 5). Island press United States of America.

Ayre, D. J. & Hughes, T. P. (2000). Genotypic diversity and gene flow in brooding and spawning corals along the great barrier reef, australia. *Evolution*, *54*(5), 1590–1605.

Ayre, D. J. & Resing, J. (1986). Sexual and asexual production of planulae in reef corals. *Marine Biology*, *90*(2), 187–190.

Babcock, R. (1985). Growth and mortality in juvenile corals (goniastrea, platygyra and acropora): The first year.

Bailey-Brock, J. H. (1989). Fouling community development on an artificial reef in hawaiian waters. *Bulletin of Marine Science*, *44*(2), 580–591.

Baine, M. (2001). Artificial reefs: A review of their design, application, management and performance. *Ocean & Coastal Management*, *44*(3-4), 241–259.

Bak, R. (1975). Ecological aspects of the distribution of reef corals in the netherlands antilles. *Bijdragen tot de Dierkunde*, *45*(2), 181–190.

Bak, R. (1976). The growth of coral colonies and the importance of crustose coralline algae and burrowing sponges in relation with carbonate accumulation. *Netherlands Journal of Sea Research*, *10*(3), 285–337.

Bak, R. (1977). Coral reefs and their zonation in netherlands antilles: Modern and ancient reefs.

Bak, R. (1978). Lethal and sublethal effects of dredging on reef corals. *Marine Pollution Bulletin*, *9*(1), 14–16.

Bak, R. & Elgershuizen, J. (1976). Patterns of oil-sediment rejection in corals. *Marine Biology*, *37*(2), 105–113.

Bak, R. & Meesters, E. H. (1998). Coral population structure: The hidden information of colony size-frequency distributions. *Marine Ecology Progress Series*, *162*, 301–306.

Baker, D., Rodríguez-Martínez, R. & Fogel, M. (2013). Tourism's nitrogen footprint on a mesoamerican coral reef. *Coral Reefs*, *32*(3), 691–699.

Baker, E. T. & Lavelle, J. W. (1984). The effect of particle size on the light attenuation coefficient of natural suspensions. *Journal of Geophysical Research: Oceans*, *89*(C5), 8197–8203.

Baker, W., Ray, S. & Landry, A. (1995). Utilization of coal combustion byproduct oyster reef substrate in texas coastal waters. *Proceedings of the Oyster Reef Habitat Restoration Symposium: A Synopsis and Synthesis of Approaches, Williamsburg, Virginia, USA, April*.

Bam international. (2017). *Mega cruise pier ii - curacao*. https://www.baminternational.com/en/projects/mega-cruise-pier-ii-curacao

Banks, S. & Foster, K. (2016). Baseline levels of siderastrea siderea bleaching under normal environmental conditions in little cayman. *Open Journal of Marine Science*, *7*(1), 142–154.

Barton, J. A., Willis, B. L. & Hutson, K. S. (2017). Coral propagation: A review of techniques for ornamental trade and reef restoration. *Reviews in Aquaculture*, *9*(3), 238–256.

Base, R. (n.d.). *Resources - coral reefs*. http://reefbase.org/global_database/default.aspx?section=r2

Battistini, R. (1975). *Eléments de terminologie récifale indopacifique*. Station marine d'Endoume.

Baynes, T. W. & Szmant, A. M. (1989). Effect of current on the sessile benthic community structure of an artificial reef. *Bulletin of Marine Science*, *44*(2), 545–566.

BBC. (2021). *Levels of organisation within an ecosystem - trophic levels*. https://www.bbc.co.uk/bitesize/guides/zcmbh39/revision/1

Beaumont, N., Austen, M., Atkins, J., Burdon, D., Degraer, S., Dentinho, T., Derous, S., Holm, P., Horton, T., Van Ierland, E. et al. (2007). Identification, definition and quantification of goods and services provided by marine biodiversity: Implications for the ecosystem approach. *Marine pollution bulletin*, *54*(3), 253–265.

Becker, J., van Eekelen, E., van Wiechen, J., de Lange, W., Damsma, T., Smolders, T. & van Koningsveld, M. (2015). Estimating source terms for far field dredge plume modelling. *Journal of environmental management*, *149*, 282–293.

Beeby, A. (1997). Ductility in reinforced concrete: Why is it needed and how is it achieved? *Structural Engineer*, *75*(18).

Bell, J. & Galzin, R. (1984). Influence of live coral cover on coral-reef fish communities. *Marine Ecology Progress Series*, *15*(3), 265–274.

Bell, P., Greenfield, P., Hawker, D. & Connell, D. (1989). The impact of waste discharges on coral reef regions. *Water Science and Technology*, *21*(1), 121–130.

Bellwood, D. R., Hoey, A. S. & Choat, J. H. (2003). Limited functional redundancy in high diversity systems: Resilience and ecosystem function on coral reefs. *Ecology letters*, *6*(4), 281–285.

Benayahu, Y. & Loya, Y. (1984). Substratum preferences and planulae settling of two red sea alcyonaceans: Xenia macrospiculata gohar and parerythropodium fulvum fulvum (forskl). *Journal of experimental marine biology and ecology*, *83*(3), 249–260.

Benayahu, Y. & Loya, Y. (1987). Long-term recruitment of soft corals (octocorallia: Alcyonacea) on artificial substrata at eilat (red sea). *Mar Ecol Prog Ser*, *38*, 161–167.

Berg, H., Öhman, M. C., Troëng, S. & Lindén, O. (1998). Environmental economics of coral reef destruction in sri lanka. *Ambio*, 627–634.

Berkelmans, R. & Van Oppen, M. J. (2006). The role of zooxanthellae in the thermal tolerance of corals: A 'nugget of hope'for coral reefs in an era of climate change. *Proceedings of the Royal Society B: Biological Sciences*, *273*(1599), 2305–2312.

Birkeland, C. (1977). The importance of rate of biomass accumulation in early successional stages of.

Birkeland, C., Reimer, A. A. & Young, J. R. (1976). *Survey of marine communities in panama and experiments with oil*. US Environmental Protection Agency, Office of Research; Development …

Bohnsack, J. A. (1991). Habitat structure and the design of artificial reefs. *Habitat structure* (pp. 412–426). Springer.

Bohnsack, J. A. & Sutherland, D. L. (1985). Artificial reef research: A review with recommendations for future priorities. *Bulletin of marine science*, *37*(1), 11–39.

Bosboom, J. & Stive, M. J. (2012). *Coastal dynamics i: Lectures notes cie4305*.

Boström-Einarsson, L., Babcock, R. C., Bayraktarov, E., Ceccarelli, D., Cook, N., Ferse, S. C., Hancock, B., Harrison, P., Hein, M. Y., Shaver, E. et al. (2020). Coral restoration–a systematic review of current methods, successes, failures and future directions. *PloS one*, *15*(1), e0226631.

Boström-Einarsson, L., Ceccarelli, D., Babcock, R. C., Bayraktarov, E., Cook, N., Harrison, P., Hein, M. Y., Shaver, E., Smith, A., Stewart-Sinclair, P. J. et al. (2018). Coral restoration in a changing world-a global synthesis of methods and techniques.

Bouchon-Navaro, Y. & Bouchon, C. (1989). Correlations between chaetodontid fishes and coral communities of the gulf of aqaba (red sea). *Environmental Biology of Fishes*, *25*(1), 47–60.

Bouw, M. & van Eekelen, E. (2020). *Building with nature: Creating, implementing and upscaling nature-based solutions*. nai010.

Box, S. J. & Mumby, P. J. (2007). Effect of macroalgal competition on growth and survival of juvenile caribbean corals. *Marine Ecology Progress Series*, *342*, 139–149.

Brainard, R., Birkeland, C., Eakin, C. M., McElhany, P., Miller, M. W., Patterson, M. & Piniak, G. A. (2011). *Status review report of 82 candidate coral species petitioned under the us endangered species act*. Citeseer.

Brander, L. M., Van Beukering, P. & Cesar, H. S. (2007). The recreational value of coral reefs: A meta-analysis. *Ecological Economics*, *63*(1), 209–218.

Brandt, M. J., Diederichs, A., Betke, K. & Nehls, G. (2011). Responses of harbour porpoises to pile driving at the horns rev ii offshore wind farm in the danish north sea. *Marine Ecology Progress Series*, *421*, 205–216.

Briand, M. J., Bonnet, X., Guillou, G. & Letourneur, Y. (2016). Complex food webs in highly diversified coral reefs: Insights from δ13c and δ15n stable isotopes. *Food Webs*, *8*, 12–22. https://doi.org/https://doi.org/10.1016/j.fooweb.2016.07.002

Bricker, S. B., Longstaff, B., Dennison, W., Jones, A., Boicourt, K., Wicks, C. & Woerner, J. (2008). Effects of nutrient enrichment in the nation's estuaries: A decade of change. *Harmful Algae*, *8*(1), 21–32.

Bridges, T. S., Bourne, E. M., King, J. K., Kuzmitski, H. K., Moynihan, E. B. & Suedel, B. C. (2018). *Engineering with nature: An atlas* (tech. rep.). Army Engineer Research Development Center VICKSBURG United States.

Briggs, J. C. (2005). Coral reefs: Conserving the evolutionary sources. *Biological Conservation*, *126*(3), 297–305.

Brown, B. E. (1997). Coral bleaching: Causes and consequences. *Coral reefs*, *16*(1), S129–S138.

Brown, B. E. & Bythell, J. (2005). Perspectives on mucus secretion in reef corals. *Marine Ecology Progress Series*, *296*, 291–309.

Brown, B. E. & Dunne, R. P. (1988). The environmental impact of coral mining on coral reefs in the maldives. *Environmental Conservation*, *15*(2), 159–165.

Brown, B. E., Le Tissier, M., Scoffin, T. & Tudhope, A. (1990). Evaluation of the environmental impact of dredging on intertidal coral reefs at ko phuket, thailand, using ecological and physiological parameters. *Marine Ecology Progress Series*, 273–281.

Bruckner, A. & Bruckner, R. (2001). Condition of restored acropora palmata fragments off mona island, puerto rico, 2 years after the fortuna reefer ship grounding. *Coral reefs*, *20*(3), 235–243.

Bruno, J. F., Selig, E. R., Casey, K. S., Page, C. A., Willis, B. L., Harvell, C. D., Sweatman, H. & Melendy, A. M. (2007). Thermal stress and coral cover as drivers of coral disease outbreaks. *PLoS biology*, *5*(6), e124.

Bryant, D., Burke, L., McManus, J., Spalding, M. et al. (1998). Reefs at risk: A map-based indicator of threats to the world's coral reefs.

Bugnot, A., Mayer-Pinto, M., Airoldi, L., Heery, E., Johnston, E., Critchley, L., Strain, E., Morris, R., Loke, L., Bishop, M. et al. (2021). Current and projected global extent of marine built structures. *Nature Sustainability*, *4*(1), 33–41.

Bulleri, F. (2005). Role of recruitment in causing differences between intertidal assemblages on seawalls and rocky shores. *Marine Ecology Progress Series*, *287*, 53–65.

Bulthuis, D. A., Brand, G. W. & Mobley, M. C. (1984). Suspended sediments and nutrients in water ebbing from seagrass-covered and denuded tidal mudflats in a southern australian embayment. *Aquatic Botany*, *20*(3-4), 257–266.

Bunce, L. & Townsley, P. (2000). Socioeconomic manual for coral reef management.

Burcharth, H. F., Sorensen, J. D. & Kim, S.-W. (2018). Optimum safety levels of breakwaters. *Handbook of coastal and ocean engineering* (pp. 313–371). World Scientific.

Burke, L., Reytar, K., Spalding, M. & Perry, A. (2011). *Reefs at risk revisited*. World Resources Institute.

Burt, J., Bartholomew, A., Bauman, A., Saif, A. & Sale, P. F. (2009). Coral recruitment and early benthic community development on several materials used in the construction of artificial reefs and breakwaters. *Journal of Experimental Marine Biology and Ecology*, *373*(1), 72–78.

Burt, J., Bartholomew, A. & Sale, P. F. (2011). Benthic development on large-scale engineered reefs: A comparison of communities among breakwaters of different age and natural reefs. *Ecological Engineering*, *37*(2), 191–198.

Bythell, J. C. & Wild, C. (2011). Biology and ecology of coral mucus release [Coral Reefs: Future Directions]. *Journal of Experimental Marine Biology and Ecology*, *408*(1), 88–93. https://doi.org/https://doi.org/10.1016/j.jembe.2011.07.028

Cabral, R. B., Bradley, D., Mayorga, J., Goodell, W., Friedlander, A. M., Sala, E., Costello, C. & Gaines, S. D. (2020). A global network of marine protected areas for food. *Proceedings of the National Academy of Sciences*, *117*(45), 28134–28139.

Cado van der Lely, J., Warning, A., Schep, S., van Beukering, P. & Wolfs, E. (2014). The total economic value of nature on st eustatius.

Cameron, C. M., Pausch, R. E. & Miller, M. W. (2016). Coral recruitment dynamics and substrate mobility in a rubble-dominated back reef habitat. *Bulletin of Marine Science*, *92*(1), 123–136.

Campbell, S. J., Edgar, G. J., Stuart-Smith, R. D., Soler, G. & Bates, A. E. (2018). Fishing-gear restrictions and biomass gains for coral reef fishes in marine protected areas. *Conservation Biology*, *32*(2), 401–410.

Cantin, N. E., Cohen, A. L., Karnauskas, K. B., Tarrant, A. M. & McCorkle, D. C. (2010). Ocean warming slows coral growth in the central red sea. *Science*, *329*(5989), 322–325.

Carleton, J. & Sammarco, P. W. (1987). Effects of substratum irregularity on success of coral settlement: Quantification by comparative geomorphological techniques. *Bulletin of Marine Science*, *40*(1), 85–98.

Carpenter, K. E., Abrar, M., Aeby, G., Aronson, R. B., Banks, S., Bruckner, A., Chiriboga, A., Cortés, J., Delbeek, J. C., DeVantier, L. et al. (2008). One-third of reef-building corals face elevated extinction risk from climate change and local impacts. *Science*, *321*(5888), 560–563.

CBS. (2021). *Caribisch nederland; bruto binnenlands product (bbp)*. https://www.cbs.nl/nl-nl/cijfers/detail/84789NED

Ceccarelli, D. M., McLeod, I. M., Boström-Einarsson, L., Bryan, S. E., Chartrand, K. M., Emslie, M. J., Gibbs, M. T., Gonzalez Rivero, M., Hein, M. Y., Heyward, A. et al. (2020). Substrate stabilisation and small structures in coral restoration: State of knowledge, and considerations for management and implementation. *PloS one*, *15*(10), e0240846.

Cesar, H. S. (2000). Coral reefs: Their functions, threats and economic value. *Collected essays on the economics of coral reefs*, *14*.

Cesar, H. S. (2002). Coral reefs: Their functions, threats and economic value.

Cesar, H. S., Burke, L. & Pet-Soede, L. (2003). The economics of worldwide coral reef degradation.

Chabanet, P., Ralambondrainy, H., Amanieu, M., Faure, G. & Galzin, R. (1997). Relationships between coral reef substrata and fish. *Coral reefs*, *16*(2), 93–102.

Chan, K. (2019). *White rock pier rebuild could cost over 16 million*. https://dailyhive.com/vancouver/white-rock-pier-repair-cost-estimate-concrete-structure

Chapman, M. & Underwood, A. (2011). Evaluation of ecological engineering of "armoured" shorelines to improve their value as habitat [Global change in marine ecosystems]. *Journal of Experimental Marine Biology and Ecology*, *400*(1), 302–313. https://doi.org/https://doi.org/10.1016/j.jembe.2011.02.025

Charbonnel, E., Serre, C., Ruitton, S., Harmelin, J.-G. & Jensen, A. (2002). Effects of increased habitat complexity on fish assemblages associated with large artificial reef units (french mediterranean coast). *ICES Journal of Marine Science*, *59*(suppl), S208–S213.

Chen, C.-T. A. & Nihoul, J. C. (2008). *Oceanography* (Vol. 3). United Nations Educational, Scientific; Cultural organization.

Cisneros-Montemayor, A. M., Pauly, D., Weatherdon, L. V. & Ota, Y. (2016). A global estimate of seafood consumption by coastal indigenous peoples. *PloS one*, *11*(12), e0166681.

Clark, S. & Edwards, A. (1994). Use of artificial reef structures to rehabilitate reef flats degraded by coral mining in the maldives. *Bulletin of Marine Science*, *55*(2-3), 724–744.

Coles, S. L. & Eldredge, L. G. (2002). Nonindigenous species introductions on coral reefs: A need for information. *Pacific Science*, *56*(2), 191–209.

Coles, S. L. & Jokiel, P. L. (2018). Effects of salinity on coral reefs. *Pollution in tropical aquatic systems* (pp. 147–166). CRC Press.

community, S. (2020). *Advantages disadvantages of steel construction*. https://structural.community/articles/advantages-of-steel-construction/

Concrete layer innovations. (2012). *Guidelines for design - accropode ii*. https://www.concretelayer.com/sites/default/files/2019-05/ACCROPODE%5C%E2%5C%84%5C%A2%5C%20II_Design%5C%20_Table_2012_0.pdf

Contributing, R., Blaney, R., Fletcher, R., Grantham, H., Ling, M., O'Connor, B., Sassen, M., Christensen, M. & Martin, C. (n.d.). Experimental biodiversity accounting as a component of the system of environmental-economic accounting experimental ecosystem accounting (seea-eea).

Cookson, L. & Barnacle, J. (1987). Predominance of the marine borer limnoria indica becker & kampf on turpentine timber. *International biodeterioration*, *23*(5), 287–293.

Cooper, J. A. G. & McKenna, J. (2008). Working with natural processes: The challenge for coastal protection strategies. *Geographical Journal*, *174*(4), 315–331.

Corburn, J. (2003). Bringing local knowledge into environmental decision making: Improving urban planning for communities at risk. *Journal of planning education and research*, *22*(4), 420–433.

Cortés, J. N. & Risk, M. J. (1985). A reef under siltation stress: Cahuita, costa rica. *Bulletin of Marine Science*, *36*(2), 339–356.

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R. V., Paruelo, J. et al. (1997). The value of the world's ecosystem services and natural capital. *nature*, *387*(6630), 253–260.

Coughanowr, C. A., Ngoile, M. N. & Linden, O. (1995). Coastal zone management in eastern africa including the island states: A review of issues and initiatives. *Ambio (Sweden)*.

Covert, T., Greenstone, M. & Knittel, C. R. (2016). Will we ever stop using fossil fuels? *Journal of Economic Perspectives*, *30*(1), 117–38.

Crabbe, M. J. C. (2008). Climate change, global warming and coral reefs: Modelling the effects of temperature. *Computational Biology and Chemistry*, *32*(5), 311–314.

Creed, J. C. & De Paula, A. F. (2007). Substratum preference during recruitment of two invasive alien corals onto shallow-subtidal tropical rocky shores. *Marine Ecology Progress Series*, *330*, 101–111.

Crosher, I., Gold, S., Heaver, M., Heydon, M., Moore, L., Panks, S., Scott, S., Stone, D. & White, N. (2019). The biodiversity metric 2.0: Auditing and accounting for biodiversity value: Technical supplement (beta version, july 2019). natural england joint publication jp029.

D, H. (1992). *Haven project sint eustatius* (tech. rep.). Van Oord ACZ.

Daby, D. (2003). Effects of seagrass bed removal for tourism purposes in a mauritian bay. *Environmental Pollution*, *125*(3), 313–324.

Dafforn, K. A., Mayer-Pinto, M., Morris, R. L. & Waltham, N. J. (2015). Application of management tools to integrate ecological principles with the design of marine infrastructure. *Journal of Environmental Management*, *158*, 61–73.

Dahlgren, C., Pizarro, V., Sherman, K., Greene, W. & Oliver, J. (2021). Spatial and temporal patterns of stony coral tissue loss disease outbreaks in the bahamas. *Frontiers in Marine Science*, 767.

Daily, G. C. et al. (1997). Introduction: What are ecosystem services. *Nature's services: Societal dependence on natural ecosystems*, *1*(1).

Dasgupta, P. (2021). The economics of biodiversity: The dasgupta review.

Data, C. T. (n.d.). *Coral trait database*. https://coraltraits.org/

Davies, R., Cripps, S., Nickson, A. & Porter, G. (2009). Defining and estimating global marine fisheries bycatch. *Marine Policy*, *33*(4), 661–672.

Daw, T., Brown, K., Rosendo, S. & Pomeroy, R. (2011). Applying the ecosystem services concept to poverty alleviation: The need to disaggregate human well-being. *Environmental Conservation*, *38*(4), 370–379.

De Freitas, J., Rojer, A., Nijhof, B. & Debrot, A. O. (2012). *A landscape ecological vegetation map of sint eustatius (lesser antilles)* (tech. rep.). IMARES.

De Groot, R. S., Wilson, M. A. & Boumans, R. M. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological economics*, *41*(3), 393–408.

De Vriend, H., van Koningsveld, M., Aarninkhof, S., de Vries, M. & Baptist, M. (2015). Sustainable hydraulic engineering through building with nature. *Journal of Hydro-environment research*, *9*(2), 159–171.

Dean, R. G. (2002). *Beach nourishment: Theory and practice* (Vol. 18). World scientific.

De'ath, G., Fabricius, K. E., Sweatman, H. & Puotinen, M. (2012). The 27–year decline of coral cover on the great barrier reef and its causes. *Proceedings of the National Academy of Sciences*, *109*(44), 17995–17999.

Debrot, A. O., Henkens, R. & Verweij, P. (2018). *Staat van de natuur van caribisch nederland 2017: Een eerste beoordeling van de staat (van instandhouding), bedreigingen en managementimplicaties van habitats en soorten in caribisch nederland* (tech. rep.). Wageningen Marine Research.

Debrot, A. O., Houtepen, E., Meesters, H. W. G., van Beek, I., Timmer, T., Boman, E., de Graaf, M., Dijkman, E., Hunting, E. R. & Ballantine, D. L. (2014). *Habitat diversity and biodiversity of the benthic seascapes of st. eustatius* (tech. rep.). IMARES.

Debrot, A. O. & Sybesma, J. (2000). The dutch antilles.

de Graaf, M., Piontek, S., Miller, D., Brunel, T. & Nagelkerke, L. (2015). *Status and trends of st. eustatius coral reef ecosystem and fisheries: 2015 report card* (tech. rep.). Imares.

de Vriend, H., van Koningsveld, M. & Aarninkhof, S. (2014). 'building with nature': The new dutch approach to coastal and river works. *Proceedings of the Institution of Civil Engineers-Civil Engineering*, *167*(1), 18–24.

de Vries, M., van Koningsveld, M., Aarninkhof, S. & de Vriend, H. (2021). A systematic design approach for objectifying building with nature solutions. *Research in Urbanism Series*, *7*, 29–50.

de Wit, L., Bliek, B. & van Rhee, C. (2020). Can surface turbidity plume generation near a trailing suction hopper dredger be predicted? *Terra et aqua*.

Dixson, D. L., Abrego, D. & Hay, M. E. (2014). Chemically mediated behavior of recruiting corals and fishes: A tipping point that may limit reef recovery. *Science*, *345*(6199), 892–897.

Díaz-Pérez, L., Rodríguez-Zaragoza, F. A., Ortiz, M., Cupul-Magaña, A. L., Carriquiry, J. D., Ríos-Jara, E., Rodríguez-Troncoso, A. P. & García-Rivas, M. d. C. (2016). Coral reef health indices versus the biological, ecological and functional diversity of fish and coral assemblages in the caribbean sea. *PLoS One*, *11*(8), e0161812.

DLG. (2011). *Assessment of opportunities for sustainable agriculture and fisheries on st. eustatius. report of mission 31 - 21 march 2011* (tech. rep.).

Doropoulos, C., Elzinga, J., ter Hofstede, R., van Koningsveld, M. & Babcock, R. C. (2019). Optimizing industrial-scale coral reef restoration: Comparing harvesting wild coral spawn slicks and transplanting gravid adult colonies. *Restoration Ecology*, *27*(4), 758–767.

Doropoulos, C., Vons, F., Elzinga, J., ter Hofstede, R., Salee, K., van Koningsveld, M. & Babcock, R. C. (2019). Testing industrial-scale coral restoration techniques: Harvesting and culturing wild coral-spawn slicks. *Frontiers in Marine Science*, *6*, 658.

Doropoulos, C., Ward, S., Roff, G., González-Rivero, M. & Mumby, P. J. (2015). Linking demographic processes of juvenile corals to benthic recovery trajectories in two common reef habitats. *PLoS One*, *10*(5), e0128535.

Duckworth, A., Giofre, N. & Jones, R. (2017). Coral morphology and sedimentation. *Marine pollution bulletin*, *125*(1-2), 289–300.

Ducruet, C. (2009). Port regions and globalization.

Dulvy, N. K., Stanwell-Smith, D., Darwall, W. R. & Horrill, C. J. (1995). Coral mining at mafia island, tanzania: A management dilemma. *Ambio*, 358–365.

Dunning, K. H. (2021). Adaptive governance: The proposed port expansion in the cayman islands and its impacts to coral reefs. *Marine Policy*, *124*, 104248.

Edwards, A. & Clark, S. (1999). Coral transplantation: A useful management tool or misguided meddling? *Marine Pollution Bulletin*, *37*(8-12), 474–487.

Edwards, A. & Gomez, E. (2007). Reef restoration. *Concepts & Guidelines. St. Lucia, Australia: Coral Reef Targeted Research & Capacity Building for Management Programme, iv*.

Edwards, A. & Gomez, E. (2010). Reef rehabilitation manual. *Reef Rehabilitation*, 1.

Ekun, M., Ehigiator-Irughe, R. & Okonofua, E. (2016). Determination of area and volume from dredged geodata set. *Nigerian Journal of Technology*, *35*(4), 707–712.

Epstein, N., Bak, R. & Rinkevich, B. (2001). Strategies for gardening denuded coral reef areas: The applicability of using different types of coral material for reef restoration. *Restoration Ecology*, *9*(4), 432–442.

Epstein, N., Bak, R. & Rinkevich, B. (2003). Applying forest restoration principles to coral reef rehabilitation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *13*(5), 387–395.

Erftemeijer, P., de Graaff, R., Boot, G. et al. (2004). Site selection for artificial reefs in bahrain (arabian gulf) based on gis technology and hydrodynamic modelling. *Journal of Marine Science and Environment No. C2*, 30.

Erftemeijer, P., de Graaff, R. & Mead, S. (2003). *Artificial reef project bahrain* (tech. rep.). Delft Hydraulics.

Erftemeijer, P., Riegl, B., Hoeksema, B. W. & Todd, P. A. (2012). Environmental impacts of dredging and other sediment disturbances on corals: A review. *Marine pollution bulletin*, *64*(9), 1737–1765.

Erickson, L. E. & Jennings, M. (2017). Energy, transportation, air quality, climate change, health nexus: Sustainable energy is good for our health. *AIMS public health*, *4*(1), 47.

Fabricius, K. E. (2005). Effects of terrestrial runoff on the ecology of corals and coral reefs: Review and synthesis. *Marine pollution bulletin*, *50*(2), 125–146.

Fayle, C. E. (2013). *A short history of the world's shipping industry*. Routledge.

Feary, D. A., Almany, G. R., Jones, G. P. & McCormick, M. I. (2007). Coral degradation and the structure of tropical reef fish communities. *Marine Ecology Progress Series*, *333*, 243–248.

Feary, D. A., Burt, J. & Bartholomew, A. (2011). Artificial marine habitats in the arabian gulf: Review of current use, benefits and management implications. *Ocean & Coastal Management*, *54*(10), 742–749.

Fenkl, F., Van Beukering, P., Lacle, F. & Schep, S. (2014). Recreational and cultural values of statia's nature to its inhabitants. *Bonaire: WKICS*.

Fernandes, L., Day, J., Lewis, A., Slegers, S., Kerrigan, B., Breen, D., Cameron, D., Jago, B., Hall, J., Lowe, D. et al. (2005). Establishing representative no-take areas in the great barrier reef: Large-scale implementation of theory on marine protected areas. *Conservation biology*, *19*(6), 1733–1744.

Ferreira, B., Rice, J. & Rosenberg, A. (2016). The oceans as a source of food. *The First Global Integrated Marine Assessment (World Ocean Assessment I). United Nations, USA*.

Fitt, W. K. (2012). Bleaching of the fire corals millepora. *Proceedings of 12th International Coral Reef Symposium, ICRS2012_9A_4*.

Fitzhardinge, R. & Bailey-Brock, J. (1989). Colonization of artificial reef materials by corals and other sessile organisms. *Bulletin of Marine Science*, *44*(2), 567–579.

Flatt, R. J., Roussel, N. & Cheeseman, C. R. (2012). Concrete: An eco material that needs to be improved. *Journal of the European Ceramic Society*, *32*(11), 2787–2798.

Fonseca, M. (1989). Sediment stabilization by halophila decipiens in comparison to other seagrasses. *Estuarine, Coastal and Shelf Science*, *29*(5), 501–507.

Forsman, Z. H., Kimokeo, B. K., Bird, C. E., Hunter, C. L. & Toonen, R. J. (2012). Coral farming: Effects of light, water motion and artificial foods. *Journal of the Marine Biological Association of the United Kingdom*, *92*(4), 721–729. https://doi.org/10.1017/S0025315411001500

Foster, T., Corcoran, E., Erftemeijer, P., Fletcher, C., Peirs, K., Dolmans, C., Smith, A., Yamamoto, H. & Jury, M. (2010). *Dredging and port construction around coral reefs. pianc environmental commission* (tech. rep.). Report.

Fox, H. E. & Caldwell, R. L. (2006). Recovery from blast fishing on coral reefs: A tale of two scales. *Ecological Applications*, *16*(5), 1631–1635.

Fox, H. E., Harris, J. L., Darling, E. S., Ahmadia, G. N. & Razak, T. B. (2019). Rebuilding coral reefs: Success (and failure) 16 years after low-cost, low-tech restoration. *Restoration ecology*, *27*(4), 862–869.

Fox, H. E., Mous, P. J., Pet, J. S., Muljadi, A. H. & Caldwell, R. L. (2005). Experimental assessment of coral reef rehabilitation following blast fishing. *Conservation Biology*, *19*(1), 98–107.

Fox, H. E., Pet, J. S., Dahuri, R. & Caldwell, R. L. (2003). Recovery in rubble fields: Long-term impacts of blast fishing. *Marine Pollution Bulletin*, *46*(8), 1024–1031.

Franke, L. & Sisomphon, K. (2004). A new chemical method for analyzing free calcium hydroxide content in cementing material. *Cement and concrete Research*, *34*(7), 1161–1165.

Frankham, R. (2005). Genetics and extinction. *Biological conservation*, *126*(2), 131–140.

Gardner, T. A., Côté, I. M., Gill, J. A., Grant, A. & Watkinson, A. R. (2003). Long-term region-wide declines in caribbean corals. *science*, *301*(5635), 958–960.

Gardner, T. A., Côté, I. M., Gill, J. A., Grant, A. & Watkinson, A. R. (2005). Hurricanes and caribbean coral reefs: Impacts, recovery patterns, and role in long-term decline. *Ecology*, *86*(1), 174–184.

Gegner, H. M., Ziegler, M., Rädecker, N., Buitrago-López, C., Aranda, M. & Voolstra, C. R. (2017). High salinity conveys thermotolerance in the coral model aiptasia. *Biology open*, *6*(12), 1943–1948.

Geoblock. (n.d.). *Eco-reefs*. https://www.geoblock.eu/eco-reef

Geographic, N. (2021). *Coral reef food web*. https://www.nationalgeographic.org/media/coral-reef-food-web/print/

Gill, A. B. (2005). Offshore renewable energy: Ecological implications of generating electricity in the coastal zone. *Journal of applied ecology*, *42*(4), 605–615.

Gilmore III, R. G. (2005). *The archaeology of new world slave societies: A comparative analysis with particular reference to st. eustatius, netherlands antilles*. University of London, University College London (United Kingdom).

Gilmour, J. (1999). Experimental investigation into the effects of suspended sediment on fertilisation, larval survival and settlement in a scleractinian coral. *Marine Biology*, *135*(3), 451–462.

Glasson, J. & Therivel, R. (2013). *Introduction to environmental impact assessment*. Routledge.

Glynn, P. W. (1993). Coral reef bleaching: Ecological perspectives. *Coral reefs*, *12*(1), 1–17.

Glynn, P. W., Gassman, N., Eakin, C., Cortes, J., Smith, D. & Guzman, H. (1991). Reef coral reproduction in the eastern pacific: Costa rica, panama, and galapagos islands (ecuador). *Marine Biology*, *109*(3), 355–368.

Glynn, P. W. & Wellington, G. M. (1983). *Corals and coral reefs of the galápagos islands*. Univ of California Press.

Goemans, B. (2012). *Salt corners aquaurium library*. http://www.saltcorner.com/AquariumLibrary/browsesection.php

Golden, C. D., Allison, E. H., Cheung, W. W., Dey, M. M., Halpern, B. S., McCauley, D. J., Smith, M., Vaitla, B., Zeller, D. & Myers, S. S. (2016). Nutrition: Fall in fish catch threatens human health. *Nature News*, *534*(7607), 317.

Goreau, T. F., Goreau, N. I. & Goreau, T. J. (1979). Corals and coral reefs. *Scientific American*, *241*(2), 124–137.

Goreau, T. F. & Wells, J. (1967). The shallow-water scleractinia of jamaica: Revised list of species and their vertical distribution range. *Bulletin of Marine Science*, *17*(2), 442–453.

Goreau, T. J., Cervino, J. M. & Pollina, R. (2004). Increased zooxanthellae numbers and mitotic index in electrically stimulated corals. *Symbiosis*.

Goreau, T. J. & Hilbertz, W. (2005). Marine ecosystem restoration: Costs and benefits for coral reefs. *World resource review*, *17*(3), 375–409.

Gorham, J. C. & Alevizon, W. S. (1989). Habitat complexity and the abundance of juvenile fishes residing on small scale artificial reefs. *Bulletin of Marine Science*, *44*(2), 662–665.

Gourlay, M. (1994). Wave transformation on a coral reef. *Coastal engineering*, *23*(1-2), 17–42.

government, S. (2020). *About st. eustatius*. https://www.statiagovernment.com/about-st.-eustatius

Gratwicke, B. & Speight, M. (2005). The relationship between fish species richness, abundance and habitat complexity in a range of shallow tropical marine habitats. *Journal of fish biology*, *66*(3), 650–667.

Gray, W. M. (1979). Hurricanes: Their formation, structure and likely role in the tropical circulation. *Meteorology over the tropical oceans*, *155*, 218.

Great barrier reef marine park authority. (2021). *Recreation on the great barrier reef*. Retrieved June 21, 2021, from https://www.gbrmpa.gov.au/our-work/Managing-multiple-uses/recreation-in-the-great-barrier-reef-marine-park

Greenberg, T. & Itzhak, D. (2005). Marine biofouling of titanium alloys in the coral reef environment. *Corrosion Reviews*, *23*(4-5-6), 405–414.

Greenough, G., McGeehin, M., Bernard, S. M., Trtanj, J., Riad, J. & Engelberg, D. (2001). The potential impacts of climate variability and change on health impacts of extreme weather events in the united states. *Environmental health perspectives*, *109*(suppl 2), 191–198.

Grigg, R. W. (1965). Ecological studies of black coral in hawaii.

Group, C. A. S. C. C. S. C. W., Group, S. C. W., Canada, N. R. C., Agriculture, C. & Branch, A.-F. C. R. (1998). *The canadian system of soil classification*. NRC Research Press.

Grove, R. (1982). Artificial reefs as a resource management option for siting coastal power stations in southern california. *Marine Fisheries Review*, *44*(6), 24–27.

Grove, R., Sonu, C. & Nakamura, M. (1991). Design and engineering of manufactured habitats for fisheries enchancement.

Guannel, G., Arkema, K., Ruggiero, P. & Verutes, G. (2016). The power of three: Coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience. *PloS one*, *11*(7), e0158094.

Hackradt, C. W., Félix-Hackradt, F. C. & García-Charton, J. A. (2011). Influence of habitat structure on fish assemblage of an artificial reef in southern brazil. *Marine environmental research*, *72*(5), 235–247.

Hallegatte, S., Green, C., Nicholls, R. J. & Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nature climate change*, *3*(9), 802–806.

Hameed, M. S. & Sekar, A. (2009). Properties of green concrete containing quarry rock dust and marble sludge powder as fine aggregate. *ARPN J. Eng. Appl. Sci*, *4*(4), 83–89.

Hardy, J. T. (2003). *Climate change: Causes, effects, and solutions*. John Wiley & Sons.

Harlaftis, G., Valdaliso, J. & Tenold, S. (2012). *The world's key industry: History and economics of international shipping*. Palgrave Macmillan.

Harriott, V. J. & Fisk, D. A. (1987). A comparison of settlement plate types for experiments on the recruitment of scleractinian corals. *Mar Ecol Prog Ser*, *37*(2-3), 201–208.

Harris, D. L., Rovere, A., Casella, E., Power, H., Canavesio, R., Collin, A., Pomeroy, A., Webster, J. M. & Parravicini, V. (2018). Coral reef structural complexity provides important coastal protection from waves under rising sea levels. *Science Advances*, *4*(2), eaao4350.

Hein, C. J. & Ashton, A. D. (2020). Long-term shoreline morphodynamics: Processes and preservation of environmental signals. *Sandy Beach Morphodynamics*, 487–531.

Hein, M. Y., McLeod, I., Shaver, E., Vardi, T., Pioch, S., Boström-Einarsson, L., Ahmed, M. & Grimsditch, G. (2020). Coral reef restoration as a strategy to improve ecosystem services a guide to coral restoration methods. *United Nations Environment Program, Nairobi, Kenya*.

Helvey, M. & Smith, R. W. (1985). Influence of habitat structure on the fish assemblages associated with two cooling-water intake structures in southern california. *Bulletin of Marine Science*, *37*(1), 189–199.

Henkel, T. P. (2010). *Coral reefs are one of the most diverse ecosystems on the planet. what are the abiotic and biotic interactions that structure this diverse ecosystem?* https://www.nature.com/scitable/knowledge/library/coral-reefs-15786954/

Herbig, J. L. & Szedlmayer, S. (2016). Movement patterns of gray triggerfish, balistes capriscus, around artificial reefs in the northern gulf of mexico. *Fisheries Management and Ecology*, *23*(5), 418–427.

Hiatt, R. W. & Strasburg, D. W. (1960). Ecological relationships of the fish fauna on coral reefs of the marshall islands. *Ecological Monographs*, *30*(1), 65–127.

Hicks, C. C. & Cinner, J. E. (2014). Social, institutional, and knowledge mechanisms mediate diverse ecosystem service benefits from coral reefs. *Proceedings of the National Academy of Sciences*, *111*(50), 17791–17796.

Hixon, M. A. & Beets, J. P. (1989). Shelter characteristics and caribbean fish assemblages: Experiments with artificial reefs. *Bulletin of Marine Science*, *44*(2), 666–680.

Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of the world's coral reefs. *Marine and freshwater research*, *50*(8), 839–866.

Hoegh-Guldberg, O. & Bruno, J. F. (2010). The impact of climate change on the world's marine ecosystems. *Science*, *328*(5985), 1523–1528.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, A., Caldeira, K. et al. (2007). Coral reefs under rapid climate change and ocean acidification. *science*, *318*(5857), 1737–1742.

Hoey, A. & Bellwood, D. (2008). Cross-shelf variation in the role of parrotfishes on the great barrier reef. *Coral Reefs*, *27*(1), 37–47.

Holmes, G. (2008). Estimating three-dimensional surface areas on coral reefs. *Journal of Experimental Marine Biology and Ecology*, *365*(1), 67–73.

Holmlund, C. M. & Hammer, M. (1999). Ecosystem services generated by fish populations. *Ecological economics*, *29*(2), 253–268.

Höök, M. & Tang, X. (2013). Depletion of fossil fuels and anthropogenic climate change—a review. *Energy policy*, *52*, 797–809.

Hopley, D., RF, M., AS, S. et al. (1978). Holocene-plaistocene boundary in a fringing reef: Hayman island, north queensland.

Hosomi, R., Yoshida, M. & Fukunaga, K. (2012). Seafood consumption and components for health. *Global journal of health science*, *4*(3), 72.

Houghton, J. T. (2005). Global warming. *Reports on progress in physics*, *68*(6), 1343.

Houghton, J. T., Jenkins, G. J. & Ephraums, J. J. (1990). Climate change.

Houk, P., Comeros-Raynal, M., Lawrence, A., Sudek, M., Vaeoso, M., McGuire, K. & Regis, J. (2020). Nutrient thresholds to protect water quality and coral reefs. *Marine Pollution Bulletin*, *159*, 111451.

Hovland, M., Vasshus, S., Indreeide, A., Austdal, L. & Nilsen, Ø. (2002). Mapping and imaging deep-sea coral reefs off norway, 1982–2000. *Hydrobiologia*, *471*(1), 13–17.

Howdyshell, P. A. (1974). *The use of coral as an aggregate for portland cement concrete structures* (tech. rep.). Construction Engineering Research Lab (Army) Champaign IL.

Hubbard, J. A. & Pocock, Y. P. (1972). Sediment rejection by recent scleractinian corals: A key to palaeo-environmental reconstruction. *Geologische Rundschau*, *61*(2), 598–626.

Hughes, T. P. (1994). Catastrophes, phase shifts, and large-scale degradation of a caribbean coral reef. *Science*, *265*(5178), 1547–1551.

Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J. B. C., Kleypas, J., Lough, J. M., Marshall, P., Nyström, M., Palumbi, S. R., Pandolfi, J. M., Rosen, B. & Roughgarden, J. (2003). Climate change, human impacts, and the resilience of coral reefs. *Science*, *301*(5635), 929–933. https://doi.org/10.1126/science.1085046

Hughes, T. P., Barnes, M. L., Bellwood, D. R., Cinner, J. E., Cumming, G. S., Jackson, J. B., Kleypas, J., Van De Leemput, I. A., Lough, J. M., Morrison, T. H. et al. (2017). Coral reefs in the anthropocene. *Nature*, *546*(7656), 82–90.

Humann, P. & Deloach, N. (2013). Reef coral identification: Florida, caribbean. *Bahamas. Third. Jacksonville, Florida: New World Publications*.

Humphrey, C., Weber, M., Lott, C., Cooper, T. & Fabricius, K. (2008). Effects of suspended sediments, dissolved inorganic nutrients and salinity on fertilisation and embryo development in the coral acropora millepora (ehrenberg, 1834). *Coral Reefs*, *27*(4), 837–850.

Huston, M. A. (1985). Patterns of species diversity on coral reefs. *Annual review of ecology and systematics*, *16*(1), 149–177.

Hylkema, A. (2021). Tropische zee-egels gekweekt voor herstel koraalriffen cariben.

Hylkema, A., Debrot, A. O., Osinga, R., Bron, P. S., Heesink, D. B., Izioka, A. K., Reid, C. B., Rippen, J. C., Treibitz, T., Yuval, M. et al. (2020). Fish assemblages of three common artificial reef designs during early colonization. *Ecological Engineering*, *157*, 105994.

Hylkema, A., Hakkaart, Q. C., Reid, C. B., Osinga, R., Murk, A. J. & Debrot, A. O. (2021). Artificial reefs in the caribbean: A need for comprehensive monitoring and integration into marine management plans. *Ocean & Coastal Management*, *209*, 105672.

Ido, S. & Shimrit, P.-F. (2015). Blue is the new green–ecological enhancement of concrete based coastal and marine infrastructure. *Ecological Engineering*, *84*, 260–272.

Initiative, H. R. (2008). *Reef health index*. https://www.healthyreefs.org/cms/?s=Reef+health+Index&lang=en

Inniss, L., Simcock, A., Ajawin, A. Y., Alcala, A. C., Bernal, P., Calumpong, H. P., Araghi, P. E., Green, S. O., Harris, P., Kamara, O. K. et al. (2016). The first global integrated marine assessment. *United Nations. Accessed at on 5th February*.

IUCN. (2021). *Iucn red list of threatened species*. https://www.iucnredlist.org/

Jaap, W. C. (2000). Coral reef restoration. *Ecological engineering*, *15*(3-4), 345–364.

Jackson, J., Donovan, M., Cramer, K. & Lam, V. (2014). Status and trends of caribbean coral reefs. *Global Coral Reef Monitoring Network, IUCN, Gland, Switzerland*, 1970–2012.

Jacob, B. & Stanev, E. V. (2021). Understanding the impact of bathymetric changes in the german bight on coastal hydrodynamics: One step toward realistic morphodynamic modeling. *Frontiers in Marine Science*, *8*, 576.

Jagerroos, S. & Krause, P. (2016). Rigs-to-reef; impact or enhancement on marine biodiversity. *Journal of Ecosystem & Ecography*, *6*(2), 1000187.

Jaleel, A. (2013). The status of the coral reefs and the management approaches: The case of the maldives. *Ocean & coastal management*, *82*, 104–118.

Jameson, S. C., Tupper, M. H. & Ridley, J. M. (2002). The three screen doors: Can marine “protected” areas be effective? *Marine pollution bulletin*, *44*(11), 1177–1183.

Jo, B.-w., Park, S.-k. & Park, J.-b. (2007). Properties of concrete made with alkali-activated fly ash lightweight aggregate (afla). *Cement and Concrete composites*, *29*(2), 128–135.

Johannes, R. (1975). Pollution and degradation of coral reef communities. *Elsevier oceanography series* (pp. 13–51). Elsevier.

Johannes, R., Maragos, J. & Coles, S. L. (1972). Oil damages corals exposed to air. *Marine Pollution Bulletin*, *3*(2), 29–30.

Johansen, J. L. (2014). Quantifying water flow within aquatic ecosystems using load cell sensors: A profile of currents experienced by coral reef organisms around lizard island, great barrier reef, australia. *PLoS One*, *9*(1), e83240.

Johns, K. A., Emslie, M. J., Hoey, A. S., Osborne, K., Jonker, M. J. & Cheal, A. J. (2018). Macroalgal feedbacks and substrate properties maintain a coral reef regime shift. *Ecosphere*, *9*(7), e02349.

Johnston, R., Halkola, H., George, R., In, C., Gauthier, R., Wild, W., Bell, M. & Martore, R. (2003). Assessing the ecological risk of creating artificial reefs from ex-warships. *Oceans 2003. Celebrating the Past... Teaming Toward the Future (IEEE Cat. No. 03CH37492)*, *2*, 804–811.

Jokiel, P. L., Rodgers, K. S., Brown, E. K., Kenyon, J. C., Aeby, G., Smith, W. R. & Farrell, F. (2015). Comparison of methods used to estimate coral cover in the hawaiian islands. *PeerJ*, *3*, e954.

Jones, G. P., McCormick, M. I., Srinivasan, M. & Eagle, J. V. (2004). Coral decline threatens fish biodiversity in marine reserves. *Proceedings of the National Academy of Sciences*, *101*(21), 8251–8253.

Jones, G. P., Srinivasan, M. & Almany, G. R. (2007). Population connectivity and conservation of marine biodiversity. *Oceanography*, *20*(3), 100–111.

Jones, R., Bessell-Browne, P., Fisher, R., Klonowski, W. & Slivkoff, M. (2016). Assessing the impacts of sediments from dredging on corals. *Marine Pollution Bulletin*, *102*(1), 9–29.

Jones, R., Giofre, N., Luter, H. M., Neoh, T. L., Fisher, R. & Duckworth, A. (2020). Responses of corals to chronic turbidity. *Scientific reports*, *10*(1), 1–13.

Jonkers, H. M. (2007). Self healing concrete: A biological approach. *Self healing materials* (pp. 195–204). Springer.

Karl, T. R. & Trenberth, K. E. (2003). Modern global climate change. *science*, *302*(5651), 1719–1723.

Kateman, I. & Bos, C. (2010). *Accesibility study harbour statia: Feasibility study improvement harbour accessibility st eustatius* (tech. rep.). Royal Haskoning 9V3461.

Kaufman, L. et al. (1977). The three spot damselfish: Effects on benthic biota of caribbean coral reefs.

Kaufman, L. (2006). If you build it, will they come? toward a concrete basis for coral reef gardening. *Coral reef restoration handbook*, 119–142.

Kaufman, L., Sandin, S., Sala, E., Obura, D., Rohwer, F. & Tschirky, T. (2011). Coral health index (chi): Measuring coral community health. *Science and Knowledge Division, Conservation International, Arlington, VA, USA*.

Kawasaki, H., Sano, M. & Shibuno, T. (2003). The relationship between habitat physical complexity and recruitment of the coral reef damselfish, pomacentrus amboinensis: An experimental study using small-scale artificial reefs. *Ichthyological Research*, *50*(1), 0073–0077.

Kempfert, H.-G. & Gebreselassie, B. (2006). Pile foundation. *Excavations and Foundations in Soft Soils*, 349–460.

Kennedy, E. V., Perry, C. T., Halloran, P. R., Iglesias-Prieto, R., Schönberg, C. H., Wisshak, M., Form, A. U., Carricart-Ganivet, J. P., Fine, M., Eakin, C. M. et al. (2013). Avoiding coral reef functional collapse requires local and global action. *Current Biology*, *23*(10), 912–918.

Keshavanath, P., Gangadhar, B., Ramesh, T., Van Rooij, J., Beveridge, M., Baird, D., Verdegem, M. & Van Dam, A. (2001). Use of artificial substrates to enhance production of freshwater herbivorous fish in pond culture. *Aquaculture Research*, *32*(3), 189–197.

Kim, D., Woo, J., Yoon, H.-S. & Na, W.-B. (2016). Efficiency, tranquillity and stability indices to evaluate performance in the artificial reef wake region. *Ocean Engineering*, *122*, 253–261.

Kinsman, D. (1964). Reef coral tolerance of high temperatures and salinities. *Nature*, *202*(4939), 1280–1282.

Kitson-Walters, K. (2017). Status coral reef sint eustatius. *GCRMN caribbean*.

Kitson-Walters, K. (2020). Final report: Status coral reef sint eustatius. *GCRMN caribbean*.

Kitson-Walters, K., Kitson, K., Rippen, J., Stelwagen, T., van Weert, Y. & van Wijk, D. (n.d.). First indication of the abundance and distribution of protected seagrass associated species in the introduced halophila stipulacea meadows on sint eustatius.

Kittinger, J. N., Finkbeiner, E. M., Glazier, E. W. & Crowder, L. B. (2012). Human dimensions of coral reef social-ecological systems. *Ecology and Society*, *17*(4).

Kjerfve, B. (1981). Tides of the caribbean sea. *Journal of Geophysical Research: Oceans*, *86*(C5), 4243–4247.

Klemm, A. & Wiggins, D. (2016). 12 - sustainability of natural stone as a construction material. In J. M. Khatib (Ed.), *Sustainability of construction materials (second edition)* (Second Edition, pp. 283–308). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-0-08-100370-1.00012-3

Klomp, K. D. & Kooistra, D. J. (2003). Netherlands antilles. a post-hurricane, rapid assessment of reefs in the windward netherlands antilles (stony corals, algae and fishes). *Atoll Research Bulletin*.

Knowlton, N. (2001). The future of coral reefs. *Proceedings of the National Academy of Sciences*, *98*(10), 5419–5425.

Koch, E. (1996). Hydrodynamics of a shallow thalassia testudinum bed in florida, usa. *Seagrass Biology: Proceedings of an International Workshop, Rottnest Island, Western Australia*, 25–29.

Komyakova, V., Munday, P. L. & Jones, G. P. (2013). Relative importance of coral cover, habitat complexity and diversity in determining the structure of reef fish communities. *PloS one*, *8*(12), e83178.

Koningsveld, M. (2004). Matching specialist knowledge with end user needs.

Kramer, P. A. (2003). Synthesis of coral reef health indicators for the western atlantic: Results of the agrra program (1997-2000). *Atoll Research Bulletin*.

Kron, W. (2013). Coasts: The high-risk areas of the world. *Natural hazards*, *66*(3), 1363–1382.

Kružić, P., Sršen, P. & Benković, L. (2012). The impact of seawater temperature on coral growth parameters of the colonial coral cladocora caespitosa (anthozoa, scleractinia) in the eastern adriatic sea. *Facies*, *58*(4), 477–491.

Kunkel, C. M., Hallberg, R. W. & Oppenheimer, M. (2006). Coral reefs reduce tsunami impact in model simulations. *Geophysical research letters*, *33*(23).

Kuyper, M. W. (1991). *Review of the ecological basis of environmental assessment of coral reefs* (Doctoral dissertation). University of Newcastle upon Tyne.

Kynch, G. J. (1952). A theory of sedimentation. *Transactions of the Faraday society*, *48*, 166–176.

Laboyrie, P., Van Koningsveld, M., Aarninkhof, S., Van Parys, M., Lee, M., Jensen, A., Csiti, A. & Kolman, R. (2018). *Dredging for sustainable infrastructure*. CEDA/IADC.

Lamb, J. B., Willis, B. L., Fiorenza, E. A., Couch, C. S., Howard, R., Rader, D. N., True, J. D., Kelly, L. A., Ahmad, A., Jompa, J. et al. (2018). Plastic waste associated with disease on coral reefs. *Science*, *359*(6374), 460–462.

Lapointe, B. E., Bedford, B. J. & Baumberger, R. (2006). Hurricanes frances and jeanne remove blooms of the invasive green alga caulerpa brachypus forma parvifolia (harvey) cribb from coral reefs off northern palm beach county, florida. *Estuaries and Coasts*, *29*(6), 966–971.

Laurance, W. F. (2010). Habitat destruction: Death by a thousand cuts. *Conservation biology for all*, *1*(9), 73–88.

Lee, Z., Weidemann, A., Kindle, J., Arnone, R., Carder, K. L. & Davis, C. (2007). Euphotic zone depth: Its derivation and implication to ocean-color remote sensing. *Journal of Geophysical Research: Oceans*, *112*(C3).

Levin, L. A. & Dayton, P. K. (2009). Ecological theory and continental margins: Where shallow meets deep. *Trends in ecology & evolution*, *24*(11), 606–617.

Lewis, S. M. (1986). The role of herbivorous fishes in the organization of a caribbean reef community. *Ecological Monographs*, *56*(3), 183–200.

Li, S., Yu, K., Shi, Q., Chen, T., Zhao, M. & Zhao, J. (2008). Interspecies and spatial diversity in the symbiotic zooxanthellae density in corals from northern south china sea and its relationship to coral reef bleaching. *Chinese Science Bulletin*, *53*(2), 295–303.

Lima, J. S., Zalmon, I. R. & Love, M. (2019). Overview and trends of ecological and socioeconomic research on artificial reefs. *Marine Environmental Research*, *145*, 81–96. https://doi.org/https://doi.org/10.1016/j.marenvres.2019.01.010

Lindahl, U. (1998). Low-tech rehabilitation of degraded coral reefs through transplantation of staghorn corals. *Ambio*, *27*(8), 645–650.

Lindahl, U. (2000). A low-tech method for reef rehabilitation by stabilisation of transplanted corals. *Coral Reef Degradation in the Indian Ocean: Status Reports and Project Presentations*.

Lindahl, U. (2003). Coral reef rehabilitation through transplantation of staghorn corals: Effects of artificial stabilization and mechanical damages. *Coral reefs*, *22*(3), 217–223.

Linde, M., Attard, R., Wilson, C. et al. (2013). Undervaluing positive impacts in the environmental impact assessment process. *Coasts and Ports 2013: 21st Australasian Coastal and Ocean Engineering Conference and the 14th Australasian Port and Harbour Conference*, 23.

Lindeboom, H. (2017). Concept delta-plan voor het redden van de koraalriffen bij, de economieen van, de veiligheid op en de relaties met de eilanden in het caribische deel van het koninkrijk der nederlanden, 1–31.

Lirman, D. & Manzello, D. (2009). Patterns of resistance and resilience of the stress-tolerant coral siderastrea radians (pallas) to sub-optimal salinity and sediment burial. *Journal of Experimental Marine Biology and Ecology*, *369*(1), 72–77.

Liu, G., Strong, A. E., Skirving, W. & Arzayus, L. F. (2006). Overview of noaa coral reef watch program's near-real time satellite global coral bleaching monitoring activities. *Proceedings of the 10th international coral reef symposium*, *1793*, 1783–1793.

LNV & IenW. (2020). *Beleidsplan natuur en milieu caribisch nederland 2020 - 2030* (tech. rep.). https://www.rijksoverheid.nl/documenten/beleidsnotas/2020/04/24/natuur--en-milieubeleidsplan-caribisch-nederland-2020-2030

Loke, L. H., Jachowski, N. R., Bouma, T. J., Ladle, R. J. & Todd, P. A. (2014). Complexity for artificial substrates (casu): Software for creating and visualising habitat complexity. *PloS one*, *9*(2), e87990.

Loke, L. H., Ladle, R. J., Bouma, T. J. & Todd, P. A. (2015). Creating complex habitats for restoration and reconciliation. *Ecological Engineering*, *77*, 307–313.

Loya, Y. & Rinkevich, B. (1980). Effects of oil pollution on coral reef communities. *Mar. Ecol. Prog. Ser*, *3*(16), 180.

Loya, Y., Sakai, K., Yamazato, K., Nakano, Y., Sambali, H. & Van Woesik, R. (2001). Coral bleaching: The winners and the losers. *Ecology letters*, *4*(2), 122–131.

Lück, M. (2008). *The encyclopedia of tourism and recreation in marine environments*. CABI.

Luckhurst, B. & Luckhurst, K. (1978). Analysis of the influence of substrate variables on coral reef fish communities. *Marine Biology*, *49*(4), 317–323.

Lugo-Fernandez, A., Roberts, H., Wiseman Jr, W. & Carter, B. (1998). Water level and currents of tidal and infragravity periods at tague reef, st. croix (usvi). *Coral Reefs*, *17*(4), 343–349.

Maekouchi, N., Ano, T., Oogi, M., Tsuda, S., Kurita, K., Ikeda, Y. & Yamamoto, H. (2008). The "eco-block" as a coral-friendly contrivance in port construction. *Proc 11th Int Coral Reef Sym, Ft. Lauderdale, Florida*, 1253–1257.

Maida, M., Coll, J. & Sammarco, P. (1994). Shedding new light on scleractinian coral recruitment. *Journal of Experimental Marine Biology and Ecology*, *180*(2), 189–202.

Malan, R., Bredemeyer, D. et al. (2001). Functional requirements and use cases. *Bredemeyer Consulting*.

Mantelatto, M. C., Póvoa, A. A., Skinner, L. F., de Araujo, F. V. & Creed, J. C. (2020). Marine litter and wood debris as habitat and vector for the range expansion of invasive corals (tubastraea spp.) *Marine Pollution Bulletin*, *160*, 111659. https://doi.org/https://doi.org/10.1016/j.marpolbul.2020.111659

Maragos, J. E. (1993). Impact of coastal construction on coral reefs in the us-affiliated pacific islands. *Coastal Management*, *21*(4), 235–269.

Maron, M., Walsh, M., Shumway, N. & Brodie, J. (2016). Reef trust offsets calculator. *Brisbane, Queensland, Australia*.

Marshall, A. & Clode, P. (2004). Calcification rate and the effect of temperature in a zooxanthellate and an azooxanthellate scleractinian reef coral. *Coral reefs*, *23*(2), 218–224.

Marubini, F. & Atkinson, M. (1999). Effects of lowered ph and elevated nitrate on coral calcification. *Marine Ecology Progress Series*, *188*, 117–121.

Massazza, F. (1993). Pozzolanic cements. *Cement and Concrete composites*, *15*(4), 185–214.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R. et al. (2018). Global warming of 1.5 c. *An IPCC Special Report on the impacts of global warming of*, *1*(5).

Mathews, H. (1981). Artificial reefs site: Selection and evaluation. *Artificial Reefs: Conference Proceedings. Florida Sea Grant Report*, *41*, 50–54.

Maya, P. H. M., Smit, K. P., Burt, A. J. & Frias-Torres, S. (2016). Large-scale coral reef restoration could assist natural recovery in seychelles, indian ocean. *Nature Conservation*, *16*, 1.

McClanahan, T. R. (1999). Is there a future for coral reef parks in poor tropical countries? *Coral reefs*, *18*(4), 321–325.

McClanahan, T. R., Maina, J., Starger, C., Herron-Perez, P. & Dusek, E. (2005). Detriments to post-bleaching recovery of corals. *Coral Reefs*, *24*(2), 230–246.

McClanahan, T. R., Marnane, M. J., Cinner, J. E. & Kiene, W. E. (2006). A comparison of marine protected areas and alternative approaches to coral-reef management. *Current biology*, *16*(14), 1408–1413.

McClanahan, T. R. & Obura, D. (1997). Sedimentation effects on shallow coral communities in kenya. *Journal of Experimental Marine Biology and Ecology*, *209*(1), 103–122. https://doi.org/https://doi.org/10.1016/S0022-0981(96)02663-9

McCook, L., Jompa, J. & Diaz-Pulido, G. (2001). Competition between corals and algae on coral reefs: A review of evidence and mechanisms. *Coral reefs*, *19*(4), 400–417.

McCulloch, M., Falter, J., Trotter, J. & Montagna, P. (2012). Coral resilience to ocean acidification and global warming through ph up-regulation. *Nature Climate Change*, *2*(8), 623–627.

McField, M. & Kramer, P. (2007). Healthy reefs for healthy people: A guide to indicators of reef health and social well-being in the mesoamerican reef region. *With contributions by M Gorrez and M McPherson. Miami, FL: Healthy Reefs for Healthy People Initiative*.

Meadows, D. H., Meadows, D. H., Randers, J. & Behrens III, W. W. (1972). The limits to growth: A report to the club of rome (1972). *Google Scholar*, *91*.

Meesters, E., Becking, L. & van der Geest, M. (2019). Achteruitgang koraalriffen caribisch nederland: Oorzaken en mogelijke oplossingen voor koraalherstel. *Wageningen Marine Research*, 1–7.

Mercader, M., Mercière, A., Saragoni, G., Cheminée, A., Crec'hriou, R., Pastor, J., Rider, M., Dubas, R., Lecaillon, G., Boissery, P. et al. (2017). Small artificial habitats to enhance the nursery function for juvenile fish in a large commercial port of the mediterranean. *Ecological Engineering*, *105*, 78–86.

Meron, D., Atias, E., Kruh, L. I., Elifantz, H., Minz, D., Fine, M. & Banin, E. (2011). The impact of reduced ph on the microbial community of the coral acropora eurystoma. *The ISME journal*, *5*(1), 51–60.

Meyer, E., Aglyamova, G. & Matz, M. (2011). Profiling gene expression responses of coral larvae (acropora millepora) to elevated temperature and settlement inducers using a novel rna-seq procedure. *Molecular ecology*, *20*(17), 3599–3616.

Meyer, E., Davies, S., Wang, S., Willis, B. L., Abrego, D., Juenger, T. E. & Matz, M. V. (2009). Genetic variation in responses to a settlement cue and elevated temperature in the reef-building coral acropora millepora. *Marine Ecology Progress Series*, *392*, 81–92.

Michener, W. K., Blood, E. R., Bildstein, K. L., Brinson, M. M. & Gardner, L. R. (1997). Climate change, hurricanes and tropical storms, and rising sea level in coastal wetlands. *Ecological Applications*, *7*(3), 770–801.

Moberg, F. & Folke, C. (1999). Ecological goods and services of coral reef ecosystems. *Ecological economics*, *29*(2), 215–233.

Molenaar, W. & Voorendt, M. (2020). *Hydraulic structures general lecture notes* (tech. rep.). TUDELFT.

Moriarty, J. (2014). The connection between stakeholder theory and stakeholder democracy: An excavation and defense. *Business & Society*, *53*(6), 820–852.

Morris, P. & Therivel, R. (2001). *Methods of environmental impact assessment* (Vol. 2). Taylor & Francis.

Moschella, P., Abbiati, M., Åberg, P., Airoldi, L., Anderson, J., Bacchiocchi, F., Bulleri, F., Dinesen, G. E., Frost, M., Gacia, E. et al. (2005). Low-crested coastal defence structures as artificial habitats for marine life: Using ecological criteria in design. *Coastal Engineering*, *52*(10-11), 1053–1071.

Mumby, P. J. & Steneck, R. S. (2008). Coral reef management and conservation in light of rapidly evolving ecological paradigms. *Trends in ecology & evolution*, *23*(10), 555–563.

Mundy, C. & Babcock, R. (1998). Role of light intensity and spectral quality in coral settlement: Implications for depth-dependent settlement? *Journal of Experimental Marine Biology and Ecology*, *223*(2), 235–255.

Munn, E. (1979). Environmental impact assessment.

Muscatine, L. (1980). Productivity of zooxanthellae. *Primary productivity in the sea* (pp. 381–402). Springer.

Muthiga, N. A. & Szmant, A. M. (1987). The effects of salinity stress on the rates of aerobic respiration and photosynthesis in the hermatypic coral siderastrea siderea. *The Biological Bulletin*, *173*(3), 539–551.

Muttray, M. & Reedijk, B. (2009). Design of concrete armour layers. *Hansa International Maritime Journal*, *6*, 111–118.

Myers, p., Espinoza, R., Parr, C., Jones, T., Hammond, G. & Dewey, T. (n.d.). *The animal diversity web*. https://animaldiversity.org

Nagrockiene, D., Pundienė, I. & Kicaite, A. (2013). The effect of cement type and plasticizer addition on concrete properties. *Construction and building materials*, *45*, 324–331.

Nakamura, M. (1982). The planning and design of artificial reefs and tsukiio. *Japanese artificial reef technology, Technical Report*, *604*, 49–66.

NASA. (n.d.). *Millenium coral reef mapping project*. https://www.nasa.gov/vision/earth/lookingatearth/coral_assessment.html

Nath, P. & Sarker, P. (2011). Effect of fly ash on the durability properties of high strength concrete. *Procedia Engineering*, *14*, 1149–1156.

NatureServe. (n.d.). *Nature serve explorer*. https://explorer.natureserve.org/Search

Naughton, J. & Jokiel, P. (2001). Coral reef mitigation and restoration techniques employed in the pacific islands: I. overview, 1–7.

Needham, M. D. (2010). Value orientations toward coral reefs in recreation and tourism settings: A conceptual and measurement approach. *Journal of sustainable tourism*, *18*(6), 757–772.

Nelson, D. S., McManus, J., Richmond, R. H., King Jr, D. B., Gailani, J. Z., Lackey, T. C. & Bryant, D. (2016). Predicting dredging-associated effects to coral reefs in apra harbor, guam–part 2: Potential coral effects. *Journal of environmental management*, *168*, 111–122.

Nemeth, R. S. & Nowlis, J. S. (2001). Monitoring the effects of land development on the near-shore reef environment of st. thomas, usvi. *Bulletin of Marine Science*, *69*(2), 759–775.

Neo, M. L., Todd, P. A., Teo, S. L.-M. & Chou, L. M. (2009). Can artificial substrates enriched with crustose coralline algae enhance larval settlement and recruitment in the fluted giant clam (tridacna squamosa)? *Hydrobiologia*, *625*(1), 83–90.

NOAA. (2000). Habitat equivalency analysis: An overview. damage assessment and restoration program national oceanic and atmospheric administration department of commerce, 1–95.

NOAA. (2021). *Coral bleaching: Alerts - real time*. https://sos.noaa.gov/catalog/datasets/coral-bleaching-alerts-real-time/
NOAA, National Oceanic and Atmospheric Administration. (2021a). *In what types of water do corals live?o*. https://oceanservice.noaa.gov/facts/coralwaters.html
NOAA, National Oceanic and Atmospheric Administration. (2021b). *What does coral have to do with medicine?* https://oceanservice.noaa.gov/facts/coral_medicine.html
NOAA, National Oceanic and Atmospheric Administration. (2021c). *Where are reef building corals found?* https://oceanservice.noaa.gov/education/tutorial_corals/coral05_distribution.html
Nozawa, Y., Tanaka, K. & Reimer, J. D. (2011). Reconsideration of the surface structure of settlement plates used in coral recruitment studies. *Zoological Studies*, *50*(1), 53–60.
of Environmental Protection, F. D. (2007). *Uniform mitigation assessment method*. https://www.flrules.org/gateway/ChapterHome.asp?Chapter=62-345
Öhman, M. C., Linden, O. & Rajasuriya, A. (1993). Human disturbances on coral reefs in sri lanka: A case study. *Ambio (Journal of the Human Environment, Research and Management);(Sweden)*, *22*(7).
Oliveira, A., Fortunato, A. B. & Rego, J. R. (2006). Effect of morphological changes on the hydrodynamics and flushing properties of the óbidos lagoon (portugal). *Continental Shelf Research*, *26*(8), 917–942.
Oliver, A. C. & Brown, W. H. (1974). *Timber for marine and fresh water construction*. Timber Research; Development Association High Wycombe, UK.
Oliver, T. & Palumbi, S. (2011). Do fluctuating temperature environments elevate coral thermal tolerance? *Coral reefs*, *30*(2), 429–440.
Olivier, H. J. (1979). A new engineering-geological rock durability classification. *Engineering Geology*, *14*(4), 255–279. https://doi.org/https://doi.org/10.1016/0013-7952(79)90067-X
Omori, M. & Iwao, K. (2014). Methods of farming sexually propagated corals and outplanting for coral reef rehabilitation; with list of references for coral reef rehabilitation through active restoration measure. *Akajima Marine Science Laboratory, Okinawa, Japan*, 1–63.
Oren, U. & Benayahu, Y. (1997). Transplantation of juvenile corals: A new approach for enhancing colonization of artificial reefs. *Marine Biology*, *127*(3), 499–505.
Palmen, E. (1948). On the formation and structure of tropical hurricanes. *Geophysica*, *3*(1), 26–38.
Pandolfi, J. M., Bradbury, R. H., Sala, E., Hughes, T. P., Bjorndal, K. A., Cooke, R. G., McArdle, D., McClenachan, L., Newman, M. J., Paredes, G. et al. (2003). Global trajectories of the long-term decline of coral reef ecosystems. *Science*, *301*(5635), 955–958.
Panini, D., Hoon, V. et al. (1997). Law and policy for conservation and management of coral reef areas in india. *Regional Workshop on the Conservation and Sustainable Management of Coral Reefs*, 91.
Pearse, V. B. & Muscatine, L. (1971). Role of symbiotic algae (zooxanthellae) in coral calcification. *The Biological Bulletin*, *141*(2), 350–363.
Pelejero, C., Calvo, E., McCulloch, M. T., Marshall, J. F., Gagan, M. K., Lough, J. M. & Opdyke, B. N. (2005). Preindustrial to modern interdecadal variability in coral reef ph. *Science*, *309*(5744), 2204–2207.
Pendleton, L. H. (1994). Environmental quality and recreation demand in a caribbean coral reef. *Coastal Management*, *22*(4), 399–404.
Pereira, P. H. C., Macedo, C. H., Nunes, J. d. A. C., Marangoni, L. F. d. B. & Bianchini, A. (2018). Effects of depth on reef fish communities: Insights of a “deep refuge hypothesis” from southwestern atlantic reefs. *PLoS One*, *13*(9), e0203072.
Perkol-Finkel, S. & Benayahu, Y. (2005). Recruitment of benthic organisms onto a planned artificial reef: Shifts in community structure one decade post-deployment. *Marine Environmental Research*, *59*(2), 79–99.
Pickering, H. & Whitmarsh, D. (1997). Artificial reefs and fisheries exploitation: A review of the ‘attraction versus production’debate, the influence of design and its significance for policy. *Fisheries research*, *31*(1-2), 39–59.
Pickett, S. T., Parker, V. T. & Fiedler, P. L. (1992). The new paradigm in ecology: Implications for conservation biology above the species level. *Conservation biology* (pp. 65–88). Springer.
Pilarczyk, K., Van Overeem, J. & Bakker, W. (1986). Design of beach nourishment scheme. *Coastal Engineering Proceedings*, (20), 107–107.

Pioch, S., Pinault, M., Brathwaite, A., Méchin, A. & Pascal, N. (2017). Methodology for scaling mitigation and compensatory measures in tropical marine ecosystems: Merci-cor. *IFRECOR Handbook*, *78*.

Piontek, S. (2016). Final report st eustatius 2016 global coral reef monitoring network. *Dutch Caribbean Biodiversity Database. pp*, *15*.

Poloczanska, E. S., Brown, C. J., Sydeman, W. J., Kiessling, W., Schoeman, D. S., Moore, P. J., Brander, K., Bruno, J. F., Buckley, L. B., Burrows, M. T. et al. (2013). Global imprint of climate change on marine life. *Nature Climate Change*, *3*(10), 919–925.

Porter, J. W. & Meier, O. W. (1992). Quantification of loss and change in floridian reef coral populations. *American Zoologist*, *32*(6), 625–640.

Poulos, H. G. & Davis, E. H. (1980). *Pile foundation analysis and design*.

Powers, S. P., Grabowski, J. H., Peterson, C. H. & Lindberg, W. J. (2003). Estimating enhancement of fish production by offshore artificial reefs: Uncertainty exhibited by divergent scenarios. *Marine Ecology Progress Series*, *264*, 265–277.

Pradhan, D., Mahobia, G. S., Chattopadhyay, K. & Singh, V. (2018). Effect of surface roughness on corrosion behavior of the superalloy in718 in simulated marine environment. *Journal of Alloys and Compounds*, *740*, 250–263. https://doi.org/https://doi.org/10.1016/j.jallcom.2018.01.042

Proppe, D. S. (2013). *Association of the threespot damelsfish (stegastes planifrons) in ridge mortality of diploria strigosa in the flower garden banks of the national marine sanctuary* (Doctoral dissertation). Texas AM University.

Pupier, C. A., Grover, R., Fine, M., Rottier, C., van de Water, J. A. & Ferrier-Pagès, C. (2021). Dissolved nitrogen acquisition in the symbioses of soft and hard corals with symbiodiniaceae: A key to understanding their different nutritional strategies? *Frontiers in microbiology*, *12*.

Purnell, P. (2013). The carbon footprint of reinforced concrete. *Advances in cement research*, *25*(6), 362–368.

Rahn, J. L. (2017). Saba and st. eustatius (statia). *Landscapes and landforms of the lesser antilles* (pp. 61–84). Springer.

Rai, B., Rushad, S. T., Kr, B. & Duggal, S. (2012). Study of waste plastic mix concrete with plasticizer. *International Scholarly Research Notices*, *2012*.

Rajasuriya, A., De Silva, M. R. N., Öhman, M. C. et al. (1995). Coral reefs of sri lanka: Human disturbance and management issues. *Ambio*, *24*(7/8), 428–437.

Randall, J. E. et al. (1967). *Food habits of reef fishes of the west indies* (Vol. 5). Institute of Marine Sciences, University of Miami Coral Gables.

Randall, J. E. (1974). *The effect of fishes on coral reefs* (tech. rep.).

Reboul, M. & Baroux, B. (2011). Metallurgical aspects of corrosion resistance of aluminium alloys. *Materials and Corrosion*, *62*(3), 215–233.

Reef resillience network. (2021). *Managing recreational use*. Retrieved June 21, 2021, from https://reefresilience.org/management-strategies/managing-local-stressors/managing-recreational-use/

Reguero, B. G., Beck, M. W., Agostini, V. N., Kramer, P. & Hancock, B. (2018). Coral reefs for coastal protection: A new methodological approach and engineering case study in grenada. *Journal of environmental management*, *210*, 146–161.

Reid, W. V., Mooney, H. A., Cropper, A., Capistrano, D., Carpenter, S. R., Chopra, K., Dasgupta, P., Dietz, T., Duraiappah, A. K., Hassan, R. et al. (2005). *Ecosystems and human well-being-synthesis: A report of the millennium ecosystem assessment*. Island Press.

Research, C. I., Association, I., en Regelgeving (Netherlands), C. C. U. R. & d'études maritimes et fluviales, C. (2007). *The rock manual: The use of rock in hydraulic engineering* (Vol. 683). Ciria.

Ricardo, G. F., Jones, R., Clode, P. L., Humanes, A. & Negri, A. P. (2015). Suspended sediments limit coral sperm availability. *Scientific Reports*, *5*(1), 1–12.

Ricardo, G. F., Jones, R., Negri, A. P. & Stocker, R. (2016). That sinking feeling: Suspended sediments can prevent the ascent of coral egg bundles. *Scientific reports*, *6*(1), 1–7.

Richmond, R. H. (1993). Coral reefs: Present problems and future concerns resulting from anthropogenic disturbance. *American Zoologist*, *33*(6), 524–536.

Riegl, B., Bruckner, A., Coles, S. L., Renaud, P. & Dodge, R. E. (2009). Coral reefs: Threats and conservation in an era of global change. *Annals of the New York Academy of Sciences*, *1162*(1), 136–186.

Ring, I., Hansjürgens, B., Elmqvist, T., Wittmer, H. & Sukhdev, P. (2010). Challenges in framing the economics of ecosystems and biodiversity: The teeb initiative. *Current Opinion in Environmental Sustainability*, *2*(1-2), 15–26.

Rinkevich, B. (1995). Restoration strategies for coral reefs damaged by recreational activities: The use of sexual and asexual recruits. *Restoration Ecology*, *3*(4), 241–251.

Rinkevich, B. (2005). Conservation of coral reefs through active restoration measures: Recent approaches and last decade progress. *Environmental Science & Technology*, *39*(12), 4333–4342.

Rinkevich, B. (2006). The coral gardening concept and the use of underwater nurseries: Lessons learned from silvics and silviculture. *Coral reef restoration handbook*, 291–302.

Rinkevich, B. (2014). Rebuilding coral reefs: Does active reef restoration lead to sustainable reefs? *Current Opinion in Environmental Sustainability*, *7*, 28–36.

Rinkevich, B. & Shafir, S. (2000). Ex situ culture of colonial marine ornamental invertebrates: Concepts for domestication. *Aquarium Sciences and Conservation*, *2*(4), 237–250.

Rioja-Nieto, R. & Álvarez-Filip, L. (2019). Coral reef systems of the mexican caribbean: Status, recent trends and conservation. *Marine pollution bulletin*, *140*, 616–625.

Risk, M. J. (1981). Artificial reefs in discovery bay, jamaica. *Atoll Research Bulletin*.

Ritchie, H. & Roser, M. (2021). Coral reefs. *Our World in Data*.

Ritson-Williams, R., Arnold, S. N., Fogarty, N. D., Steneck, R. S., Vermeij, M. & Paul, V. J. (2009). New perspectives on ecological mechanisms affecting coral recruitment on reefs. *Smithsonian Contributions to the Marine Sciences*, *38*, 437.

Roberts, C. M. (1997). Connectivity and management of caribbean coral reefs. *Science*, *278*(5342), 1454–1457.

Roberts, C. M. & Ormond, R. F. (1987). Habitat complexity and coral reef fish diversity and abundance on red sea fringing reefs. *Marine Ecology Progress Series*, 1–8.

Rocha, L. & Rosa, I. (2001). Baseline assessment of reef fish assemblages of parcel manuel luiz marine state park, maranhão, north-east brazil. *Journal of Fish Biology*, *58*(4), 985–998.

Rogers, C. S. (1979). The effect of shading on coral reef structure and function. *Journal of Experimental Marine Biology and Ecology*, *41*(3), 269–288.

Rogers, C. S. (1983). Sublethal and lethal effects of sediments applied to common caribbean reef corals in the field. *Marine Pollution Bulletin*, *14*(10), 378–382.

Rogers, C. S. (1990). Responses of coral reefs and reef organisms to sedimentation. *Marine ecology progress series. Oldendorf*, *62*(1), 185–202.

Rogers, C. S. (1993). Hurricanes and coral reefs: The intermediate disturbance hypothesis revisited. *Coral Reefs*, *12*, 127–137.

Rogers, C. S., McLain, L. N. & Tobias, C. R. (1991). Effects of hurricane hugo(1989) on a coral reef in st. john, usvi. *Marine ecology progress series. Oldendorf*, *78*(2), 189–199.

Rogers, J. S., Monismith, S. G., Koweek, D. A., Torres, W. I. & Dunbar, R. B. (2016). Thermodynamics and hydrodynamics in an atoll reef system and their influence on coral cover. *Limnology and oceanography*, *61*(6), 2191–2206.

Rotjan, R. D. & Lewis, S. M. (2008). Impact of coral predators on tropical reefs. *Marine ecology progress series*, *367*, 73–91.

RRAP. (n.d.). *Reef structures and interventions*. https://gbrrestoration.org/interventions/

Samoilys, M., Maina, G. W. & Osuka, K. (2011). Artisanal fishing gears of the kenyan coast. *Mombasa CORDIO/USAID. 36pp*.

Sano, M., Shimizu, M. & Nose, Y. (1984). Changes in structure of coral reef fish communities by destruction of hermatypic corals: Observational and experimental views.

Sato, M. (1985). Mortality and growth of juvenile coral pocillopora damicornis (linnaeus). *Coral Reefs*, *4*(1), 27–33.

Scarcella, G., Grati, F., Bolognini, L., Domenichetti, F., Malaspina, S., Manoukian, S., Polidori, P., Spagnolo, A. & Fabi, G. (2015). Time-series analyses of fish abundance from an artificial reef and a reference area in the central-adriatic sea. *Journal of Applied Ichthyology*, *31*, 74–85.

Schoonees, T., Mancheño, A. G., Scheres, B., Bouma, T., Silva, R., Schlurmann, T. & Schüttrumpf, H. (2019). Hard structures for coastal protection, towards greener designs. *Estuaries and Coasts*, *42*(7), 1709–1729.

Schutter, M., Crocker, J., Paijmans, A., Janse, M., Osinga, R., Verreth, A. & Wijffels, R. H. (2010). The effect of different flow regimes on the growth and metabolic rates of the scleractinian coral galaxea fascicularis. *Coral Reefs*, *29*(3), 737–748.

Selig, E. R. & Bruno, J. F. (2010). A global analysis of the effectiveness of marine protected areas in preventing coral loss. *PLos one*, *5*(2), e9278.

Sen, G. (2001). *Earth's materials: Minerals and rocks*. Prentice Hall.

SER. (2002). The ser primer on ecological restoration.

Shadwell, L. H. A. (1930). Damage to and repair of the breakwater, table bay harbour, 1928. *Selected Engineering Papers*, *1*(102).

Shafir, S. & Rinkevich, B. (2008). The underwater silviculture approach for reef restoration: An emergent aquaculture theme. *Aquaculture research trends*, 279–295.

Shaish, L., Levy, G., Gomez, E. & Rinkevich, B. (2008). Fixed and suspended coral nurseries in the philippines: Establishing the first step in the “gardening concept” of reef restoration. *Journal of Experimental Marine Biology and Ecology*, *358*(1), 86–97.

Sharma, D. & Ravindran, C. (2020). Diseases and pathogens of marine invertebrate corals in indian reefs. *Journal of Invertebrate Pathology*, *173*, 107373. https://doi.org/https://doi.org/10.1016/j.jip.2020.107373

Sherman, R. L., Gilliam, D. S. & Spieler, R. E. (2002). Artificial reef design: Void space, complexity, and attractants. *ICES Journal of Marine Science*, *59*(suppl), S196–S200.

Shulman, M. J. (1984). Resource limitation and recruitment patterns in a coral reef fish assemblage. *Journal of experimental marine biology and ecology*, *74*(1), 85–109.

Shulman, M. J. (1985). Recruitment of coral reef fishes: Effects of distribution of predators and shelter. *Ecology*, *66*(3), 1056–1066.

Silva, R., Mendoza, E., Mariño-Tapia, I., Martínez, M. L. & Escalante, E. (2016). An artificial reef improves coastal protection and provides a base for coral recovery. *Journal of Coastal Research*, (75 (10075)), 467–471.

Skidmore, A. K., Pettorelli, N., Coops, N. C., Geller, G. N., Hansen, M., Lucas, R., Mücher, C. A., O'Connor, B., Paganini, M., Pereira, H. M. et al. (2015). Environmental science: Agree on biodiversity metrics to track from space. *Nature News*, *523*(7561), 403.

Slijkerman, D., van Maren, B., Debrot, D., Stapel, J., Meesters, E., Davaasuren, N. & van Dalfsen, J. (2011). *Quick scan environmental impact assessment of the st. eustatia harbour extension* (tech. rep.). IMARES.

Smith, A., Foster, T., Corcoran, E. & Monkivitch, J. (2007). Dredging and material relocation in sensitive coral environments. *proceedings 18th world dredging congress (WODCON XVIII)*, 945–955.

Smith, G. B., Hensley, D. A. & Mathews, H. H. (1979). Comparative efficacy of artificial and natural gulf of mexico reefs as fish attractants.

Smith, J. E., Shaw, M., Edwards, R. A., Obura, D., Pantos, O., Sala, E., Sandin, S. A., Smriga, S., Hatay, M. & Rohwer, F. L. (2006). Indirect effects of algae on coral: Algae-mediated, microbe-induced coral mortality. *Ecology letters*, *9*(7), 835–845.

Smith, S., Mücher, C., Debrot, A. O., Roupioz, L., Meesters, H. W. G., Hazeu, G. & Davaasuren, N. (2013). *Use of satellite data for the monitoring of species on saba and st. eustatius* (tech. rep.). IMARES.

Smith, S. H. (1988). Cruise ships: A serious threat to coral reefs and associated organisms. *Ocean and Shoreline Management*, *11*(3), 231–248.

Smithers, S. (2011). Fringing reefs. In D. Hopley (Ed.), *Encyclopedia of modern coral reefs: Structure, form and process* (pp. 430–446). Springer Netherlands. https://doi.org/10.1007/978-90-481-2639-2_15

Song, H.-W. & Saraswathy, V. (2007). Corrosion monitoring of reinforced concrete structures-a. *Int. J. Electrochem. Sci*, *2*(1), 1–28.

Soong, K. & Chen, T.-a. (2003). Coral transplantation: Regeneration and growth of acropora fragments in a nursery. *Restoration Ecology*, *11*(1), 62–71.

Sorokin, Y. I. (2013). *Coral reef ecology* (Vol. 102). Springer Science & Business Media.

Soto-Santiago, F. j., Mercado-Molina, A. E., Reyes-Maldonado, K. & Sabat, A. M. (2017). Physiological response to thermal stress of the caribbean corals orbicella annularis and porites astreoides. *Research Journal of Environmental Sciences*, *11*.

Souter, D. W. & Linden, O. (2000). The health and future of coral reef systems. *Ocean & Coastal Management*, *43*(8-9), 657–688.

Spalding, M. & Grenfell, A. (1997). New estimates of global and regional coral reef areas. *Coral reefs*, *16*(4), 225–230.

Spalding, M., Ravilious, C. & Green, E. (2001). *World atlas of coral reefs* (1st ed.). University of California Press.

Spalding, M., Ruffo, S., Lacambra, C., Meliane, I., Hale, L. Z., Shepard, C. C. & Beck, M. W. (2014). The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean & Coastal Management*, *90*, 50–57.

Spieler, R. E., Gilliam, D. S. & Sherman, R. L. (2001). Artificial substrate and coral reef restoration: What do we need to know to know what we need. *Bulletin of Marine Science*, *69*(2), 1013–1030.

Spurgeon, J. P. (1992). The economic valuation of coral reefs. *Marine pollution bulletin*, *24*(11), 529–536.

Srinivasan Chandrasekaran, A. K. J. (2016). Materials for ocean structures. *Ocean structures*. CRC Press. https://doi.org/10.1201/9781315366692-4

Stark, D. (1995). *Long-time performance of concrete in a seawater exposure* (tech. rep.).

Stimson, J. (1990). Stimulation of fat-body production in the polyps of the coral pocillopora damicornis by the presence of mutualistic crabs of the genus trapezia. *Marine Biology*, *106*(2), 211–218.

Subcommittees, A. R., Lukens, R. R. & Selberg, C. (2004). Guidelines for marine artificial reef materials. *Atlantic and Gulf States Marine Fisheries Commissions*, 1–4.

Sukhodolov, A., Uijttewaal, W. S. & Engelhardt, C. (2002). On the correspondence between morphological and hydrodynamical patterns of groyne fields. *Earth Surface Processes and Landforms*, *27*(3), 289–305.

Supriharyono, S. (2004). Effects of sand mining on coral reefs in riau islands. *Journal of Coastal Development*, *7*(2), 89–100.

SURASWADI, P. & YEEMIN, T. (2013). Coral reef restoration plan of thailand. *Galaxea, Journal of Coral Reef Studies*, *15*(Supplement), 428–433.

Syms, C. & Jones, G. P. (2000). Disturbance, habitat structure, and the dynamics of a coral-reef fish community. *Ecology*, *81*(10), 2714–2729.

Szmant, A. M. (2002). Nutrient enrichment on coral reefs: Is it a major cause of coral reef decline? *Estuaries*, *25*(4), 743–766.

Talbot, F. & Wilkinson, C. (2001). *Coral reefs, mangroves and seagrasses: A sourcebook for managers*. Australian Institute of Marine Science,

Talo, A., Passiniemi, P., Forsen, O. & Yläsaari, S. (1997). Polyaniline/epoxy coatings with good anticorrosion properties. *Synthetic Metals*, *85*(1-3), 1333–1334.

Teichert, C. (1958). Cold-and deep-water coral banks. *AAPG Bulletin*, *42*(5), 1064–1082.

Telesnicki, G. J. & Goldberg, W. M. (1995). Effects of turbidiy on the photosynthesis and respiration of two south florida reef coral species. *Bulletin of Marine Science*, *57*(2), 527–539.

Tibbetts, J. (2004). The state of the oceans, part 1: Eating away at a global food source. *Environmental Health Perspectives*, *112*(5), A282–A291.

Tieskens, K., Schep, S., Van Beukering, P., Van Beek, I. & Wolfs, E. (2014). Mapping the economic value of ecosystems on st eustatius. *IVM Institute for Environmental Studies*.

Tillinghast, W., Shah, B. & Sturdevant, L. (1987). Laying flexible pipelines over coral reefs in the geisum field, gulf of suez, egypt. *Offshore Technology Conference*.

Tomascik, T. (1991). Settlement patterns of caribbean scleractinian corals on artificial substrata along a eutrophication gradient, barbados, west indies. *Marine ecology progress series. Oldendorf*, *77*(2), 261–269.

Tseng, C.-T., Chen, S.-C., Huang, C.-S. & Liu, C.-C. (2001). Gis-assisted site selection for artificial reefs. *Fisheries Science*, *67*(6), 1015–1022.

Tsinker, G. P. (2004). *Port engineering: Planning, construction, maintenance, and security*. John Wiley & Sons.

Tuinhof, T. (2014). *Modelling far-field dredge plume dispersion*, TU Delft. unpublished thesis.

Tunnicliffe, V. (1982). The effects of wave-induced flow on a reef coral. *Journal of Experimental Marine Biology and Ecology*, *64*(1), 1–10. https://doi.org/https://doi.org/10.1016/0022-0981(82)90064-8

Turner, C. H., Ebert, E. E. & Given, R. R. (1969). *Man-made reef ecology* (Vol. 146). State of California, Department of Fish; Game.

Turner, R. K., Burgess, D., Hadley, D., Coombes, E. & Jackson, N. (2007). A cost–benefit appraisal of coastal managed realignment policy. *Global Environmental Change*, *17*(3-4), 397–407.

Uijttewaal, W. S. (2005). Effects of groyne layout on the flow in groyne fields: Laboratory experiments. *Journal of Hydraulic Engineering*, *131*(9), 782–791.

USACE, C. (2002). Coastal engineering manual. *Engineer Manual*, 1110–2.

Ushiama, S., Smith, J. A., Suthers, I. M., Lowry, M. & Johnston, E. L. (2016). The effects of substratum material and surface orientation on the developing epibenthic community on a designed artificial reef. *Biofouling*, *32*(9), 1049–1060.

Valadez-Rocha, V. & Ortiz-Lozano, L. (2013). Spatial and temporal effects of port facilities expansion on the surface area of shallow coral reefs. *Environmental management*, *52*(1), 250–260.

Van de Kerkhof, S., Schep, S., van Beukering, P., Brander, L. & Wolfs, E. (2014). The tourism value of nature on st eustatius. *IVM Institute for Environmental Studies. Report R14-07*.

Van Der Burgt, C. (1994). Permanent international association of navigation congresses (pianc). *Marine pollution bulletin*, *29*(6-12), 398–400.

Van der Meer, J. W. (1995). Conceptual design of rubble mound breakwaters. *Advances in coastal and ocean engineering: (volume 1)* (pp. 221–315). World Scientific.

Van der Weide, J. et al. (1993). A systems view of integrated coastal management.

van der Leer, N., Bodde, W., Marquering, L., Peters, R., de Wit, L. & Ridderinkhof, W. (2018). *Port development st. eustatius harbour* (tech. rep.). Witteveen+Bos.

van Andel, T., van der Hoorn, B., Stech, M., Arostegui, S. B. & Miller, J. (2016). A quantitative assessment of the vegetation types on the island of st. eustatius, dutch caribbean. *Global Ecology and Conservation*, *7*, 59–69.

van Koningsveld, M., ter Hofstede, R., Elzinga, J., Smolders, T., Schutter, M. & Osinga, R. (2017). Reefguard: A scientific approach to active reef rehabilitation. *Terra et Aqua*, *147*, 5–16.

Venera-Ponton, D., Diaz-Pulido, G., McCook, L. & Rangel-Campo, A. (2011). Macroalgae reduce growth of juvenile corals but protect them from parrotfish damage. *Marine Ecology Progress Series*, *421*, 109–115.

Verhagen, H. J. (1992). Method for artificial beach nourishment.

Verhagen, H. & van den Bos, J. (2017). Breakwater design. *Collegedictaat CIE5308 (draft edition)*.

Vermeij, M. (2006). Early life-history dynamics of caribbean coral species on artificial substratum: The importance of competition, growth and variation in life-history strategy. *Coral Reefs*, *25*(1), 59–71.

Vermeij, M. (2017). The consequences of construction activities associated with the building of the second megapier on the coral reefs near the holiday beach hotel, curacao.

Vermeij, M., Marhaver, K. L., Huijbers, C. M., Nagelkerken, I. & Simpson, S. D. (2010). Coral larvae move toward reef sounds. *PloS one*, *5*(5), e10660.

Veron, J., Stafford-Smith, M., Turak, E. & DeVantier, L. (2016). *Corals of the world*. http://www.coralsoftheworld.org/page/home/

Viehman, T. S., Hench, J. L., Griffin, S. P., Malhotra, A., Egan, K. & Halpin, P. N. (2018). Understanding differential patterns in coral reef recovery: Chronic hydrodynamic disturbance as a limiting mechanism for coral colonization. *Marine Ecology Progress Series*, *605*, 135–150.

Vriend, H. D. & Koningsveld, M. V. (2012). Building with nature: Thinking, acting and interacting differently.

Wagner, L., Ross, J. & Possingham, H. (2007). Catastrophe management and inter-reserve distance for marine reserve networks. *Ecological Modelling*, *201*(1), 82–88.

Wallace, C. (1985). Seasonal peaks and annual fluctuations in recruitment of juvenile scleractinian corals. *Marine Ecology Progress Series*, 289–298.

Wallace, K. J. (2007). Classification of ecosystem services: Problems and solutions. *Biological conservation*, *139*(3-4), 235–246.

Wang, C. & Wang, B. (2015). Large floating structures. *Ocean Engineering & Oceanography*, *3*.

Wang, X., Yu, R., Shui, Z., Song, Q. & Zhang, Z. (2017). Mix design and characteristics evaluation of an eco-friendly ultra-high performance concrete incorporating recycled coral based materials. *Journal of Cleaner Production*, *165*, 70–80.

Wasmus, H., Zitman, T. & Lanzafame, R. (n.d.). *Guidelines msc thesis project hydraulic engineering cie5060-09*. TU Delft.

Wedemeyer, G., McLeay, D. & Goodyear, C. (1984). Assessing the tolerance of fish and fish populations to environmental stress: The problems and methods of monitoring.

Weeks, R., Aliño, P. M., Atkinson, S., Beldia, P., Binson, A., Campos, W. L., Djohani, R., Green, A. L., Hamilton, R., Horigue, V. et al. (2014). Developing marine protected area networks in the coral triangle: Good practices for expanding the coral triangle marine protected area system. *Coastal Management*, *42*(2), 183–205.

Weinberg, S. et al. (1981). A comparison of coral reef survey methods. *Bijdragen tot de Dierkunde*, *51*(2), 199–218.

Wen, K.-C., Hsu, C.-M., Chen, K.-S., Liao, M.-H., Chen, C.-P. & Chen, C. A. (2007). Unexpected coral diversity on the breakwaters: Potential refuges for depleting coral reefs. *Coral Reefs*, *26*(1), 127–127.

West, J. M. & Salm, R. V. (2003). Resistance and resilience to coral bleaching: Implications for coral reef conservation and management. *Conservation Biology*, *17*(4), 956–967.

Widén, J., Carpman, N., Castellucci, V., Lingfors, D., Olauson, J., Remouit, F., Bergkvist, M., Grabbe, M. & Waters, R. (2015). Variability assessment and forecasting of renewables: A review for solar, wind, wave and tidal resources. *Renewable and Sustainable Energy Reviews*, *44*, 356–375.

Wielgus, J., Chadwick-Furman, N. E., Zeitouni, N. & Shechter, M. (2003). Effects of coral reef attribute damage on recreational welfare. *Marine Resource Economics*, *18*(3), 225–237.

Wilkinson, C. (2000). *Status of coral reefs of the world: 2000*. Australian Institute of Marine Science.

Wilkinson, C., Green, A., Almany, J. & Dionne, S. (2003). Monitoring coral reef marine protected areas: A practical guide on how monitoring can support effective management of mpas.

Wilkinson, C. & Souter, D. (2008). Status of caribbean coral reefs after bleaching and hurricanes in 2005.

Winkel, s. (2021). *Breakwater types*. https://breakwater.readthedocs.io/en/latest/types.html

Wong, L., Tan, H., Wang, C., Lim, H., Ho, H., Wang, C., Tay, Z. & Gao, R. (2013). Floating wetlands at punggol. *The IES Journal Part A: Civil & Structural Engineering*, *6*(4), 249–257.

Woodroffe, C. D. & Biribo, N. (2011). Atolls. In D. Hopley (Ed.), *Encyclopedia of modern coral reefs: Structure, form and process* (pp. 51–71). Springer Netherlands. https://doi.org/10.1007/978-90-481-2639-2_4

Wooldridge, S. A. (2009). Water quality and coral bleaching thresholds: Formalising the linkage for the inshore reefs of the great barrier reef, australia. *Marine Pollution Bulletin*, *58*(5), 745–751.

Wooldridge, S. A. & Done, T. J. (2009). Improved water quality can ameliorate effects of climate change on corals. *Ecological Applications*, *19*(6), 1492–1499.

Xu, Q., Ji, T., Yang, Z. & Ye, Y. (2019). Preliminary investigation of artificial reef concrete with sulphoaluminate cement, marine sand and sea water. *Construction and Building Materials*, *211*, 837–846.

Yadav, S., Rathod, P., Alcoverro, T. & Arthur, R. (2016). "choice" and destiny: The substrate composition and mechanical stability of settlement structures can mediate coral recruit fate in post-bleached reefs. *Coral reefs*, *35*(1), 211–222.

Yanovski, R. & Abelson, A. (2019). Structural complexity enhancement as a potential coral-reef restoration tool. *Ecological Engineering*, *132*, 87–93.

Zhang, L., Niu, D., Wen, B., Peng, G. & Sun, Z. (2020). Corrosion behavior of low alloy steel bars containing cr and al in coral concrete for ocean construction. *Construction and Building Materials*, *258*, 119564.

A

Systematic method

In this chapter the main systematic method and the natural method are displayed in larger size, to make the methods better visible. The main systematic method included the systematic steps. The natural system

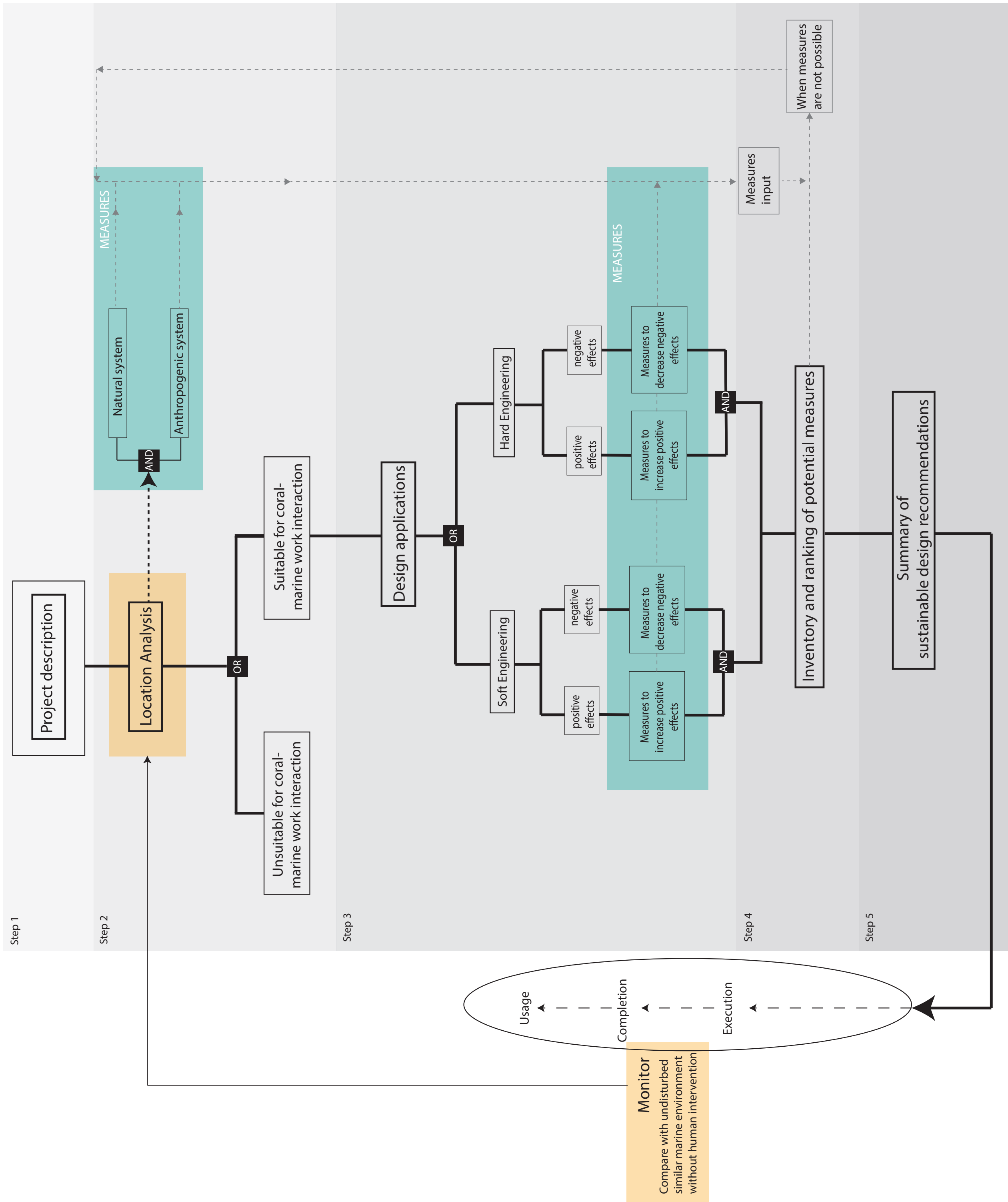


Figure A.1: Main systematic method

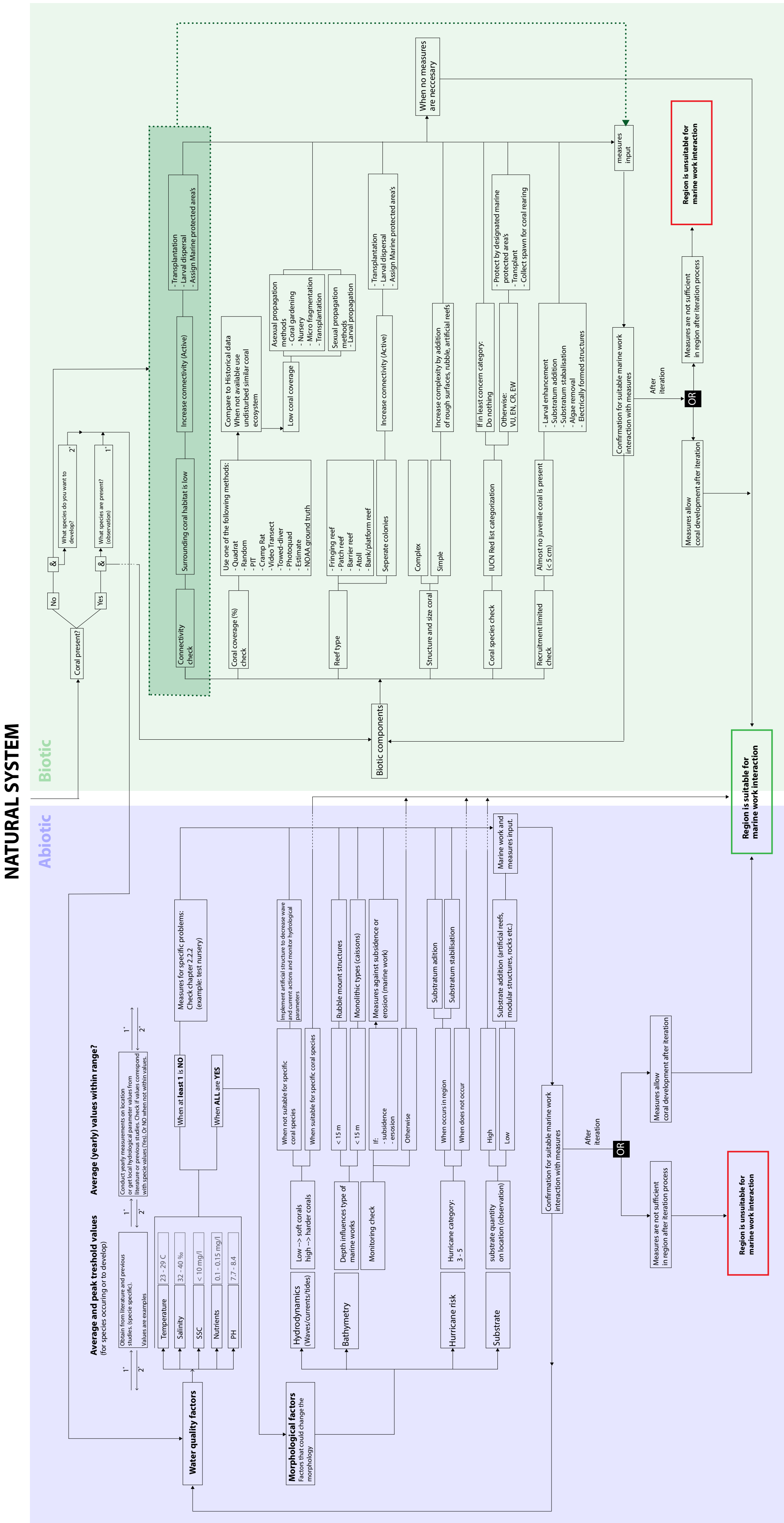


Figure A.2: Natural method

B

Approach for soft engineering infrastructure to use in the systematic method (elaboration of Chapter 4)

B.1. Elements of marine infrastructure

B.1.1. Soft Engineering

The elements that have repercussions on coral reefs are discussed here. To know the consequence of marine projects, first the elements from Table 2.1 need to be assessed that could possibly have an effect on coral habitat. This is done by checking the order size of the possible impact.

- **Suspended sediment plume**

  The suspended sediment plume is a cloud of small particles resulting from dredging works or other sediment disturbances (Laboyrie et al., 2018). Two factors arise from dredging plumes: turbidity and sedimentation. This is further elaborated in Appendix Section C.2. Turbidity is the amount of Suspended Sediment Concentration (SSC's) in the water column. High turbidity values can be observed by a vast amount of sediments in the water, resulting in opaque cloudy waters.
  Sedimentation is the formation of a deposition layer on the bottom surface. The settling velocity is in proportionate relationship with the particle size (Kynch, 1952). For more information, see Section C.2.

- **Placement/mining area**

  The soft Engineering footprint is indicated by affected nourished or deepened areas. The area before starting a dredging activity (greenfield), will be subjected to filling on top or extraction of existing soil or dredging material. The dredging unit price is generally lower for larger scale dredging projects, since with the same equipment more material is dredged. Furthermore, the lifetime of the nourished area tends to be longer. However, this depends on local conditions. An over-nourished profile is reached when the total volume is larger than needed for a specific site. The profile that is created then becomes steeper than necessary and disproportionate erosion will take place (Pilarczyk et al., 1986).
  The footprint is influenced by the volume of dredging material that is needed to fill or be extracted. Furthermore, this volume is dependent on the nourished sediment sizes. Smaller grain sizes than native sand, can lead to a bigger net loss of sediment due to erosion. Larger grain sizes than native sand can lead to steep profiles or sediment flux disturbances (H. J. Verhagen, 1992; Pilarczyk et al., 1986). Moreover, the depth is an important characteristic to determine the actual sediment volume that is needed. To overcome larger depths, flatter slopes are needed. The exact slope depends however on the grain size. (Pilarczyk et al., 1986; H. J. Verhagen, 1992)

- **Morphological changes**

  Change in morphology is another element that influences its environment. If sediment is nourished or extracted, the bottom profile (morphology) tends to change. Changes in profile are site and project specific but could result in different circumstances. As an example: an increase in sediment transportation (positive gradient) could be the result of nourishments. This leads to more sediment transport in the area. Which could affect the coastal region by creating shallower and more turbid coastal waters (Dean, 2002). Coastal morphodynamics is the altering of morphology and hydrodynamics, where sediment transport is involved (Bosboom & Stive, 2012). The equilibrium state of coastal profiles, is temporarily disturbed by the implementation of soft engineering. A coastal system always tries to reach its equilibrium. Human interventions, such as beach nourishments will, over the long term, reach an equilibrium state. This means that the sediment transport and beach profile are not subjected to fluctuations and zero transport gradients are reached. The equilibrium state could be altered compared to the previous situation before the intervention. This can lead to a difference in depths, altered wave breaking, different current directions and velocities and altered sediment transportation. (Bosboom & Stive, 2012)

B.2. Potential effects of marine infrastructure on corals

B.2.1. Soft Engineering

Soil type (grain size)

Soil types occur in all ranges. From coarse sand to silt, clay and fine clay (see Table C.1). A soil type is characterised by its grain size. When sediment is needed for nourishment, it is ideal to use similar grain sizes as the original sediment (USACE, 2002). The imbalance and disturbances are by using native grain sizes, limited to a minimum. Therefore, the categorisation of coarse, medium and fine soil is made. The categorisation is based on a comparison with local sediment grain sizes. For example; when beach nourishment takes place with a D_{50} of 0.8 mm (Coarse sand) but sand originally occurs to have a D_{50} of 0.3 mm (Medium sand), this soil type is classified as 'Coarse' during this study.

The sensitivity to sedimentation and turbidity impacts is related to the duration of exposure and the intensity of the stressor (see Figure B.1). Furthermore, the frequency of exposure to high sediment rates is critical (Erftemeijer et al., 2012). Relatively coarse sand has some negative and positive effects. One of the negative effects is the large impact on extraction and the dumping area. Course soils for dredging, affect corals by destruction of coral structures due to the large weight (R. Jones et al., 2016). Light attenuation depends on particle size but also on concentration of particles, shape and refraction characteristics (R. Jones et al., 2016). Rough materials, tend to scatter light more and therefore cause higher turbidity values. Softer materials likely scatter less. The problem with dredging is that not all dredged particles are similar in shape (R. Jones et al., 2016). Coarser sediments, can cause more light attenuation (E. T. Baker and Lavelle, 1984; R. Jones et al., 2020) and are more likely to settle, as explained by Equation C.1. This means that especially the placement area is affected, instead of a large area as for fine materials. Sedimentation covers coral reef organisms and therefore attenuate photosynthesis by zooxanthellae (C. S. Rogers, 1990; R. Jones et al., 2016). species that are sensitive to sedimentation, can only undergo short term (days) hindrance from elevated sediment concentrations to 1000 mg/L (Erftemeijer et al., 2012). Species with higher tolerance could survive these sediment concentrations for weeks (Erftemeijer et al., 2012). Excessive sedimentation duration, will lead to coral mortality (see Figure B.1. Coral structures are affected and therefore also their functions as shelter for marine life and biological processes (C. S. Rogers, 1990). C. S. Rogers (1990) indicates that the maximum sedimentation rate for coral reefs with sufficient resistance is < 10 mg/l (C. S. Rogers, 1990; R. Jones et al., 2016; Kuyper, 1991; R. Jones et al., 2020). Large particle sizes, contribute to this process in a relatively small area, while finer particle sizes tend to mix and transform easier into passive plumes which will reach larger distances. Smothering effects on corals are species specific. Branching corals in general are better able to use their self-cleaning mechanism than other morphologies (Duckworth et al., 2017). In the same study it is concluded that during high sediment deposition rates, coarse silt was easier self-cleaned by corals than fine silt (Duckworth et al., 2017). For 'regular' sedimentation rates, polyps experience more problems cleaning larger sized grains. As expected, energy consumption is used for a self- cleaning mechanism, influencing coral growth (Bak and Elgershuizen, 1976; Hubbard and Pocock, 1972; Bak, 1978).

A probably negative effect of finer grain sizes, is that their mobility threshold is lower and therefore they are easier transferred. Heavy weather circumstances or human activities could relatively easy increase turbidity and sedimentation values which damage coral reefs. (Laboyrie et al., 2018; C. S. Rogers, 1990)

A positive effect of larger grain sizes is that passive plumes will, in general, occur less and only a relatively small area is probably affected (Laboyrie et al., 2018). Diatoms (a form of algae) attach to (fine) sediment. They have an important role in the food chain. This means that if suspended solids in the water column is comparable to the amount of SSC before the intervention, there is no disturbance. Periodic resuspension of increased levels of fine sediment following dredging is possible but this generally tends to fade away within a 14-day tidal cycle. Significant measurable effects and the overall increased presence of fine grain sizes (fines), could tend to fade away within several months to over a year, depending on local site specific conditions (R. Jones et al., 2016). These effects however, are minor, localised and not necessarily attributed to dredging. This means that over a longer period, natural balance could be restored and could remain a well-functioning system. The natural system could stay healthy if threshold values for coral are not exceeded. (Bak, 1978)

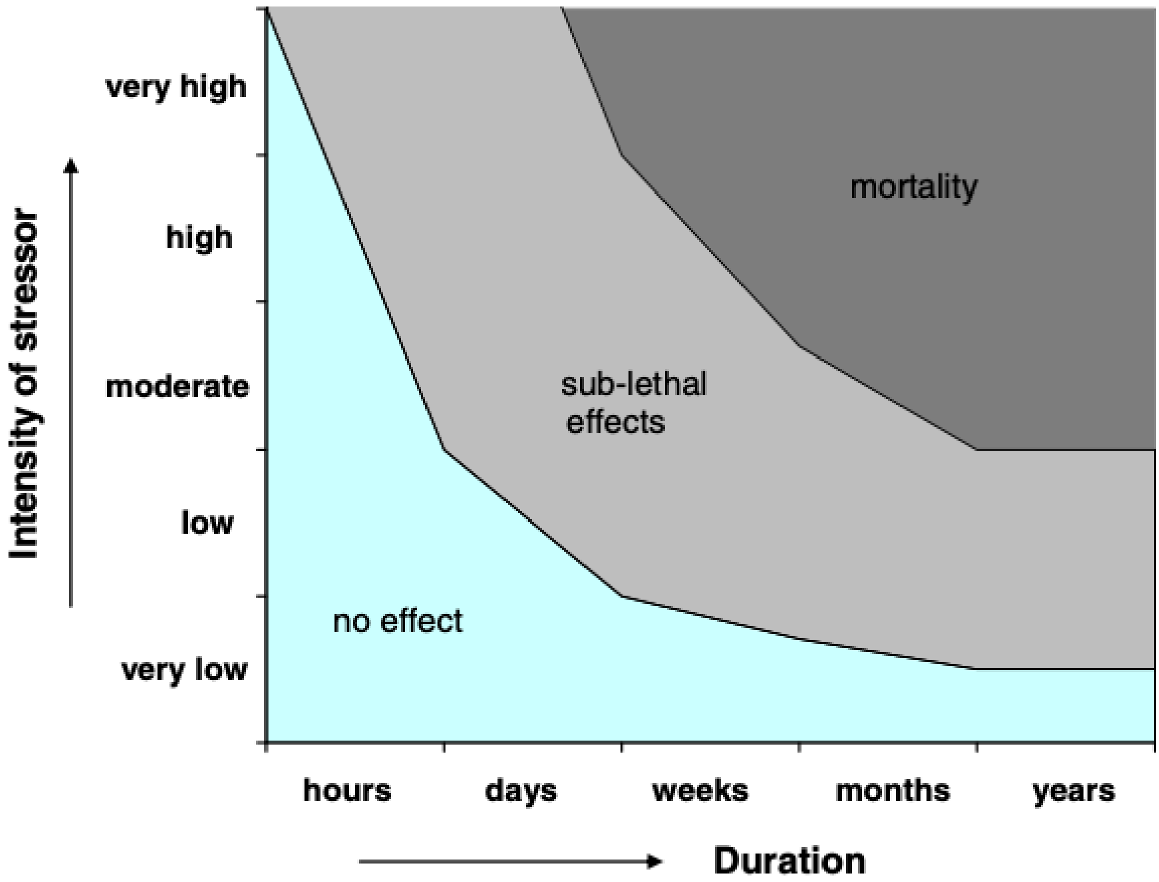


Figure B.1: Consequences of turbidity and sedimentation intensities and duration on corals (Erftemeijer et al., 2012).

Placement/mining area

In the Riau Islands in Indonesia, sand was dredged for a certain period. Pumping material did not only appear to be sand, corals were also pumped through by the dredging vessel (Supriharyono, 2004). This indicates that the mining area, intended for dredging purposes, should therefore be chosen at a distance far away, which will less likely affect corals (R. Jones et al., 2016). The larger the placement or excavation of sediment where coral is present, the larger the area of coral destruction will be. Effects of a small placement area, is that coral species will likely be destroyed or damaged but the impact overall will be generally lower than for larger placement areas. If coral is present at the placement area, coral will commonly be buried and will not likely survive this threat. The distance that plumes travel, can be mapped by modelling dredging plumes. A nourished beach, especially on places where originally no sand was present, will typically lead to less suitable substrate for larvae settlement and coral development (Erftemeijer et al., 2004).

Change in morphology
Morphological changes can be induced by dredging and reclamation works. These works can cause changes in bathymetry, which could affect residence times, water quality, larval dispersal, food availability etc. (Jacob & Stanev, 2021). Sediment transport is changed before returning to its equilibrium, which affects the bathymetry. This change has an effect on hydrodynamics. This includes the flow, tide, water levels etc. (P. Erftemeijer, personal communication, August 20, 2021; Oliveira et al., 2006). Sediments will less likely settle on steep slopes, this indicates that the highest coral diversity is often associated with steeper slopes (C. S. Rogers, 1990; Kuyper, 1991). This theory could lead to altered bathymetry by differences in sand accumulation and coral growth.

B.3. Potential measures for coral-inclusive marine infrastructure

B.3.1. Soft Engineering

Within soft engineering (dredging), management questions and monitoring techniques arise. A structured questionnaire should be executed. This is formulated according to A. Smith et al. (2007) and can be found in Figure D.8.

The following elements are discussed with appropriate measures:

- Soil type
- Placement/mining area
- Change in morphology

Soil type
To obtain an overview of the sediment dispersion and the range in sediment sizes and turbidity fluctuations, a field check on measured concentrations can be executed. This includes the variation of measured concentrations to realize a correlation graph of turbidity values in a region.

When mapping the project area, plume modelling and current patterns have to be taken into account. When the equilibrium is changed, this indicates negative effects as described in Section B.2.1. Dredging solutions during the execution of dredging works need to be executed but these are outside the scope of this research. Calculating dredging plumes and setting a strategy should be done according to the the book: Dredging for Sustainable Infrastructure (Laboyrie et al., 2018). Nevertheless, the dredging limitation values refer to the max SSC thresholds of coral species.

One of the measures that can be taken is the one for nourishment activities. The same material should be used as occurs in the area (USACE, 2002). This is done to minimise field disturbances. Preferably, the placement of sand, should be in areas where coral will not be or is not available. If this is not the case, try to minimise impact by transplanting threatened or low tolerant coral species. Another measure should be to minimise the passive sediment plume. It should be done by limiting fine sediment transport in the water column. This should be executed during dredging activities. Another mitigating measure when larger concentrations of fines are expected for the longer term, is to develop catchments in the form of sea grass beds. In Mauritius, hotels decided to remove sea grass areas to provide, according to their belief, ”aesthetically pleasant swimming zones” (Daby, 2003). These removal activities lead to areas with high turbidity and an unstable sediment seabed (Daby, 2003). Sea grass stabilizes the bottom of the sea (Fonseca, 1989), diminishes wave and current actions (Koch, 1996), reduce turbidity values (Bulthuis et al., 1984) and diminishes coastal erosion (Almany et al., 2009). Therefore, sea grass should not be removed for the benefit of aesthetics. Corals profit from nearby sea grass fields, due to minimizing fines in the water column which is beneficial for corals. Another measure is the implementation of artificial structures as groynes by perturbing natural ’sediment’ flow (Sukhodolov et al., 2002). This could help hampering sediment flow by altering current patterns. A thorough modelling approach of this area would be needed beforehand. It is crucial to monitor the area strictly to observe changes in biodiversity and SSC values and an option would be to collect spawn from colonies that proves to be resilient to high SSC values according to literature. Artificial structures could also provide substrate for recruitment (Section 4.3.1).

Placement/mining area

Measures can be executed when sand is deposited in a certain area or mined from an area. Coral occurring in this area needs to be relocated towards an area that will not be affected by the placement or mining of sediment. To execute this, coral species in this area need to be mapped first. Low resistant and endangered coral species that will be affected by the dredging works, need to be relocated towards areas that are not influenced. This 'receptor' site, should be studied carefully to check if any coral development disturbances are present. The guideline should be the natural system Section 3.2.

In general, different restoration methods are possible (Boström-Einarsson et al., 2020). For dredging processes and the involved coral area, direct transplantation is the commonly used method (Boström-Einarsson et al., 2020). This can be done with coral fragments or with entire coral colonies from the donor towards the 'new' reef. According to Bostrom, frequent cases used branching corals (Boström-Einarsson et al., 2020). For maximizing coral development, an intermediate nursery phase could be used, before planting in the recipient site. One of the advantages is that a nursery phase offers protective systems in which coral can develop. Ex-situ and In-situ coral nurseries are both effective. In situ coral nurseries should be installed in zones which are not affected by disturbances. Coral recruits are during an in-situ nursery phase, more adapted to environmental factors (Epstein et al., 2001; Rinkevich, 2006). For ex situ nurseries, genetic variability can be increased and environmental factors are controlled (Rinkevich, 1995; Boström-Einarsson et al., 2020). The coral recruits grow to an adequate size in which they are large enough to be relocated on the receptor site (Rinkevich, 2005). A study about the fragmentation of Acropora species, revealed that the sizes should be around four cm long for implementation in the coral nursery phase (Soong & Chen, 2003). After a generation of these coral species during the nursery phase, these 'old' fragments can be fragmented again to broaden coral development for extra coral colonies (Boström-Einarsson et al., 2020).

Change in morphology

As explained in Section B.2.1.3, changes in morphology are also prone to influencing hydrodynamics and other factors as water quality. If unfavourable circumstances arise, this could be solved by the implementation of artificial structures or alteration of sediment properties by changing balance of inflow/outflow sediment. It is important to check these altered circumstances per site and per coral species. Every coral species has its own circumstances which it favours.

Coral species occurring and surviving in a sediment rich area, have high tolerance for large sediment fluxes. If the natural situation and therefore its equilibrium is perturbed, local measures as artificial structures could be helpful to diminish sedimentation in coral areas. Frequently monitor the affected area and compare this location to another undisturbed location with similar functions. If positively affected, no further measures need to be taken. If negatively affected, coral species should be protected by transplanting.

C

In depth research

More in depth research of biotic components, suspended sediment plume and hard engineering categories is described in this chapter. This information is not directly needed to understand the systematic method. However, substantiation of elements, categories and components can be helpful to gain more knowledge and to support the main matter of this thesis.

C.1. In depth biotic components

- **Coral predator check**

  Coral predators, belonging to the secondary consumers, consume coral tissue and are called corallivores (Rotjan & Lewis, 2008). According to Rotjan and Lewis (2008), these predators consume and therefore damage corals differently. Some predators, called: browsers, only feed themselves with coral tissue (Hiatt & Strasburg, 1960). Another feeder only consumes mucus (Rotjan & Lewis, 2008). Coral mucus are glycoproteins with the characteristic to develop a gel that protects epithelium from pathogens and other disturbances and stresses (Brown and Bythell, 2005; Bythell and Wild, 2011). This surface mucosa is also known as the coral surface mucus layer (SML) (Bythell & Wild, 2011).

  According to Rotjan and Lewis (2008), two more types are distinguished; excavators and scrapers. The excavator removes large parts of live coral tissue including skeleton and the scrapers remove live coral tissue with a small part of skeleton involved.

  Damage from coral predation depends on the type of consumer (browsers, feeders etc.). Only a few species cause lethal coral damage. According to Rotjan and Lewis (2008), Pacific and Indian reefs have more to deal with corallivore species compared with Caribbean reefs (Rotjan & Lewis, 2008). For an overview of corallivory across the globe, see the figure below:

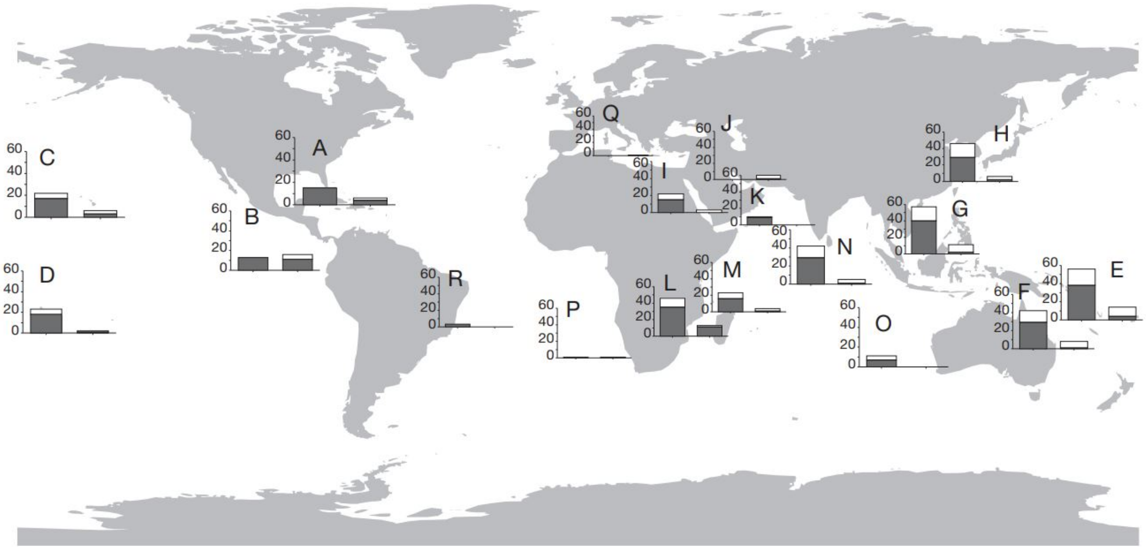


Figure C.1: Corallivory around the world according to Rotjan and Lewis (2008). The white bars indicate the amount of obligate coralllivory species and the dark bars are the facultative species. The letters indicate the region of coral reefs. For the exact locations, see Rotjan and Lewis (2008).

Typical coral consumers are listed in appendix Figure D.27, D.28, D.29, D.30. Below, some species are highlighted:

- The parrotfish (Bolbometopon muricatum) is of great concern, regarding its coral consuming rate. It consumes 13.5 kg live coral m^2/year (Bellwood et al., 2003). The parrotfish consumes almost all coral species, except for slower growing coral as the montipora species (Hoey & Bellwood, 2008). Possibly, this could enhance biotic diversity, but requires more study (Rotjan & Lewis, 2008).

- Another corralivory is the butterflyfish. Coral tissue is desired food, contrary to coral skeleton which is frequently not affected (Randall et al., 1967; Randall, 1974). A variety on coral consumption rates exist. 14 of 53 butterflyfish species are completely dependent on coral as food resource and are described in Rotjan and Lewis (2008).

- Damselfishes, by enhancing algal growth due to the removing of coral tissue and its aggressive algal protective behaviour (Kaufman et al., 1977; Glynn and Wellington, 1983). (Ridge) Mortality of Diploria spp. corals and Acropid corals have been observed (Proppe, 2013; Bruckner and Bruckner, 2001).
- crabs (tetralia and Trapezia) consume coral mucus (Stimson, 1990).
- seastar
- Snails (drupella)
- Sea urchin (Eucidaris Thouarsii)
- see other examples in the appendix Figure D.27, D.28, D.29, D.30.

Corralivory is not the cause of the worldwide decline in coral reefs. However, they could play a role by stimulating coral decline. A herbivory-corallivory balance is needed, since some corallivores are also grazers and are needed for the maintenance of coral reefs by preventing algal overgrowth. The sea urchin and the scarid parrotfish are two examples who also decline macroalgae cover by grazing. (Rotjan and Lewis, 2008; Hughes, 1994; Birkeland, 1977; Lewis, 1986; McClanahan et al., 2005)

The occurrence of corralivory species has not per definition a negative impact as described before. However, when is known that coral species are fragile and are balancing on their tolerance limits and when corralivory species are over populated, then corralivory is fatal (Rotjan & Lewis, 2008).

Measures that are proposed that could help in these circumstances are:

- Target fishing
- Injection
- Manual removal
- Underwater fences
- If the above measures cannot be applied, implement species that are not prone to corralivory

- **Algae check**

  Macroalgae can be space competitors to corals and could be the reason that coral development hampers or that no coral development occurs (Fabricius, 2005; McCook et al., 2001). This has to do with light availability, growth rate, nutrient availability and other environmental factors. Further details about this topic is outside the scope for this research. If en excessive amount of algae is observed on the reef or greenfield, the following are possible causes:

  - Assess the water quality characteristics
  - Observe the amount of herbivore species. If low: outplant herbivore species as sea urchins.
  - Eutrofication measures

- **Coral diseases check**

  For an endangered system, coral reefs are present that facilitate endangered species. These specific species are threatened with extinction due to a variety of factors, named in Section 2.3.7 with global climate change effects and impacts of human activities acting as some of the main underlying causes of decline in pristine reefs (Hughes et al., 2003). To define an endangered system, IUCN's Red List (The International Union for Conservation of Nature's Red List of Threatened Species) of threatened species shows the status of animals, fungi and plant species (IUCN, 2021). By using the Red List search function, categories and criteria of each species are displayed. The nine categories according to IUCN, 2021 are: Not Evaluated, Data Deficient, Least Concern, Near Threatened, Vulnerable, Endangered, Critically Endangered, Extinct in the Wild and Extinct. The options; Endangered (EN) and Critically Endangered (CR) are the two options that need to be featured. If in an investigated marine area one of the coral species is enlisted as EN or CR, this area is labelled as an 'Endangered System'.

  If species are reduced by new invasive species, it reduces the options for species higher up the food chain. This has a consequence for algal growth on corals and risks coral extinction. The lionfish is an invasive species in many coral regions. This fish threatens corals, because it prevents population growth by consuming juveniles (herbivores). Herbivores, consume algae, growing exorbitantly without having algal 'grazers'. This will lead to coral health decrease for all coral ecosystems. This is especially a problem for endangered systems, since resilience is low and endangered coral species have a high risk of extinction. This is also the case for seagrass. Native seagrass supports native cues for species in general. If harm is done to native seagrasses in the surroundings, this can result in the same effect as explained before.

  Functions: Protection of threatened species
  Positive influence: create protected zones, implement barriers for fishermen etc, coral larval rearing (broadcast spawning or brooding), lion fish removal
  Negative influence: doing nothing to stimulate or improve living conditions of threatened species, overfishing

- **Turbidity**

  is one of the sediment disturbances on corals. Turbidity hinders light to reach coral due to undissolved particles in the water (Erftemeijer et al., 2012). Turbidity can also be seen as impure water. The clearer the water column is, the lower turbidity values will be measured. These turbidity values can be measured and expressed in different ways. TSS (Total Suspended Solids), SSC (Suspended Sediment Concentration), NTU (Nephelometric Turbidity Units) are some of the impact indicators that are widely used (Erftemeijer et al., 2012). Frequent used and therefore the prevailing indicator is the SSC indicator (Laboyrie et al., 2018). Depending on the equipment that is used, the water quality, soil type and volume to be dredged, the suspended sediment concentration could range with a factor 100 on a certain location (Erftemeijer et al., 2012).

C.2. In depth suspended sediment plume

(see: section paragraph B.1.1) Suspended sediment plume is a dredging plume that results from dredging works or other sediment disturbances (Laboyrie et al., 2018). Two factors arise from dredging plumes: Turbidity and Sedimentation.

C.2.1. Turbidity

Turbidity values are influenced in different ways. For the project effects, the following factors prevail considering only project effects (Laboyrie et al., 2018):

- Sediment type differences
- Sediment cohesiveness
- Amount of dredged material
- Procedure of dredging (which is mainly of influence for project effects of marine works and for maintenance dredging)
- Amount and type of contaminants
- Hydrodynamic conditions during and after dredging

Increased temporal turbidity values are the result of dredging and port construction (Erftemeijer et al., 2012). Dredging activities cause a 'dredging plume'. There are plenty of ways to dredge. A range in dredging equipment and methods is available to select the optimal dredging method. The book: Dredging for Sustainable Infrastructure, provides dredging and placement strategies belonging to specific locations and situations and provides guidance to create added value for natural and socio economic systems (Laboyrie et al., 2018).

C.2.2. Sedimentation

Sedimentation is another effect that can result from dredging works. The discrepancy with turbidity is that for sedimentation, settlement of suspended solids prevails. The sediment particles which are subjected to gravity, form a deposition layer on the bottom surface. The settle velocity has a proportionate relationship with the particle size as explained below. (Kynch, 1952)

The drag (F_D) and gravity (F_G) forces that are subjected to particles, can be seen in Figure C.2. In F_G, the buoyancy force should be deducted.

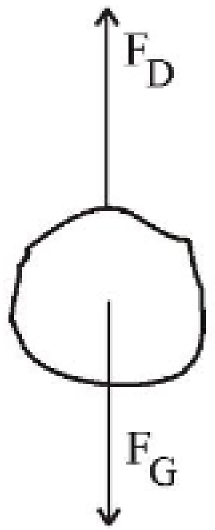


Figure C.2: Particle forces (Bosboom & Stive, 2012)

Over time, F_D and F_G reach an equilibrium, whereby the fall velocity (w_s) is constant. In equation Equation C.1, the calculation of w_s is shown for still and clear water (Bosboom & Stive, 2012).

$$w_s = \sqrt{\frac{4(s-1)gD}{3C_D}} \tag{C.1}$$

where	w_s	Particle fall velocity	[m/s]
	s	Relative density (ratio $\frac{\rho_s}{\rho}$)	[$\sim$2.65]
	g	Acceleration of gravity	[m/s^2]
	D	Particle diameter	[m]
	C_D	Drag coefficient	[-]

Equation C.1 shows that the particle fall velocity is dependent on, among other things, the particle diameter (D). As indicated before, is an increase in particle size, inextricably linked with an increase in w_s. This shows that range in particle sizes, presents variety in settling velocities.

Particle size	Diameter [mm]
Very coarse sand	2.0 - 1.0
Coarse sand	1.0 - 0.5
Medium sand	0.5 - 0.25
Fine sand	0.25 - 0.1
Very fine sand	0.1 - 0.05
Silt	0.05 - 0.002
Clay	$\leq$0.002
Fine clay	$\leq$0.0002

Table C.1: Grain size distribution (Group et al., 1998)

Concluding, each soil type from very coarse sand to fine clay, has its own significance on behalf of settling velocities. Since coastal waters are to the utmost extent subjected to water movements in the form of currents, sedimentation rate is not only dependent on grain sizes, but also on hydrodynamic conditions. Hydrodynamic conditions and settling of particles are dealing with site specific morphological circumstances (Bosboom & Stive, 2012). So, per location these hydrodynamic, morphodynamic and other factors influencing the settling velocity, are location specific. Precipitated sediment could also be stirred up by new or other dredging activities. As for turbidity, sedimentation is also an element that originate from sediment plumes while dredging (Laboyrie et al., 2018).

C.2.3. Dredging plume coverage

This plume is a significant element to understand, since this provides an indication about the actual range that is affected by the sediment plume. In order to indicate when a dredging plume is small, medium or large, the effects on ecosystems is from importance. This will be specified later on. First information is provided about the zone of influence.

Near field and far field are two terms regarding dredging plumes that are being distinguished. Near field zone is for dredging plumes close to the dredging vessel. The interaction is between plume, velocity differences between vessel and ambient water. Air entrapped in the overflow of a dredger and density differences between plume and water have influences on the dredging plume in this zone. Further detailing of the near field concept is not within the scope of this research. (de Wit et al., 2020).

For a far field zone, no vessel influences on plume are present. Therefore the near field interactions are less or even not present at all. Waves and currents, cause the plume to develop in a 'passive plume' and dispersion. Mixing of plume content with ambient water, is affected by the depth, tidal influences, wind effects, Coriolis influences and ocean stratification, according to Taco Tuinhof's TU Delft master thesis (Tuinhof, 2014). For far field zone dredging plume simulation, diverse hydrodynamic flow models are available as Delft3d, FINEL or MIKE (de Wit et al., 2020). Near shore sediment plume results can function as a source term for far field models (Becker et al., 2015; Laboyrie et al., 2018).

C.3. In depth hard engineering categories

C.3.1. Rubble mound structures

Rubble mound (RM) structures are frequently built of quarried rock and finished by a covering armour layer consisting of heavy rocks or concrete units whereby the core consists of smaller rocks or gravel. (Research et al., 2007)
The exact functions depend per location and per structure type. Structure examples are groynes, jetties, (detached) breakwaters, seawalls, covered pipelines or cables and artificial reefs. These can be found in Table 2.1. Typically, frequent RM structures are breakwaters (Research et al., 2007).
For all rubble mound structure types, the intention is to provide backwaters or hinterland which are less affected by waves and currents.
RM structures can offer protection against storm surges, high waves, strong currents and erosion problems. As examples: the outer slope of an RM breakwater could force waves to break and an RM groyne could interrupt longshore sediment transport to prevent erosion.

An advantage of RM structures is that these structures are relatively easy to build. It does not require exceptional techniques to place rocks correctly. The rocks that could be used are most of the time easily accessible and larger stones can be taken from local quarries. Other advantages are the easy repair works on RM structures. When stones are damaged or moved, they can easily be replaced by new stones. Providing land-based access for equipment contributes to the simple handling of repairs. Finally, RM structures suffer less from settlements or collisions. Where monolithic types are more sens¬itive to settlements or collisions, due to their rigid structures, an RM structure consists of relatively 'loose' material and is therefore less attached to other structural components. The 'damage development' is ductile or more flexible than for monolithic types.(Research et al., 2007)

Disadvantages of RM structures could be problems with rock supply. Large amounts of rocks are necessary to fill the whole volume. If the water where this structure will be built is deeper, a larger quantity will be necessary. Due to higher costs, implementation of RM structures is generally viable for depths shallower than 10 meters (Research et al., 2007). Transport costs could become high due to the transport of all rocks. Since mooring of vessels to an RM structure is frequently not possible due to slope irregularities, a separate structure is needed to make it suitable for mooring activities. Another disadvantage is the susceptibility of RM for hurricanes. Hurricanes could displace stones and internal displacement of the RM structure. Over time, this will result in sooner and more replacement of RM material in regions where hurricanes occur. (Burcharth et al., 2018)

Design
As stated before, frequent RM structures are in coastal areas breakwaters or structural types comparable to breakwaters (Research et al., 2007). RM structures, that do not function as breakwaters, could be designed in smaller dimensions since they do not have to withstand forces that are subjected to breakwaters. The 'standard' RM breakwater design looks as follows:

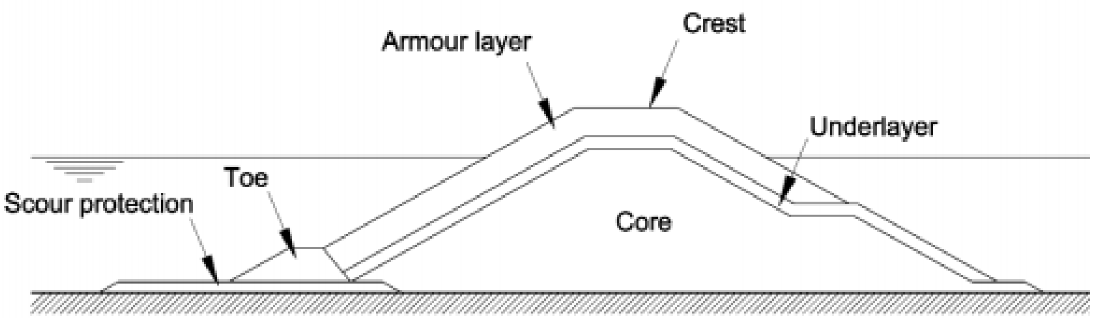


Figure C.3: RM breakwater design (Research et al., 2007)

The core of the breakwater design consists of gravel or smaller sized stones (quarry run). This is the part that uses most material, so it is convenient if the stones that are used are readily and widely available. The outer layer (armour layer) and the under layer are important for this research, since they are in direct contact with marine life.
Classification of RM structures is done using the following formula (Van der Meer, 1995):

$$\frac{H}{\Delta D} \tag{C.2}$$

where	H	(Significant) wave height	[m]
	Δ	Relative mass density	[kg/m^3]
	D	Diameter of structure, armour unit, stone or sand	[m]

Equation C.2 is used to classify certain structures due to the indication of static stability. According to van der Meer, $H/\Delta D$ = 1-4 is the case for static stable structures that need to withstand wave forcing. This is the case for RM breakwaters. (Van der Meer, 1995; H. Verhagen and van den Bos, 2017)
Dynamically stable structures allow wave action to displace materials as rock, gravel and sand. When an equilibrium profile is reached due to a net zero transport of particles, the structure can be called a dynamically stable structure. These structure types meet: $H/\Delta D$ > 6 and are frequently the case for rock slopes, beaches and dunes. For an overview of these structures, see Appendix Figure D.4. (Van der Meer, 1995)

According to the Rock Manual, different RM structure types can be distinguished (see Appendix Figure D.5).
The options are (adapted from the Rock MAnual (Research et al., 2007)):

1. **Conventional rubble mound** the armour layer encompasses the largest coverage of the structure. These structures are generally built to protect backwaters, the hinterland or other structures.
2. **Conventional rubble mound with crown wall** is used to provide a safe environment for harbours. The crown wall is used to enter harbour facilities, quays or for maintenance activities.

3. **Berm breakwater** has the aim to protect the hinterland by preventing coastal erosion. Static stable or dynamic stable structures are both possible. For the berm breakwater, a layer of stones is placed on top of the berm.
4. **Submerged breakwater** is placed to dissipate wave energy, but when overtopping is still allowed. Submerged breakwaters protect shorelines from wave impacts and can function as anti-erosion measures.
5. **Horizontally composite breakwater** is comparable to vertically composite breakwater, as explained in monolithic structures, with the combination of RM and caisson. Instead of placing the caisson on top of RM, the caisson is placed behind RM. This could result in a more stable unit. Because one side is covered with rubble units, the rubble will have a large influence on the interaction with the marine environment. Therefore this structure type belongs to RM structures.
6. **Pipeline or cable coverage** is necessary if damaging or illegal tapping needs to be averted. A trench in the sea bottom by dredging could be made. Since not all soils are suitable for dredging (rock bottoms) or if the use of an RM armour layer is considered cheaper, RM material is used to cover up the cables, pipelines or other similar materials. Other factors for the use of RM in these cases is to prevent buckling by creating resistance through the weight of the stones. Internal pressures or high temperatures are mostly the cause of buckling.
7. **Artificial reefs** could be used to provide calm waters for harbour operations and to function as substrate for biodiversity. Artificial reefs can solely be implemented to enhance marine life. Crests could be lower or above water surface.

Elements
In this paragraph, the elements of RM structures that could affect the environment positively or negatively are discussed. For the RM structures, the placement area and construction materials are of importance.

- **Material properties**
  The materials used in the typical structures are elaborated in this paragraph.
  RM structures are structures that are characterized by material of different sizes, placed on top of each other (layering). Conventional material that is used, are: (Research et al., 2007)

  – Grouted stone
  – prefab asphalt mattress
  – concrete blocks
  – Grout filled mattresses

  The armour layer is in typical direct contact with the marine environment and belongs therefore to the elements that are important for the structure-marine environment interaction. Different design considerations are possible for the armour layer. Once, all RM armour layers where made of large randomly placed rubble units (Muttray & Reedijk, 2009). Over time, different designs came up where interlocking and friction between placed units and unit shapes got more attention. Interlocking or friction improves the rigidness of the structure and together with the custom shape, forces are better transferred and cause minor point loads. Friction and interlocking decreases the probability of failure, since units are more easily kept in place and can therefore withstand larger forces. Replacement of interlocked units is more difficult than for randomly placed units. But new inventions are devised to improve strength and longevity of marine structures. The following units are examples of armour layer units that are widely used (Muttray & Reedijk, 2009):

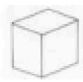
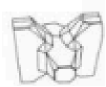
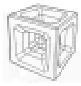
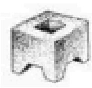
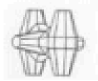
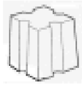
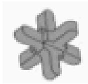
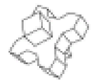
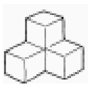
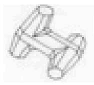
Randomly placed armour units			Uniformly placed armour units
Double layer placement		Single layer placement	
Stability factor: Own weight	Own weight and interlocking	Interlocking	Friction
Cube 	Tetrapode France, 1950 	Accropode France, 1980 	Cob UK, 1969 
Modified Cube USA, 1959 	Akmon NL, 1962 	Core-loc® USA, 1996 	Diahitis Ireland, 1998 
Antifer Cube France, 1973 	Tribar USA, 1958 	A-Jack USA, 1998 	Seabee Australia, 1978 
Haro Belgium, 1984 	Stabit UK, 1961 	Xbloc NL, 2003 	Shed UK, 1982 
Tripod NL, 1962 	Dolos South Africa, 1963 		

Figure C.4: armour units for rubble mound structures (Muttray & Reedijk, 2009)

- **Size**
  Sizes of RM structures, are completely dependent on the site. All sizes are related to other projects that have been executed before.
- **Placement area**
  For larger depths, RM slopes need to be larger to have a stable construction. This results in a larger 'placement area'. If depths are too large, and therefore too costly, this can be solved by using horizontally or vertically composite breakwaters and hence decrease the placement area.

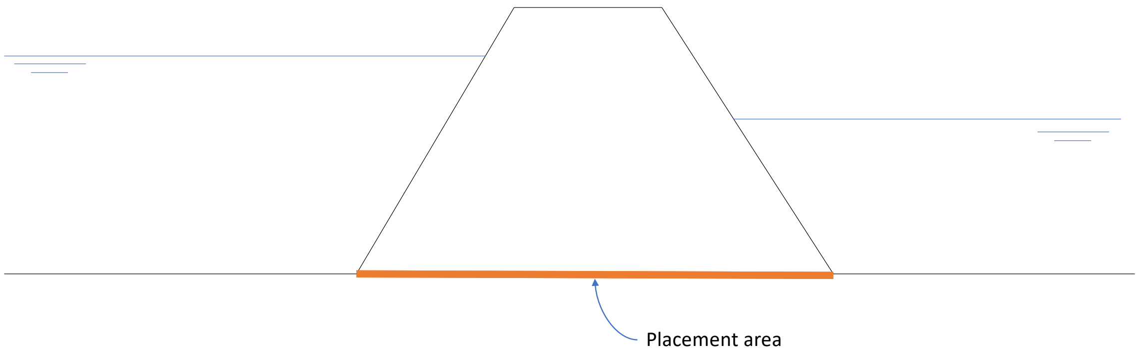


Figure C.5: Placement area

- **Wet surface area**
  This element is to quantify the area where coral growth would be possible and is called a wet surface area. A larger wet surface area, creates more possible and suitable living place. The wet surface area for RM structures is relatively large. The inclination angle is dependent on rock size, depth and structural function of the RM structure. The gentler the slope, the larger the actual wet surface area becomes.

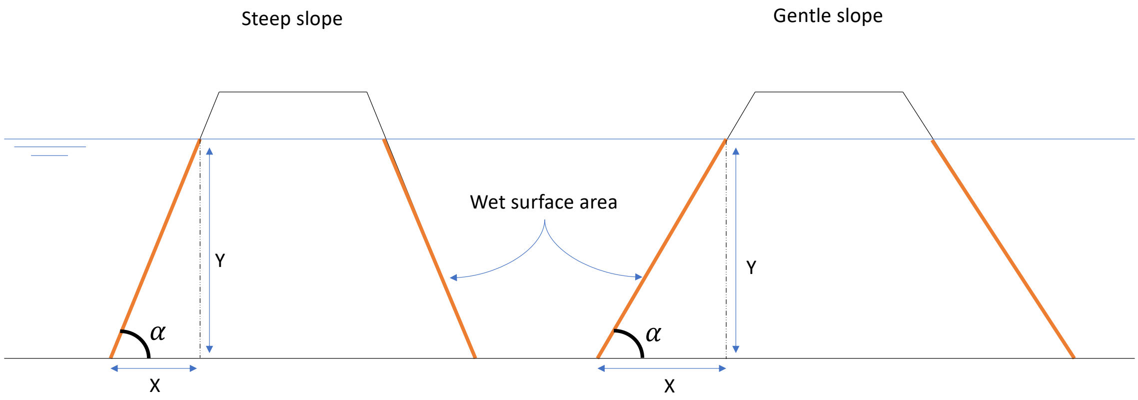


Figure C.6: Wet surface area for different slopes

The 2 dimensional wet surface area is being calculated with:

$$\alpha = \tanh \frac{y}{x} \tag{C.3}$$

$$\text{2D Wet surface area} = \frac{y}{sin(\alpha)} \tag{C.4}$$

A larger slope angle for equal depths (y) values, results in a larger 2D wet surface area. The slope angle is dependent on rock diameter ($Dn50$), hydrodynamic conditions and incoming wave angles. Slopes could be in range from 1:1 to 1:4.

C.3.2. Monolithic structures

Gravity based structures that are rigid and have less unevenness compared to RM structures are called monolithic structures. Monolithic mainly consist of one part, acting as a rigid (solid) structure (H. Verhagen & van den Bos, 2017). Therefore, these structures experience less dynamic behaviour as RM structures do. Structural examples are combi-walls, jackets, enclosed piers, quay walls, pipelines, groynes, jetties, breakwaters, etc. as long as the structure is gravity based and consists of a joined construction without separate parts such as loose rock.

The first positive for the use of monolithic structures is the relatively short construction time on site. This causes fewer environmental implications during the construction phase and could result in a shorter con¬struction time. A second advantage is the amount of material needed. Monolithic structures such as caissons frequently have hollow centres. This makes the structures easier and cheaper both to transport towards and to deposit on the construction site. Since less material is used, the whole construction becomes cheaper compared to RM structures. Monolithic structures are most of the time

easier to implement if larger depths need to be covered.
Because monolithic structures are even (no rough sides and surfaces), mooring systems can directly be implemented in monolithic structures without the construction of an added structure for the same purpose. And monolithic structures such as caissons are more favourite for larger depths since the building process is easier and less costly. Usually, for depths from 15 meters and deeper, caissons are to be used for economic reasons. Location characteristics remains the prevailing factor (Research et al., 2007). (Burcharth et al., 2018)

Monolithic structures have mostly straight, vertical walls. This increases wave-induced stresses. Since in the case of RM structures, the 'walls' have a certain angle (inclined), waves break and dissipate energy over a larger area, which does not act perpendicular on the RM side. Waves acting on vertical walls induce large pressures perpendicular on these walls and could more easily lead to brittle failure. Another disadvantage is the high reflection of waves due to vertically constructed walls. This causes turbulent waters.
Monolithic structures are, as RM structures, gravity-based. For both kind of structures, the structural stability is dependent on subsoil foundation. Consolidation, due to increased weight by implementation of the structure, could lead to settlements. Since monolithic structures are rigid, they are not able to perform well under soil settlement and shifting which again could lead to brittle failure. (Burcharth et al., 2018)

Design
Monolithic structures could be built in water or outside water (prefab) and inserted after construction. Gravity block quay walls are an example where large blocks made from concrete or stone are applied. Caissons are prefabricated and mounted together on site.
For increasing depths, width increases to meet the stability requirements. The conventional monolithic design looks as follows:

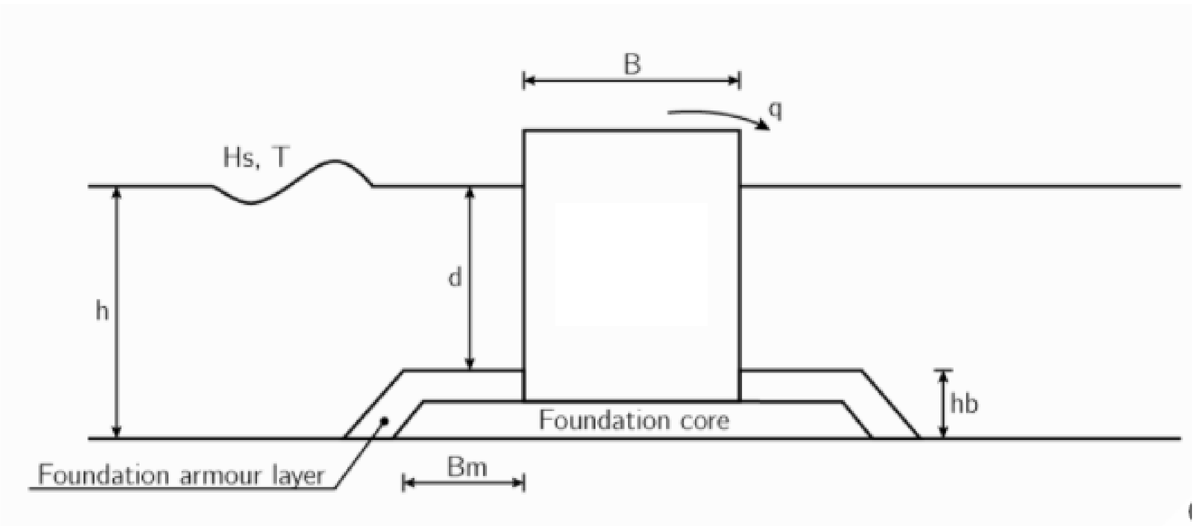


Figure C.7: Monolithic structure design (Winkel, s, 2021)

The monolithic structure type from Figure C.7 has a foundation core. However, this could not be necessary and depends on soil conditions. However, monolithic structures require stable foundations (H. Verhagen & van den Bos, 2017). As for the RM structures, the area is in direct contact with marine life, and it is therefore important to investigate the interaction between coral and infrastructure.

Using the stability formula Equation C.2, presents a value of $H/\Delta D < 1$. See Appendix Figure D.4. This is the case for solid structures (Van der Meer, 1995). Exceeding stability requirement values, could lead to the direct loss of stability of the entire structure (H. Verhagen & van den Bos, 2017). Therefore it is important to apply sufficient safety factors for the design of such structures.

The following monolithic structure types are distinguished:

1. **Conventional caisson structures** have the function of protecting waters against storm surges and providing mooring place, preferably both at the same time. This structure type could also function as a pier or jetty. Caissons are usually implemented for water depths of 15 meters or more due to economic viability (Research et al., 2007) but are typically dependent on the location.
2. **Vertically composite breakwaters** have another form than other monolithic structures mentioned. These 'composite' breakwaters make use of caisson on top of the RM structure. The RM structure is in this case serving as a foundation, but still interacts with the environment. These structures are common if depths are (too) large (> 10-meter depth) to cover only by RM material or if a solid found¬ation is required. Since RM covers a part of the construction, but most of the construction consists of a rigid structure, the structure is categorized as a monolithic structure. These com¬posite breakwaters are used to protect harbours. These 'vertically composite breakwaters' are prone to the failure mechanisms showed in Figure C.8.
3. **quay walls** are structures that allow ships to berth and keep soil in place by protecting against landslides and settlements. Monolithic quay walls could have blocks, caisson, counterfort, cantilever or combined wall structures (Allen & Moore, 2016). The combined wall is in fact a piled structure. But due to the fact that a sheet pile wall is created, the outer structure will be a 'solid' structure and therefore belongs to this monolithic structure category.
4. **Revetments** are walls that protect against subsidence and erosion and can be called monolithic if the surface has a 'smooth' and equal surface. Examples are asphalt or concrete revetments.
5. **submerged monolithic structures**, such as tunnels and pipelines, are gravity based structures that consist of components that can be prefabricated on the 'dry'.

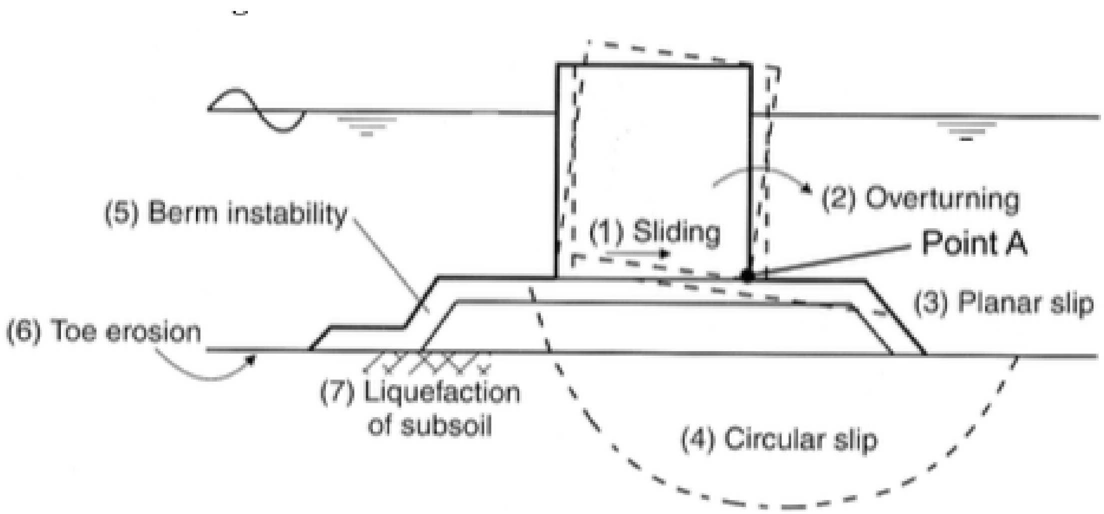


Figure C.8: Failure mechanisms Vertically composite breakwater (Research et al., 2007)

Elements

- **Material properties** Monolithic types are constructed of concrete, steel, timber or masonry. Es¬pecially for prefabricated elements, concrete is often used. Also, for 'blocked' walls and caissons, concrete is mostly used, such as for monolithic jetties, groynes and piers. Retaining walls are some¬times made of steel, concrete or wood. Sheetpile walls are mostly made of steel but can sometimes be made of wood or reinforced concrete. For revetments, different options are pos¬sible. An outer asphalt layer is sometimes used, but concrete could also be applied as long as the structure remains relatively smooth.
- **Placement area** is smaller for quay walls than for large caissons. The bottom surface where monolithic structures are placed, is fully covered with the structures bottom.
- **Wet surface area** is often relatively small, since the structures entailed are typically vertical walls.

C.3.3. Pile foundations

After monolithic and RM structures, structures made of piles is the third hard marine 'shape' category. Examples of marine piled or pier constructions are jetties, piers, bridge pillars, mooring systems etc. Pile foundations are literally constructions on piles. The piles could be deep, but also shallow founded. The piles need to be in contact with marine life. Therefore, piles that are totally covered in soil, are not pile foundations that could interact with coral. For this study, piled structures are constructions whereby piles are actually visible in the marine environment.

frequently, piles would carry a superstructure and function as foundation. This can be done for different soils but are typically done for unstable and weaker soils where no implementation of a gravity based structure is possible and the superstructure needs to be elevated. Possibilities in piled constructions are: Bored piles, displacement piles, micropiles, precast concrete piles (Kempfert & Gebreselassie, 2006). The type of piles depends on soil, loads, settlements, space requirements and water conditions (Kempfert & Gebreselassie, 2006). Kempfert explains that every pile type has its own advantages and disadvantages. An important general characteristics of pile foundations is the transfer from loads from the 'super structure' through the piles towards the ground. Super structures that need to be be built above the water level, can use piles as foundation. Space occupancy is lower and natural flows of sediment are still possible. Furthermore, if the soil bearing capacity is low, piles are suitable. Three main pile foundations exist: driven or precast piles, cast-in-situ and a combination of the two (Poulos & Davis, 1980).

Disadvantages for the use of piles; are that piles can easily be damaged during driving through hard soils (stones), piles need to be in deep soils. Moreover, the process of pile driving causing negative effects on the environment (Brandt et al., 2011). For all pile types and associated advantages and disadvantages, see Kempfert and Gebreselassie (2006).

Design

Since piles should be visible above the bottom, there are different structure types.

- pile supported piers
- pile supported jetties
- breakwater (curtain wall-pile breakwater)
- bridge pillars
- pile supported mooring system
- groynes
- jackets

Quay walls are typical walls made out of driven sheet piles. Since the piles together form one monolithic wall, these types of structures are put underneath monolithic structure types. Jackets are other types and could be driven in soil or function as gravity based structures. Since the design inside the water column is a structure consisting of piles, this design falls under piled structures.

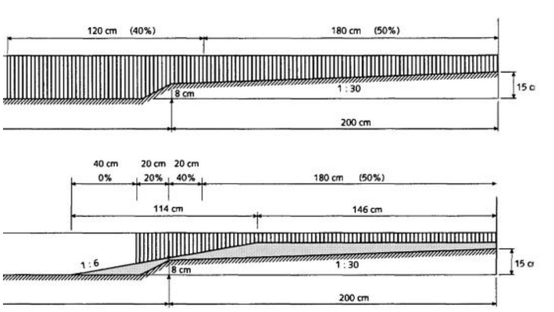


Figure C.9: Groyne design examples (Uijttewaal, 2005)

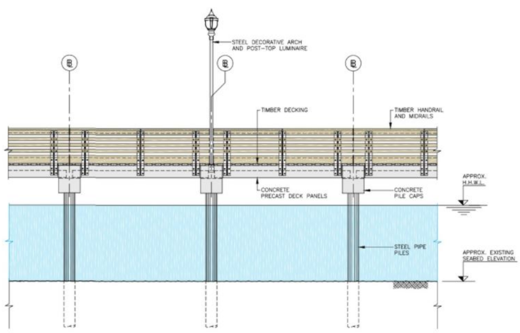


Figure C.10: Pier design example (Chan, 2019)

In figures C.9 and C.10, two design examples are shown. piers and piles used in the design could be placed vertically in the ground, but also at an angle. Sizes could also differ between small piles used for groynes towards large pier 'foundations' that need to withstand vertical forces of heavy bridges or other substructures.

Elements

- **Material properties** Piles could be made of timber, concrete and steel or be a composite (Abebe & Smith, 2005). All information regarding material properties is obtained from Abebe Smith (Abebe & Smith, 2005). Timber piles are the first type of piles that are used in piled constructions. Keeping timber below water surface, protects against decay. Concrete is likely to be more used these days. The reason is that concrete piles can be prefabricated. Design could be triangular, round square or octagonal. On site, parts or precast parts can be connected together with reinforcement, to form strong and large structures. Steel piles are relatively easy to drive into the ground and have strong characteristics. A combination of mentioned materials is also possible. This is called composite piles. For example, wooden piles could be used as the lower part that is surrounded by water. Concrete or steel is then attached above water.
- **Size** Sizes of pile foundations are totally dependent on structure type. It could entail large bridge supporting piles that cross large waters, but also a small recreational pier.
- **Placement area** is the smallest of all marine works. Space occupancy by superstructures supported by piles, is low. This is one of the large advantages of a pile foundation.
- **Wet surface area** is large and can be increased when piles are placed more diagonal and when diameter and circumference are increased. The wet surface area is also much smaller than for other marine works, but depend on the amount of piles and dimensions.

C.3.4. Floating structures

The last marine 'shape' hard engineering category is floating structures. Examples are structures used that need to protect the underlying area. Another option is for deep waters, where construction can only be attached to the bottom with anchors. Floating structures are: docks, breakwaters, systems for solar panels etc. Floating structures are easily attached and detached and could be prefabricated. The production process takes place on land and installation only entails mounting on the sea bottom. This makes it environmentally friendly (C. Wang & Wang, 2015). If a construction needs to be adapted, this can more easily be done for floating structures, since these are more flexible than for example reclamated areas (C. Wang & Wang, 2015). Floating marine structures remain within an equal distance to the water surface. This is desirable for berthing of ships. Another advantage is that these structures are more protected from earthquakes due to their isolated environment. Sediment fluxes, currents and other hydrodynamic processes are not hampered. Floating structures could make use of natural processes as waves, currents etc. to produce energy. The use of space on the sea surface, reduces space occupancy on earth surface. (C. Wang & Wang, 2015) A disadvantage is that floating structures cover sea surface areas which become impenetrable for sun light. Zooxanthellae receive less sunlight and coral development is therefore slowed down (Spalding et al., 2001).

Design

Type of designs are pontoons or semi-submersibles. They have to conquer surge, sway, heave, roll, pitch and yaw motions. This is done by the 'static stability requirement' (C. Wang & Wang, 2015). Below the type of designs are distinguished.

- Docks
- Breakwaters
- Artificial islands
- Solar farms
- Wind farms
- Floating energy generators (wave, tidal, current)
- Bridges
- Floating airports, cities, etc.

Different floating structures are possible in the marine environment. Combinations of structures together with floating structures are also a possibility.

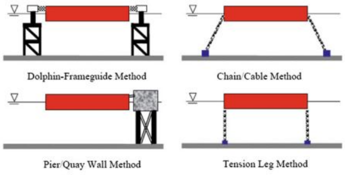


Figure C.11: Mooring examples for pontoons (C. Wang & Wang, 2015)

Figure C.12: Pontoon combination with jacket functioning as a breakwater (C. Wang & Wang, 2015)

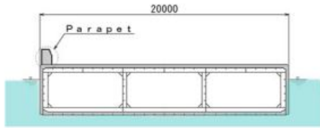


Figure C.13: Cross section pontoon (C. Wang & Wang, 2015)

Elements

- **Material properties** Vulcanised rubber is material that was used for the first built floating constructions. Nowadays, steel, concrete, a combination of the two (composite) and plastics are possible material options (C. Wang & Wang, 2015). Material should be water tight. Concrete is heavy and therefore, steel is frequently used as less heavy, strong construction material. Furthermore, 'new' materials are more used such as high density polyethylene. (Wong et al., 2013)
- **Size** Diversity in sizes ranges from small floating pontoons to large floating bridges or floating solar fields.
- **Placement area** Solar and wind energy fields are frequently placed further offshore in deeper waters. The placement area is directly on the water surface and therefore does not destroy corals on the sea bottom. The only two problems are the anchoring system, but that is a relatively small area on the sea bottom floor. Sunlight blockage is as earlier explained the other negative effect of placement of large floating structures.
- **Wet surface area** The wet surface area is generally small. Corals cannot attach since the structure is constantly in motion. No real opportunities for corals to attach to floating structures are present.

D

Appendix A

D.1. Map of tropical coral distribution

In the figure below, an overview is given of the locations of coral reefs worldwide. The purpose of this is to indicate locations where coral infrastructure can be built inclusively. By seeing the location of corals, an indication can be given whether or not coral could possibly occur.

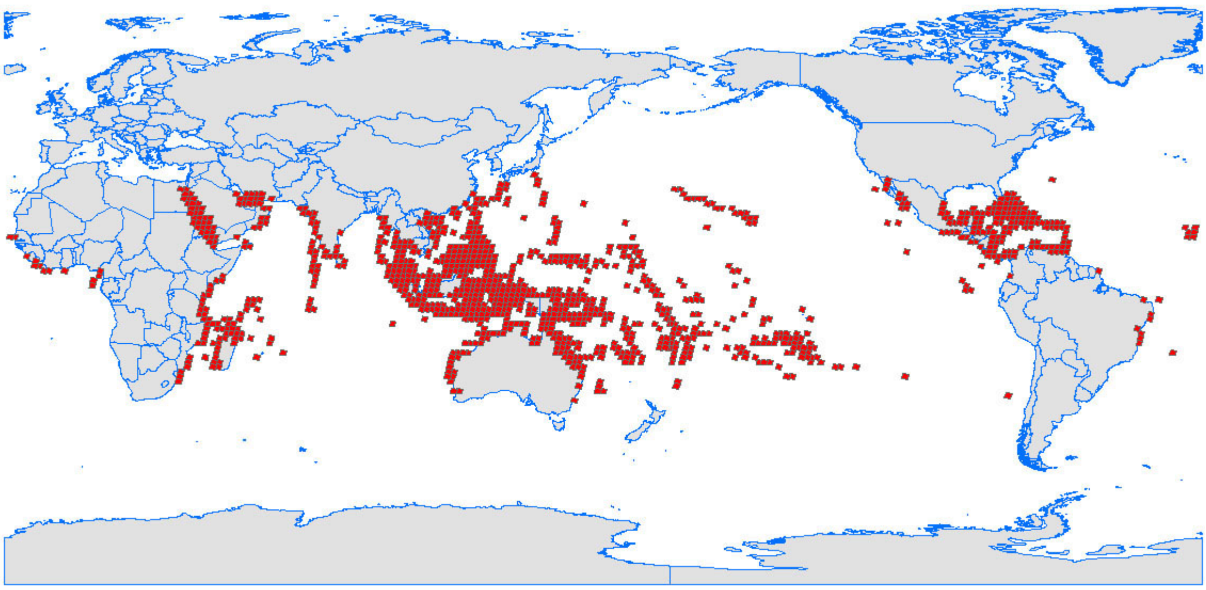


Figure D.1: Worldwide tropical coral reef distribution (NASA, n.d.)

D.2. Food chain

Figure D.2 illustrates the arrangement of the food web. The aim is to indicate the complexity of factors within an ecosystem. By looking at the image, the difference in ranking between consumers is clarified.

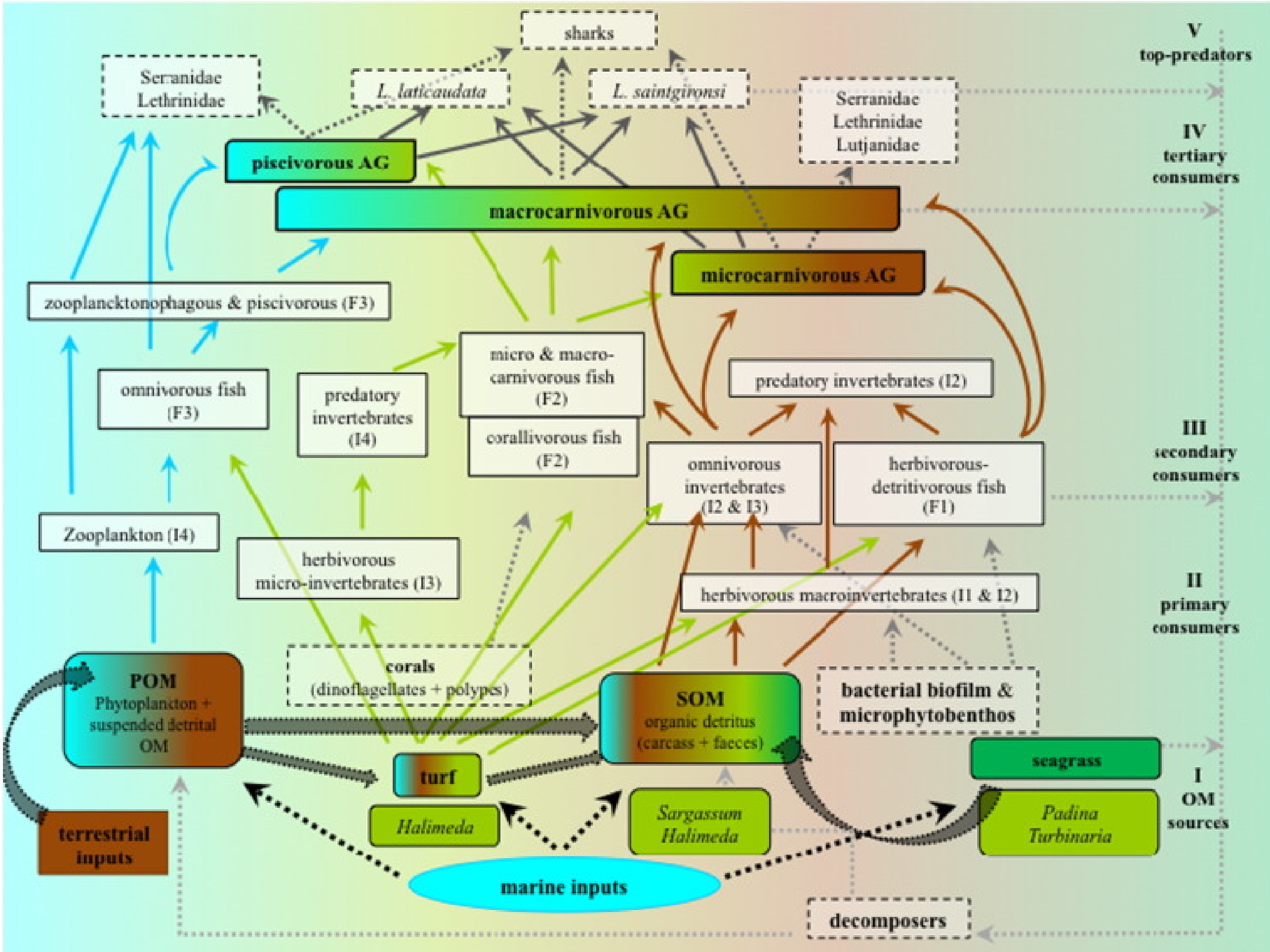


Figure D.2: Food chain in coral ecosystems (Briand et al., 2016)

D.3. Biodiversity metrics

The table with the biodiversity metrics gives insight in what the metrics take into account to check the habitat quality. This is needed in order to see which metric can be used for a certain area.

Metric	Baseline Assessement/Post-Remediation Assessment: Habitat Quality: Area [ha]	Distinctiveness	Condition	Strategic significance	Connectivity	Other Quality Indictors: Fish	Macro Algae	Microbes (small marine life..)	Offset Quantification: Risk: Location risk	Temporal risk	Difficulty risk	Finance Component	Company (Source)	Source	Date	Comments
Biodiverity Metric 2,0	Y	Y	Y	Y	Y				Y	Y	Y		DEFRA	Crosher, I., Gold, S., Heaver, M., Heydon, M., Moore, L., Panks, S., Scott, S., Stone, D. and White, N., The Biodiversity Metric 2.0: auditing and accounting for biodiversity–User Guide. 2019a. *Natural England* .	2019	Due to be updated Spring 2021
Habitat Equivalency Analysis (HEA)	Y									Y			NOAA	NOAA, U., 2000. Habitat equivalency analysis: An overview. Unites States National Oceanic and Atmosphere Administration Damage Assessment & Restoration Progrome, pp.95-1.	2000	
Uniform Mitigation Assessment (UMA)	Y	Y			Y					Y	Y		Florida Department of Environmental Protection	https://www.flrules.org/gateway/ChapterHome.asp?Chapter=62-345	2007	
Coral Health Index (CHI)		Y	Y			Y		Y					Conservation International	Kaufman L, Sandin S, Sala E, Obura D, Rohwer F, and Tschirky T (2011) Coral Health Index (CHI): measuring coral community health. Science and Knowledge Division, Conservation International, Arlington, VA, USA.	2011	Averaged over Area
Reef Health Index (RHI)	Y		Y			Y	Y						Healthy Reefs Initiative (HRI)	https://www.healthyreefs.org/cms/?s=reef+health+index&lang=en	2008	Currently being updated.
System of Environmental-Economic Accounts – Experimental Ecosystem Accounts (SEEA_EEA)									Y	Y			United Nations	UNEP-WCMC (2015) Experimental Biodiversity Accounting as a component of the System of Environmental-Economic Accounting Experimental Ecosystem Accounting (SEEA-EEA). Supporting document to the Advancing the SEEA Experimental Ecosystem Accounting project. United Nations	2015	
MERCI-COR	Y	Y	Y	Y	Y	Y			Y	Y			IFRECOR	Methodology for scaling mitigation and compensatory measures in tropical marine ecosystems	2018	Depending on the specific case and on the project's stage of advancement, the compensation measures may not yet be known. However, if the terrain has already been identified, knowing the proposed effects of the project on environment (Δ impact), the impacted area, the available compensation area and making assumptions regarding adjustment factors linked to the environmental risk (R) and the time delay (T) an estimation of potential gross environmental gain (Δ compensation) is possible. If one wants to assign a particular value to certain functions, extra points or "value-added metrics" can be used. However, these should be clearly separated and distinguishable from the assessment of the ecological state.
Reef Trust Offset Calculator	Y	Y	Y							Y		Y		https://www.environment.gov.au/system/files/pages/661595d3-749f-4aef-9c4a-6e4d245ecc59/files/how-use-reef-trust-offsets-calculator.pdf	2017	The Reef Trust offsets calculator has been designed to be consistent with the EPBC Act Environmental Offsets Policy 2012. For shallow reefs (<30m) The Reef Trust Offsets Calculator is not suitable for use for marine environments other than the Great Barrier Reef

Figure D.3: Biodiversity metrics

D.4. Infrastructure types

Infrastructure categorized with $H/\Delta D$ to indicate the stability. $H/\Delta D$ = 1-4 is the case for static stable structures that need to withstand wave forcing. This is the case for RM breakwaters. Dynamically stable structure types meet: $H/\Delta D$ > 6. The $H/\Delta D$ value classification gives the type/shape of the structure. For statically stable structures, no or only small damage is allowed under design conditions (displacements etc.). Dynamically stable structures, the profile constantly develops.

This information is needed to describe the structure in terms of stability and structure type to know what profile development is allowed. See paragraph C.3.1 for more information.

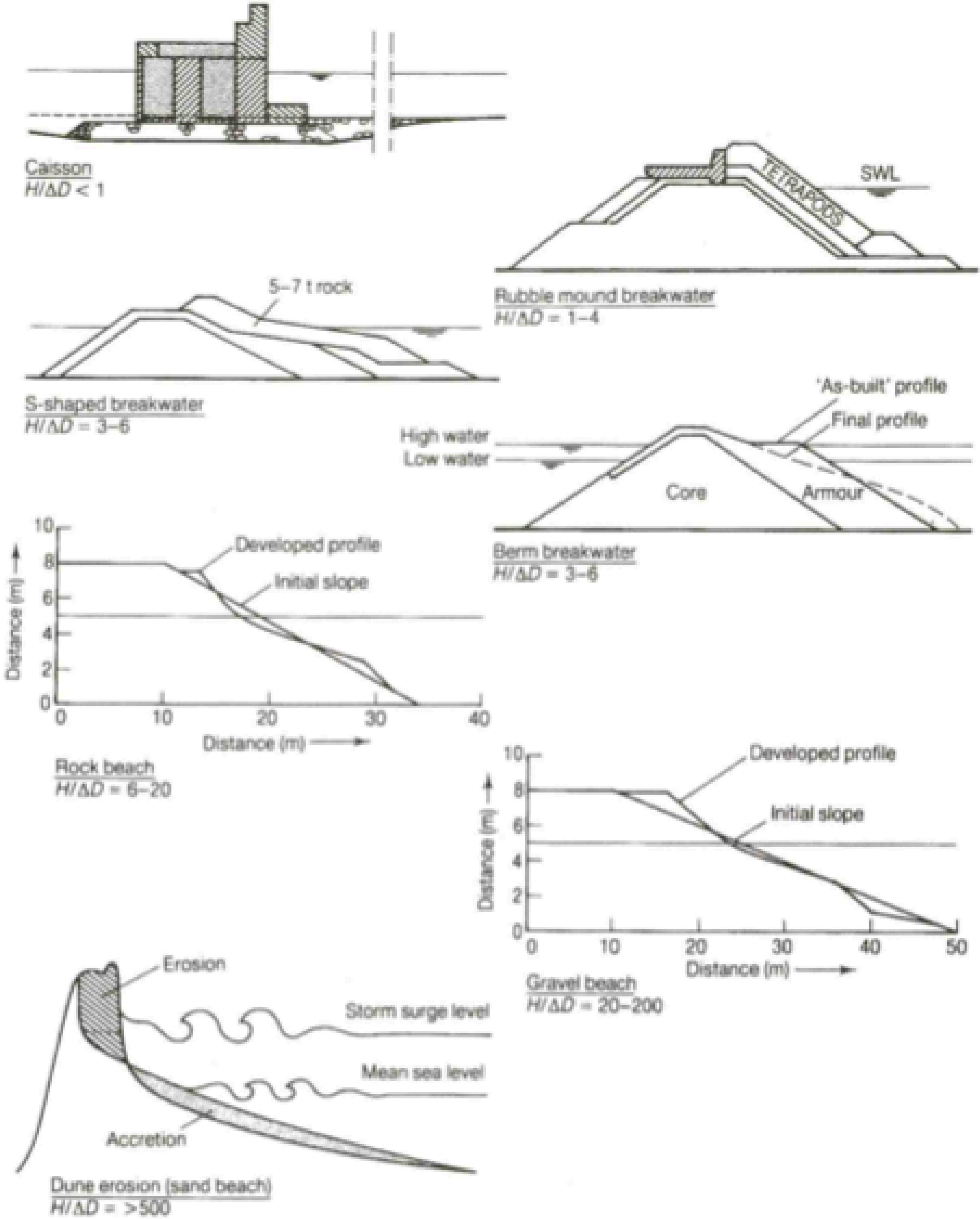


Figure D.4: Structure types categorized by $H/\Delta D$ (Van der Meer, 1995)

D.5. Rubble mount en monolithic structures

This image illustrates the different possible RM and Monolithic structures, to give the reader an idea what possibilities are.

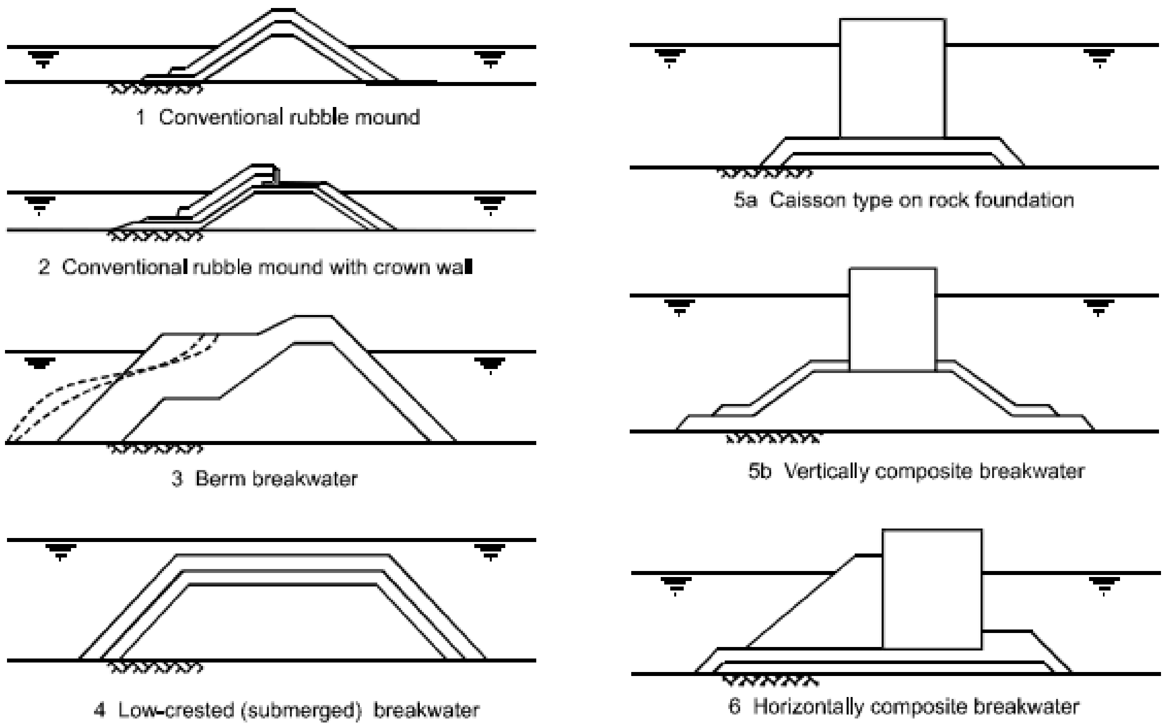


Figure D.5: Types of RM (1-4) and monolithic (5ab, 6) designs (Research et al., 2007)

D.6. Material types

Materials are divided into sub-materials. This shows that different materials can be used and that within e.g. woods, also other types are present.

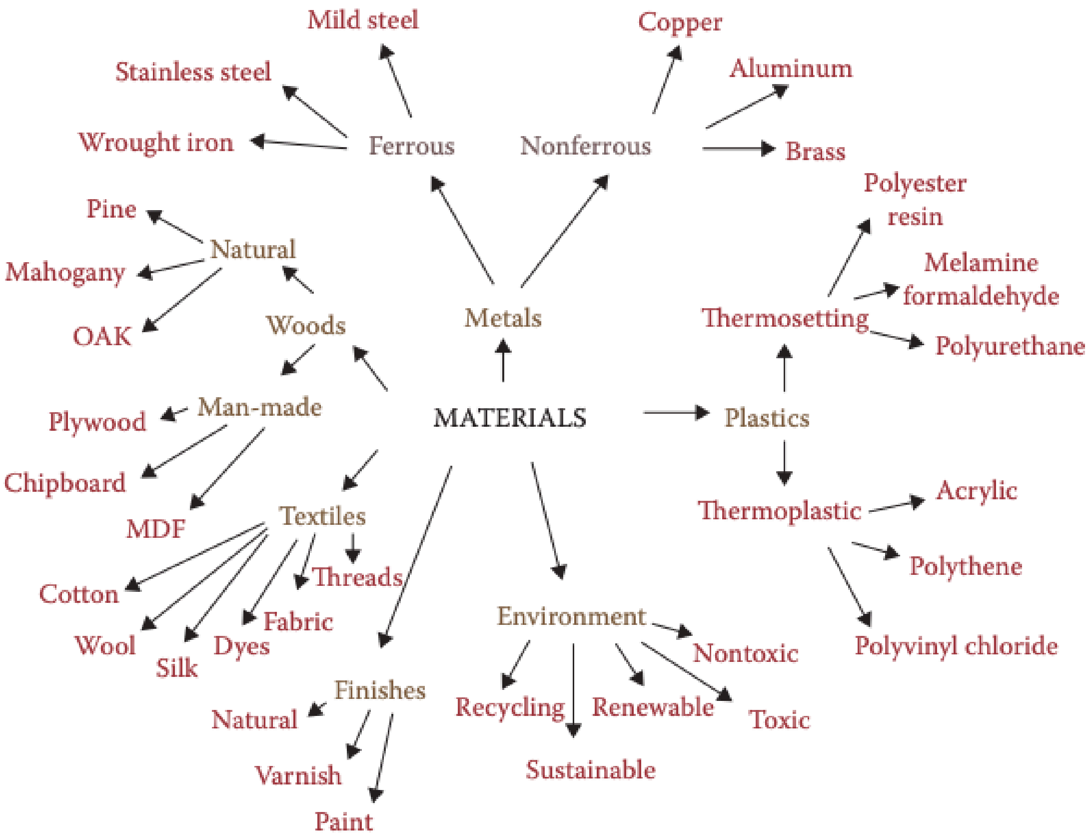


Figure D.6: Material types that are used for marine applications (Srinivasan Chandrasekaran, 2016)

D.7. Materials for artificial structures

A list, functioning as an example to what is possible in artificial structures can be found in the following figure.

Material	Number of citations
Concrete	79
Rock, stone, boulders, gravel, etc.	29
FADs	17
Offshore platforms	16
Tyres	15
Stabilised ash waste, harbour mud	14
Plastic, PVC, etc.	12
Vessels, barges, shipwrecks	11
Wood, trees, etc.	11
Breakwaters, coastal structures	12
Steel, metal	10
Rope, netting	9
Automobiles, train cars	6
Unspecified mix of materials	6
Review of wide range of materials	13
Other materials	18
Unspecified	31
Total	309

Figure D.7: Type of material used in artificial structures with indicated number of citations (Baine, 2001)

D.8. Questionnaire soft engineering

Within soft engineering (dredging), management questions and monitoring techniques arise. A structured questionnaire should be executed by the following figure.

Question	Technique	Description	Advantages/ Disadvantages	Data collected
Is coral likely to be impacted by dredging or material relocation?	Scoping Risk Modelling Baseline	Search of existing information Meetings	Scoping and risk assessment meetings focus all stakeholders on key issues and mitigation Modelling provides visual options but requires good information, and if environment is variable, it may be inaccurate (up to 300 %, Morris, 2004)	Presence/absence of coral Scale and risks of works on coral Wind, wave, currents, turbidity Options
What is the area or species impacted?	Quantitative surveys, maps at impact and controls Risk assessment Satellite photos	Field surveys to investigate impact and possible control sites	Surveys useful for small areas (10's to 100's metres) Satellite photos useful for large area (km's)	Percentage cover and diversity of coral at several locations
What are the communities views?	Consultation	Brochure, letter, meetings, media	Have all key stakeholders been consulted? Have they been involved in decisions?	Perceptions, values, community activities, existing use
How can impacts be minimised?	EMP Modelling Management Reference Group Rehabilitation Risk assessment	Regulatory tools such as permit Adaptive tools such as MRG Project refinement / redesign	Changes and unpredicted impacts will occur Need decision-makers to work in partnership with developer Managers input into acceptable levels	Options for works impacts on environmental, economic and other values
Are the predicted impacts in the EIA accurate?	Modelling verification Monitoring	Computer printouts, reports Field data on realised response	Monitoring may be costly (often 0.5-10% of construction costs) Provides feedback for continual improvement Essential for managers and community	Comparison of EIA hypothesis with what happened
Has the dredging complied with all legislation, permits?	ESS Auditing Partnership	In-house or independent review or audit	Transparent and adaptable process	What has happened?

Figure D.8: Questions for management strategy of coral reef ecosystem related to dredging works (A. Smith et al., 2007)

D.9. Gardening techniques

This table gives insight in different materials for gardening techniques. This is needed to provide information per material about the effects, time of development etc. for the user.

			Coral Materials	
Points for Consideration	*Branches*	*Small Colonies*	*Coral Larvae*	**Nubbins*
General ecological impact	Negative; replacement of established genotypes with ramets	Positive; rescuing genotypes settled in areas subjected to frequent disasters	Highly positive; increasing survivorship of sexual recruits by several orders of magnitude	Negative; development of monocultures
Effect on survivorship	Negative; increasing colony mortality with pruning	Positive; survival of genotypes supposed to die in place of origin	No effect	Minimal negative impact resulting from limited pruning protocol used
Effect on reproductive activity	Negative effects on donor colonies; no effect on isolated branches	No documented effects	No documented effects	Unknown
Effect on colony pattern formation	Negative; takes considerable time for proper patterning of lost parts	No effect	No effect	Moderate impacts resulting from the limited pruning protocol used
Amount of material derived from donor colonies	Moderate; each donor colony supplies several units	Minimal; only a single unit by each genotype	Few gravid colonies may produce high numbers of larvae	Few branches from a donor colony may provide hundreds of nubbins
Availability of type material	Year round	Following the reproductive season	Only during reproductive season	Year round
Contribution of material to the species genetic pool	Reduces genetic heterogeneity	No effect	Increases genetic heterogeneity	Highly reduces genetic heterogeneity
Potential biomass added to the reef	Moderate; few added colonies per genotype	Moderate to high, depending on number of rescued colonies	Significantly higher than natural recruitment rate	High; large numbers of added colonies per donor genotype
Transplant survivorship	Variable, according to conditions	High	Low, but several orders of magnitude higher than under natural conditions	High
Transplant growth rate	Moderate	Fastest	Fast	Lowest
Estimated mariculture period	>5 years	2 years	4—5 years	Longer
Working sites	All *in situ*	All *in situ*	*Ex situ* followed by *in situ*	*Ex situ* followed by *in situ*
Manpower	Low at pruning and transplantation and during nursery maintenance	Low at transplantation and during nursery maintenance	High at the stages of larval collection and *ex situ* maintenance; low thereafter	High at all phases
Operational costs	Low	Low	High	High
Priority of use	Recommended for cases where coral fragments are already scattered on reef bottom with low recovery rates	Highly recommended for reefs with areas subjected to frequent disasters	Highly recommended where *ex situ* facilities and manpower are available to support larval collection and maintenance protocols	Recommended where coral materials, especially branches, are limited in quantities

* From Rinkevich and Shafir (2000); Shafir et al. (2001).

Figure D.9: Four type of gardening techniques (Epstein et al., 2001)

D.10. Nursery types

Type of nurseries (floating and fixed), functioning as examples for the user of this method. However, the shape/type of nurseries depend on the specific location and location characteristics.

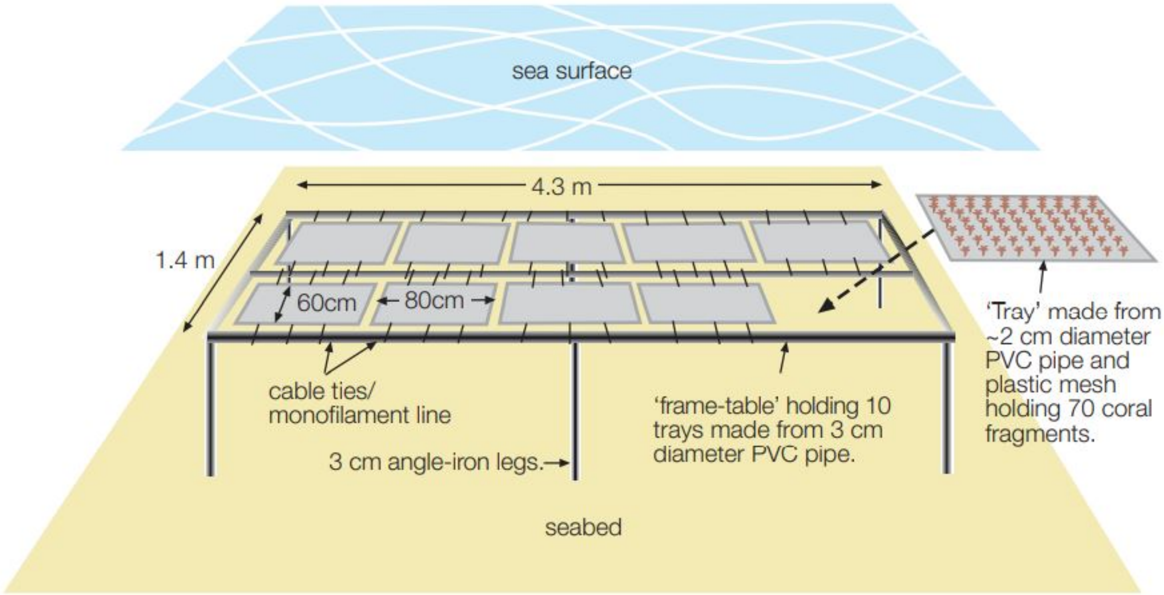


Figure D.10: Fixed tray nursery design that rears towards 700 coral fragments (Shaish et al., 2008; Edwards and Gomez, 2010)

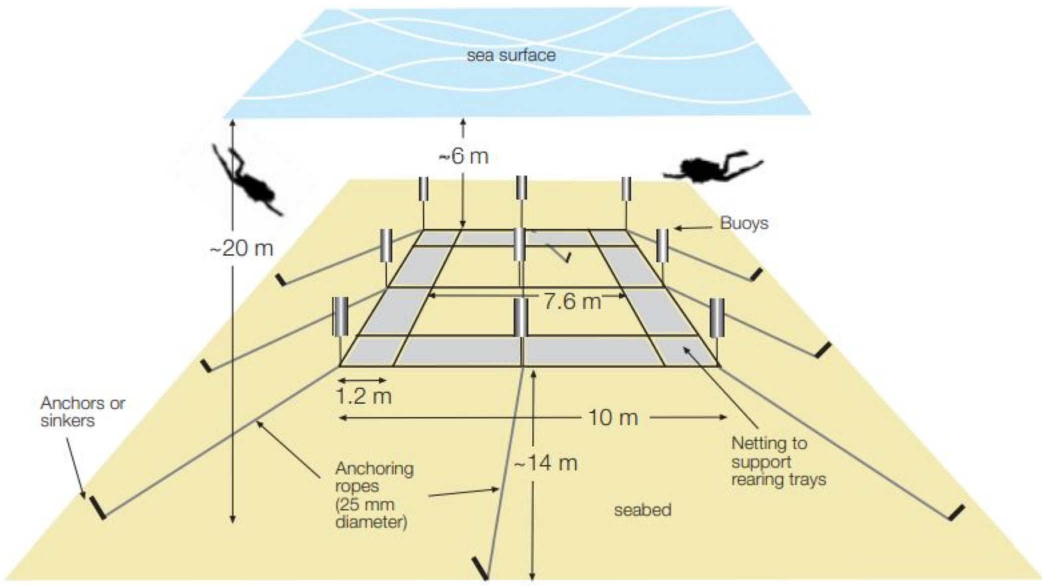


Figure D.11: Large floating nursery towards 10.000 rearing per year (Shafir and Rinkevich, 2008; Edwards and Gomez, 2010)

D.11. Coral nursery photograph

Here, I took a picture of a coral nursery in the Caracas baai in Curacao. This picture is added to the appendix with the aim to give an example of a possible in-situ coral nursery.

Figure D.12: Coral nursery in Curacao, caracas baai (next to the old jetty of shell)

D.12. Recreational values coral reefs per region

The values of coral reefs per region, activity and assessment method are provided in the following figure. The aim is to provide an indication of coral values and check if the value of coral reefs in a region is possible high or lower and what activities are around coral reefs.

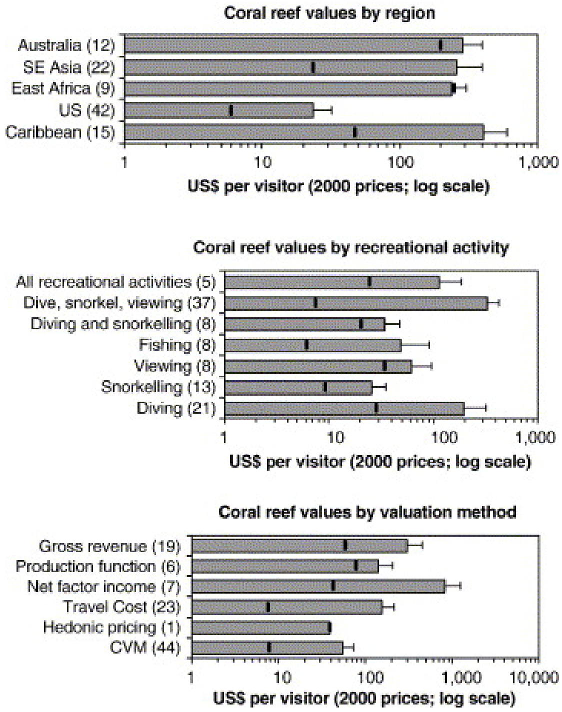


Figure D.13: Recreational values of coral reefs per region, activity and assessment method (Brander et al., 2007)

D.13. Restoration costs

The costs of coral restoration techniques provide indications what possible techniques could cost. This can be used to estimate costs for restoration techniques. However, the costs of restoration techniques are highly dependent on the area and species.

Restoration technique	Restoration cost (2010 US$/ha)			
	n	Median (± SD)	Minimum	Maximum
Coral gardening	3	351,661 (± 136,601)	130,000	379,139
Coral gardening - Nursery phase	5	5,616 (± 22,124)	2,808	55,071
Coral gardening - Transplantation phase	2	761,864 (± 1,033,831)	30,835	1,492,893
Direct transplantation	21	73,893 (± 867,877)	4,438	3,680,396
Enhancing artificial substrates with an electrical field	0			
Larval enhancement	6	523,308 (± 1,878,862)	6,262	4,333,826
Substrate addition - Artificial reef	15	3,911,240 (± 36,051,696)	14,076	143,000,000
Substrate stabilisation	8	467,652 (± 9,015,702)	91,052	26,100,000

Figure D.14: Relative costs in US $ per ha. n is amount of observations in literature. (Boström-Einarsson et al., 2018)

D.14. Armour with gutters

Example of armour units with processed surfaces, in this case with gutters to function as an example of what belongs to the possibilities.

Figure D.15: Armour units made of concrete, with gutters on surface (Akakura, 2005).

D.15. Pictures coral on breakwater

Overview of corals occurring at the breakwater. This is needed to investigated what species are able to grow, which should better be protected and what possible actions/recommendations could be executed.

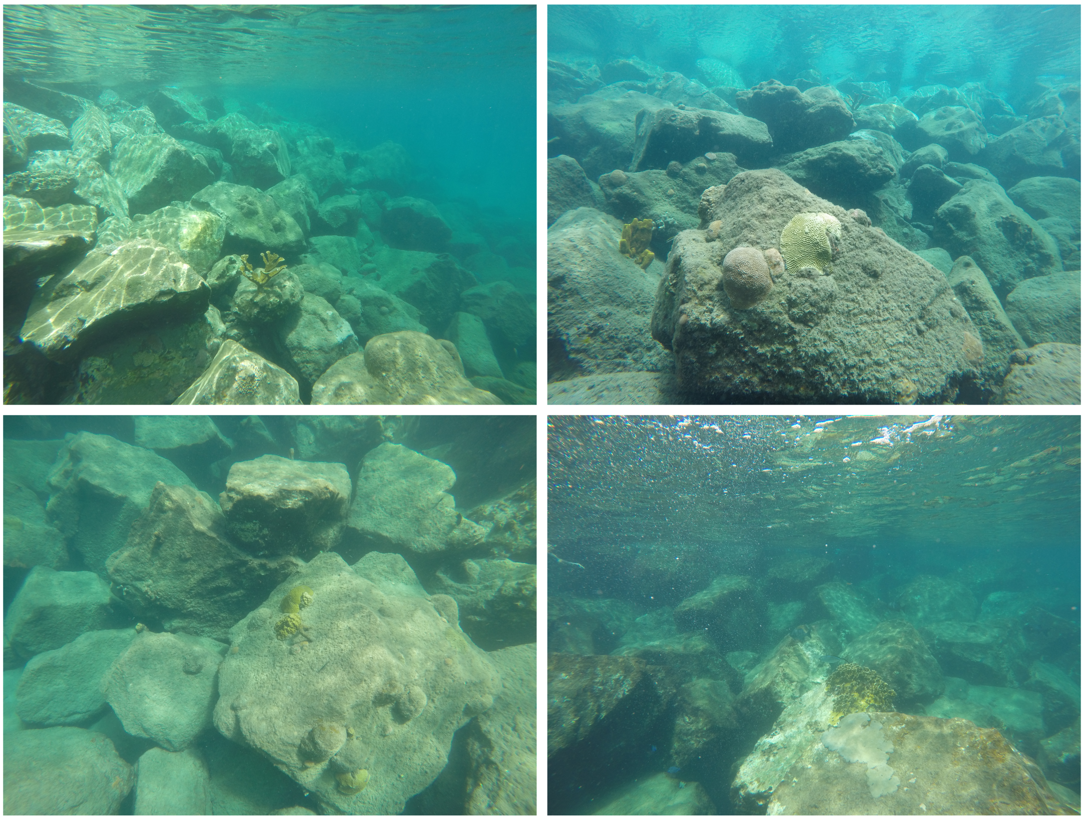


Figure D.16: Some of the pictures that were taken during coral field observations at the breakwater of the harbour of St. Eustatius. On the left upper picture; Acropora palmata is photographed. Right upper photo: Siderastrea siderea and pseudodiploria strigosa. Bottom Left: Porites astrieodes and Porites strigosa. Bottom right: Millipora complanata.

D.16. Ships in Sint Eustatius

A table with ships occuring in the harbour of St Eustatius. This provides an overview of types, capacity and frequency to take into account for the harbour expansion.

	Capacity	Frequency	Duration of stay
Cargo vessels			
Inter-island cargo vessels	100 – 300 tons (28 TEU)	250 per year	< 1 day
Sand and gravel vessels	1,500 – 2,000 tons	4 to 6 per year	24 hours
Cement ships	2,000 tons	5 to 6 per year	1 day
General cargo vessels (blocks)	700 tons	8 per year	1 day
Auxiliary vessels			
Tug, pilot, emergency response and crew boats	variable	> 10 per day	< 1 hour
Passenger vessels			
Inter-island ferries	20 to 150 PAX	1 per week	< 1 day
Cruise ships	100 – 300 PAX	2 per year	2 days
Luxury yachts	10 - 20 PAX	6 per year	3 days
Sailing yachts	6 PAX	450 per year	1 day

Figure D.17: Ships occurring in the harbour of St Eustatius according to Kateman and Bos (2010)

D.17. Design original breakwater

In this part, the design of the current breakwater can be found. This is needed to become acquainted with the current design in order to integrate the new infrastructure design of the breakwater extension.

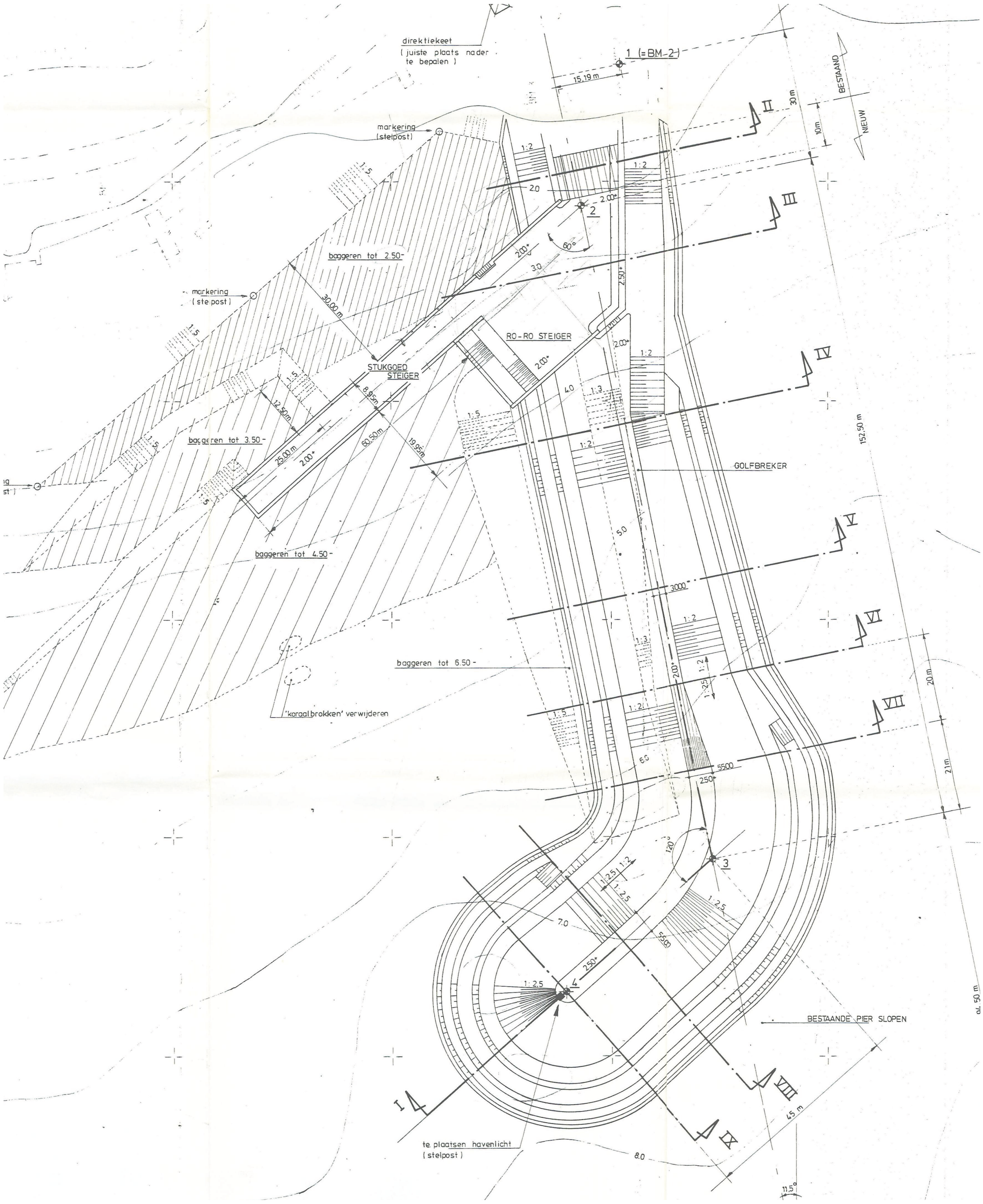


Figure D.18: A drawing of the top view of the design of the current breakwater, build between 1993 and 1995 (D, 1992).

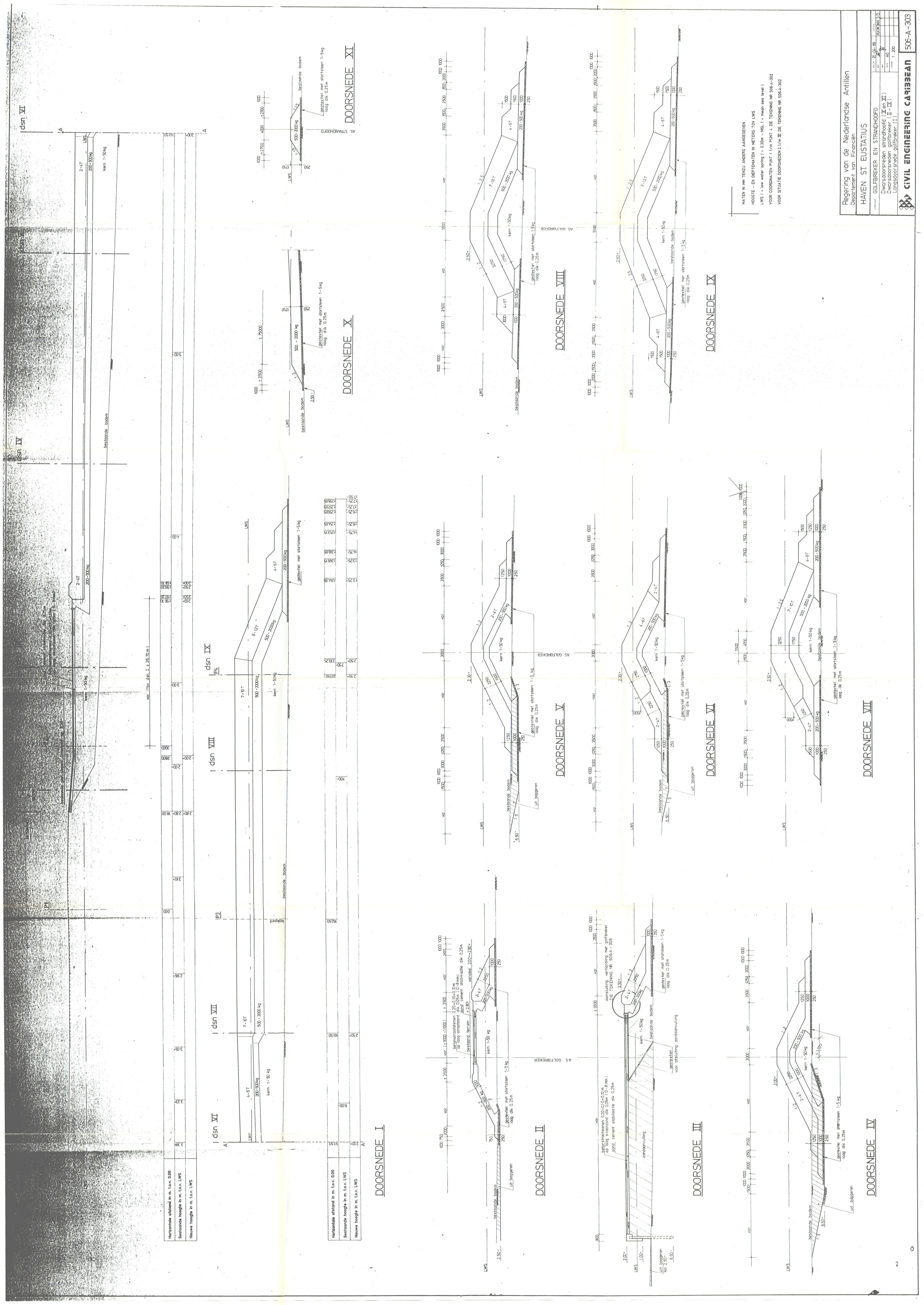


Figure D.19: Cross-sections of the design of the current breakwater (D, 1992).

D.18. Data collection Sint Eustatius

Below, graphs are presented to illustrate data acquired from literature or measurement devices to analyse the location.

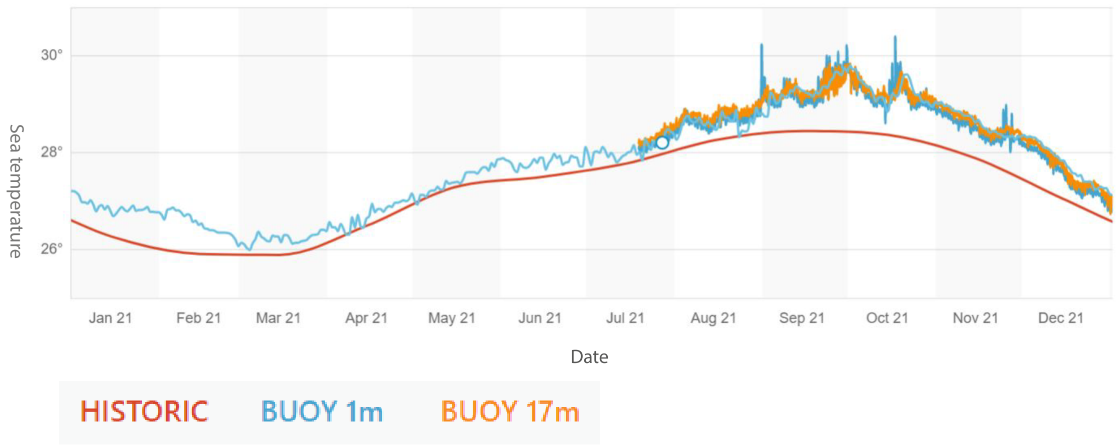


Figure D.20: Temperature in °C measured with a buoy from Stenapa on the SW side of Statia (https://aqualink.org/sites/978).

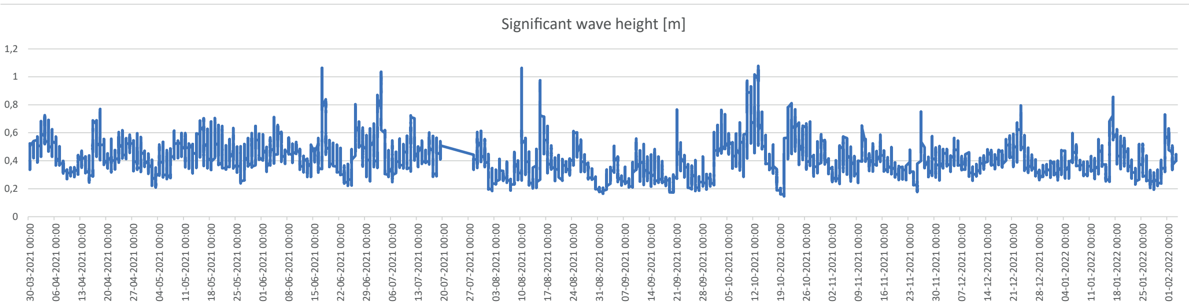


Figure D.21: Significant wave height (Hs) measured with a buoy from RWS in oranjebaai. https://obscape.com/portal/live

Figure D.22: Significant wave height (Hs) measured by a buoy from Stenapa on the SW side https://aqualink.org/sites/978.

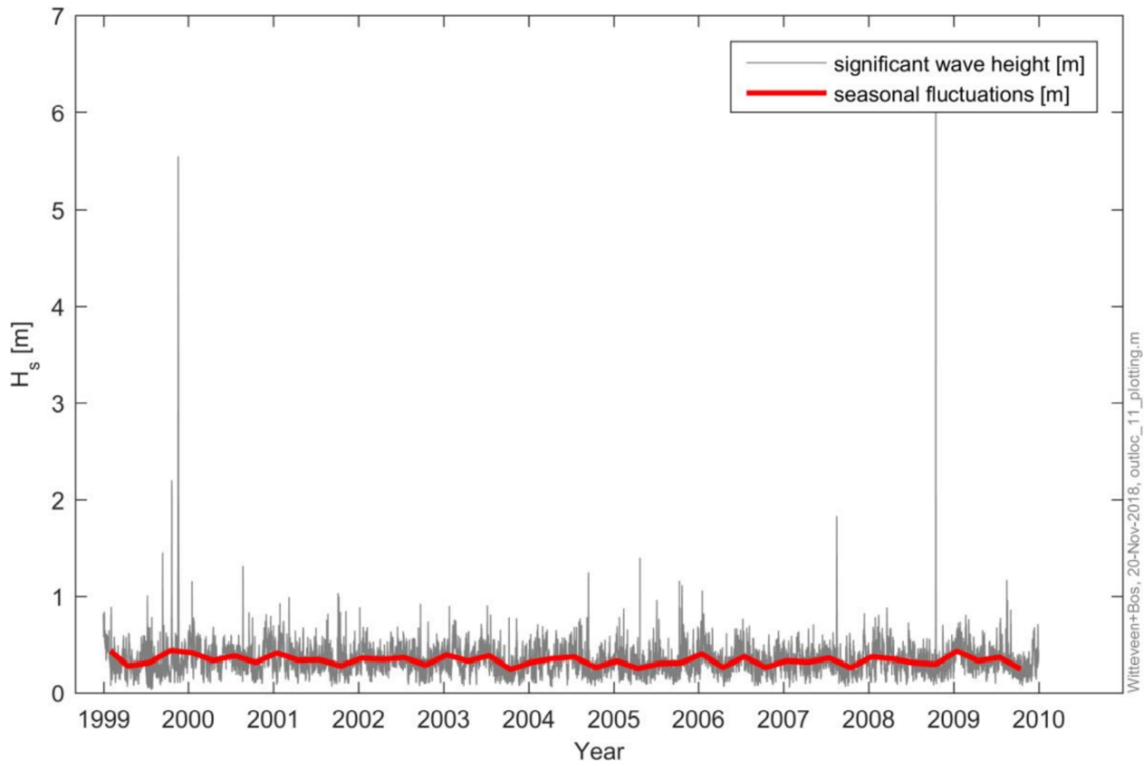


Figure D.23: Seasonal fluctuations of H_s from 1999 to 2010 (van der Leer et al., 2018)

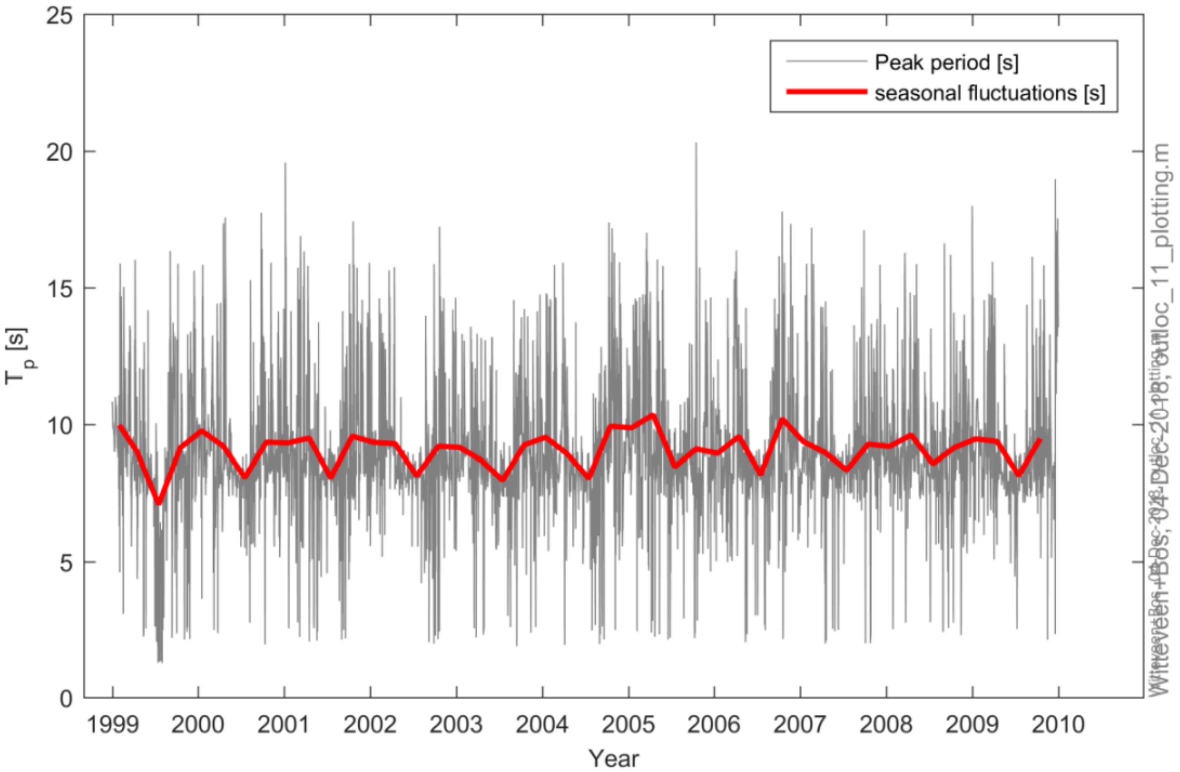


Figure D.24: Seasonal fluctuations of T_p from 1999 to 2010 (van der Leer et al., 2018)

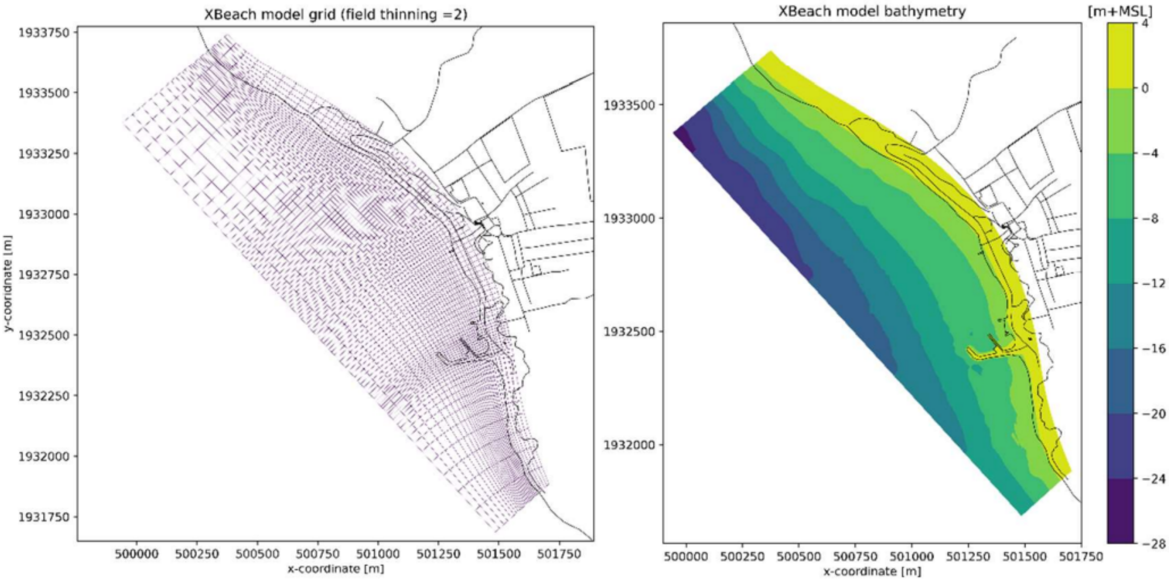


Figure D.25: Bathymetry of statia harbour and environment (van der Leer et al., 2018).

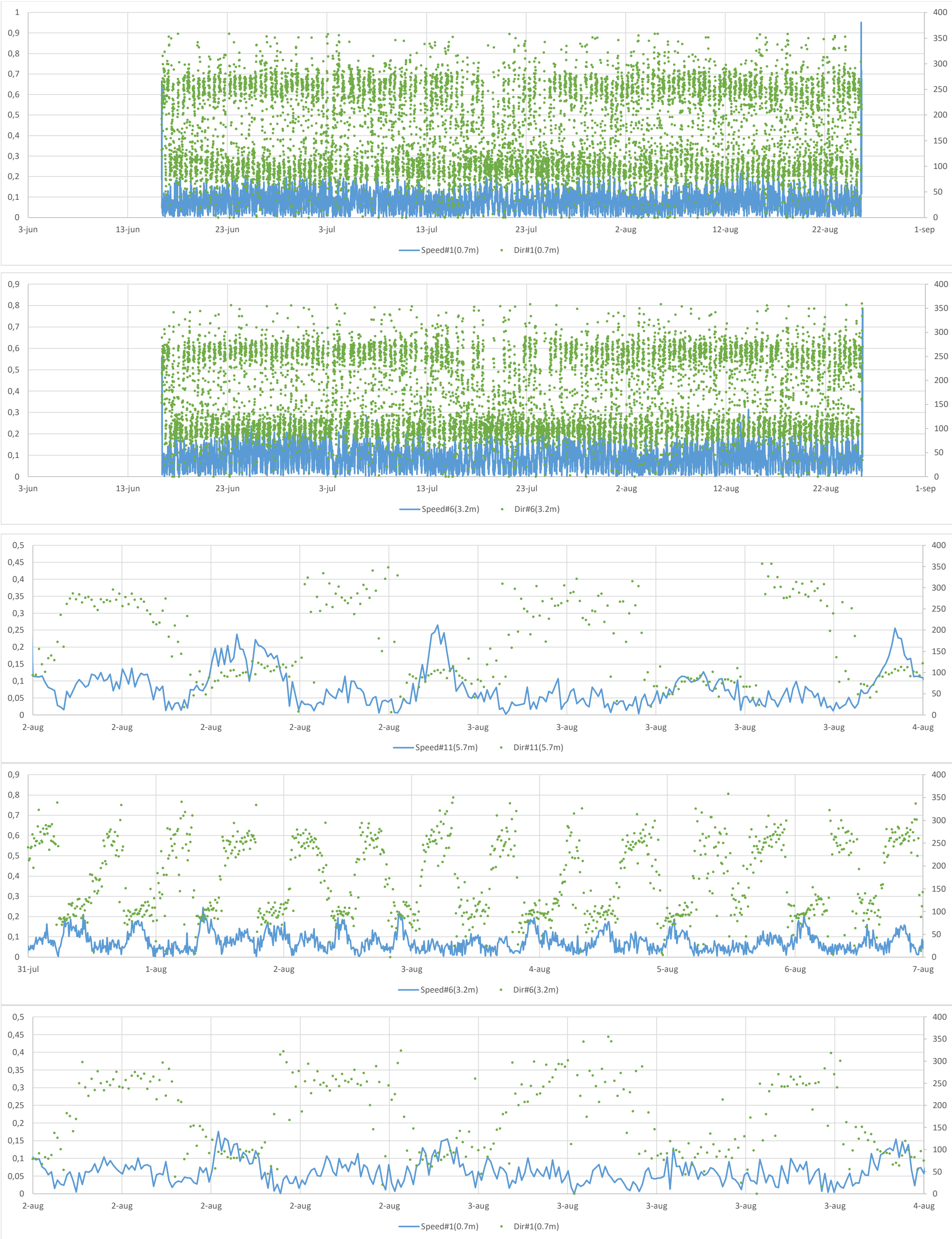


Figure D.26: Flow velocity measurement data on the SW side of Statia, executed with an ADCP.

D.19. Coral consumers

Below, a list of coral consumers is provided and categorised. This list is included to check what possible coral consumers could be in a region, how they feed etc. This is needed to protect corals against possible over consumption.

Taxa	Region	Feeding mode	Consumption rate	Style	Coral prey	Literature cited
Invertebrates (51)						
Annelida (1)						
Hermodice carunculata	A, P, Q	F	12.9 $cm^2\ d^{-1}$	T	Acr, Mil, Ocu, Por	1,2
Arthropoda, Crustacea (9)						
Alpheus lottini	B, J	F		M	Poc	3
Aniculus elegans	B	F	1.24 g (dry wt) d^{-1}	T, S	Poc	4
Calcinus obscurus	B			T, S		
Pyrgoma monticulariae	G, M, N	O		T		5
Tetralia glaberrima	E, F, J	O		T, M	Acr, Ser	6
Tetralia cavimana	F, I, J	O		T, M	Acr	7
Trapezia cymodoce	B, F, G, I, J	O	1.3–1.5 $cm^2\ d^{-1}$	T, M	Poc, Sty	6,8
T. ferruginea	B, E, F, G, J	O		M	Poc	4,6,9
Trizopagurus magnificus	B	F	10.3 mg d^{-1}	T, S	Poc	4
Echinodermata, Asteroidea (10)						
Acanthaster ellisii	B	F	145 $cm^2\ d^{-1}$	T	Pav, Poc, Por, Psa	10
A. planci	B, E, F, G, H	F	116–187 $cm^2\ d^{-1}$	T	Acr, Gar, Monti, Poc	11-15
Culcita novaguinaeae	C, D, E, G, N	F	28 $cm^2\ d^{-1}$	T	Acr, Poc	16
C. schmideliana	L	F		T	Acr, Gal, Gon	17
Echinaster purpureus	L	F		M	Por	17
Linckia laevigata	L	F		M	Por	17
Nardoa variolata	L	F		M	Por	17
Nidorellia armata	B	F		T	Pav	18
Pentaceraster cumingi	B	F		T	Psa	12
Pharia pyramidata	B	F		T	Poc	10,18
Echinodermata, Echinoidea (11)						
Astropyga radiata	L	F		T		19
Diadema antillarum	A	F		T, S	Acr, Aga, Mad, Monta, Por	20,21
D. setosum	L	F		T		19
Echinothrix calamaris	L	F		T		19
Eucidaris thouarsii	B	F	0.47–1.83 g $m^2\ d^{-1}$	T	Pav, Poc	11, 18, 22
Echinometra mathaei	E, L, M	F		T		19
E. viridis	A	F		T		23
Echinoneus cyclostomus	L	F		T		19
Microcyphus rousseaui	L	F		T		19
Stomopneustes variolaris	L	F		T		19
Tripneustes gratillia	L	F		T		19

Figure D.27: Part 1 of list of species that consume coral. Listed, studied and categorised by Rotjan and Lewis (2008). Region numbers can be compared with Figure C.1. Feeding mode consists of corralivores who are fully dependent on live coral consumption; 'obligate' (O) and 'facultative' (F), who also eat coral but also eat other products. The Style indicates what part of corals is consumed. T = Tissue, M = Mucus, S = Skeleton. The coral prey indicates what species are prone to consumption per corallivore (Rotjan & Lewis, 2008) See for corresponding references; Appendix 2 of the same article.

Taxa	Region	Feeding mode	Consumption rate	Style	Coral prey	Literature cited
Mollusca (20)						
Aeolidia edmondsoni	C	O		T	Por	24
Phestilla melanobrachia	E, G, F	O			Tur	25, 26
P. minor	E, L	O			Por	27
P. sibogae (*P. lugubris*)	C, E, F, G	O	6.4 $cm^2 d^{-1}$	T	Por	27, 28
Coralliophilla abbreviata	A	O	0.08–16 $cm^2 d^{-1}$	T	Acr, Aga, Col, Dic, Dip, Eus, Fav, Hel, Mad, Mea, Monta Myc, Por Sid	29–32, 83
C. violacea	D, E, G, N		0.25 $cm^2 d^{-1}$	T	Por	25, 33
C. caribaea	A			T	Acr, Por	31, 34
Drupella cornus	C, E, F, H, I, N	O	2.6 $cm^2 d^{-1}$	T	Acr, Monti, Poc, Por, Ser, Sty	25, 35–38
D. elata	G, H	O		T	Acr, Monti, Poc, Por	37, 39
D. fragum	E, H	O		T	Acr, Monti, Poc, Ser, Sty	35, 37, 39, 40
D. rugosa	E, F, G, H	O	137–229 min d^{-1}	T	Acr, Monti, Poc, Ser, Sty	37, 39, 40
Epitonium ulu	C			T	Fun	41
Habromorula spinosa	H					42
Jenneria pustulata	B	O	0.8 g d^{-1}	T	Poc, Por, Sid	4
Latiaxis hindsii	B			T	Poc	18, 43
Muricopsis zeteki	B			T	Poc	18, 43
Pedicularia decussata	A			T	Sol	44
Philippia radiata	C	F		T	Por	45
Quoyula madreporarum	B, E, G, L, M, N	O		T	Monti, Poc, Por, Ser, Sty	25, 46
Q. monodonta	B, E, M	O	0.64 $cm^2 d^{-1}$	T	Monti, Poc, Por, Ser, Sty	43
Vertebrates (114)						
Chordata, Tetraodontiformes						
Tetraodontidae (8)						
Arothron hispidus	B, C, E, K, L, M, N	F		T, S	Poc	4, 47, 48
A. meleagris	B, C, D, E, G, H, K, L	F	10.13 – 16.38 g d^{-1}	T, S	Acr, Poc, Por, Pav, Psa, Monti	4, 11, 48–50
A. nigropunctatus	E, F, H, I, K, L, M, N	F	1.73 bites min^{-1}	T, S	Acr, Pav, Poc, Por	47, 51, 52
A. stellatus	D, E, F, G, H, I, K, L, M, N	F		T, S		47, 48
Canthigaster amboinensis	B, C, D, E, F, G, H, M, N	F	3.7 % live coral diet	T, S		48, 53
C. jactator	C	F	1.0 % gut contents	T, S		53
C. solandri	C, E, G, K, L, M, M, N	F	11.1 % live coral diet	T, S		53-55
C. valentini	B, E, F, G, H, L, N	F	0.06 – 3 bites min^{-1}	T, S	Pav, Poc, Por	52
Balistidae (7)						
Balistapus undulatus	D, E, F, G, I, L, M, N	F	1.87 bites min^{-1}	T, S	Pav, Poc, Por	47, 48, 52
Balistes polyepis	B, C	F		T, S	Pav, Por	4
B. vetula	A, P	F	0.2 % gut contents	T, S		56
Balistoides viridescens	G, M, N	F		T, S		47
Melichthys niger	A, B, C, E, G, H, L, M, N	F	0.6 % gut contents	T, S	Col	56
Rhinecanthus aculeatus	G, I, K, L, M, N	F		T, S		48
Sufflamen verres	B	F		T, S	Poc, Por, Pav	4
Monacanthidae (5)						
Amanses scopas	E, F, G, H, I, L, N	O		T, S		48
Cantherhines dumerilii	B, D, E, F, G, L, M, N	F		T, S	Acr, Poc, Monti, Lep, Por	47, 48, 50
C. pullus	A	F	0.7 % gut contents	T, S		56
C. sandwichiensis	C, D	F		T, S		48
Oxymonacanthus longirostris	E, F, G, H, L, M, N	O	10.5 bites min^{-1}	M, T	Acr	47, 48, 51, 57

Figure D.28: Part 2 of list of species that consume coral. Listed, studied and categorised by Rotjan and Lewis (2008). Region numbers can be compared with Figure C.1. Feeding mode consists of corralivores who are fully dependent on live coral consumption; 'obligate' (O) and 'facultative' (F), who also eat coral but also eat other products. The Style indicates what part of corals is consumed. T = Tissue, M = Mucus, S = Skeleton. The coral prey indicates what species are prone to consumption per corallivore (Rotjan & Lewis, 2008) See for corresponding references; Appendix 2 of the same article.

Taxa	Region	Feeding mode	Consumption rate	Style	Coral prey	Literature cited
Chordata, Perciformes						
Gobiidae (1)						
Gobiodon citrinus	E, F, G, H, I, L, N	O	99% gut contents	T, M	Acr	51
Labridae (8)						
Coris aygula	G, N, O	F	0.13 bites min^{-1}	T	Pav, Poc, Por	52
Diproctacanthus xanthurus	E, F, G	F		T, S		47
Gomphosus caeruleus	N	F	0.13 bites min^{-1}	T	Pav, Poc, Por	52
Labrichthys unilineatus	E, F, G, H, L, M, N	O	1.9 bites min^{-1}	T, S	Acr, Monti	47, 48, 51, 58
Labropsis australis	E, F	O		T, S		47, 48
L. polynesica	E	O		T, S		48
L. xanthonota	E, F, G, H, L, N	O		T, S		48
Thalasomma lunare	E, F, G, H, I, L, N	F	0.13 bites min^{-1}	T	Pav, Poc, Por	52
Blennidae (1)						
Exallias brevis	G, H, K, L, M, N	F	72% gut contents	T, S	Acr	47, 51
Scaridae (21)						
Bolbometopon muricatum	E, F, G, H, I, L, N	F	6.09 bites min^{-1}	T, S	Acr, Poc, Por, Mont	47, 48, 59–61
Calotomus carolinus	B, C, D, E, F, G, H, L	F	0.13 bites min^{-1}	T	Pav, Poc, Por	52
Cetoscarus bicolor	G, L	F	0.4 bites min^{-1}	T, S	Por	62
Chlororus gibbus	I	F	1.1 bites min^{-1}	T, S	Por	48, 62, 63
C. microrhinos	E, F, G, H	F		T, S		48, 63
C. sordidus	E, F, G, I, K, L, M, N	F	2.2 bites min^{-1}	T, S		48, 62
C. strongylocephalus	G, L, N	F	0.26 bites min^{-1}	T, S	Pav, Poc, Por	48, 52
Scarus coelestinus	A	F	0.2% gut contents	T, S		56
S. frenatus	E, F, G	F	< 1% live coral diet	T, S	Por	84
S. guacamaia	A	F		T, S		
S. ghobban	B, D, E, F, G, H, I, K, L	F		T, S	Por	
S. perrico	B	F		T, S	Poc	4
S. perspicillatus	C	F		T, S	Por	61
S. rivulatus	E, F, G, H, O	F	1.7 bites min^{-1}	T, S	Por	62
S. taeniopterus	A	F		T, S	Mad, Por	64
S. trispinosus	R	F	0.8% live coral diet	T, S	Fav, Muss, Sid	49
S. vetula	A	F		T, S	Monta, Sid	64, 65
S. viridifucatus	L	F	0.2 bites min^{-1}	T, S	Pav, Poc, Por	52
Sparisoma aurofrenatum	A	F	0.2% gut contents	T, S	Monta, Por, Mad	56, 64, 65
S. amplum	R	F	8.1% live coral diet	T, S	Fav, Muss, Sid	49
S. viride	A	F	25 cm^2 d^{-1}	T, S	Col, Por, Monta, Sid, Dip, Aga	65–67
Pomacanthidae (2)						
Centropyge multispinus	L	F	0.2 bites min^{-1}	T	Pav, Poc, Por	52
Pomacanthus semicirculatus	E, F, G	F	0.13–0.26 bites min^{-1}	T	Pav, Poc, Por	52
Pomacentridae (7)						
Cheiloprion labiatus	F, G, H	F	93% gut contents	T, S	Acr	51
Neoglyphidodon melas	I, G	F		T		51
Pomacentrus leucostictus	A	F	1.5% gut contents	T		56
P. variabilis	A	F	1.7% gut contents	T		56
Plectroglyphidodon dickii	D, E, F, G, H, L	F	37% gut contents	T	Acr. Poc	51
P. johnstonianus	C, D, F, G, H, L	F	96% gut contents	M, T	Acr	51
Stegastes planifrons	A	F	0.6% gut contents	T	Acr, Monta	56, 68
Zanclidae (1)						
Zanclus canascens/ cornutus	B, C, D, E, F, G, L, M, N	F	0.53 bites min^{-1}	T, S	Pav, Por, Poc	52
Chaetodontidae (53)						
Chaetodon aculeatus	A	F	0.43 bites min^{-1}	T	Aga, Monta, Sid	69
C. andamanensis	K, M, N	O		T	Acr	70
C. aureofasciatus	E, F, O	F		T		47, 71
C. auriga	E, G, H, I, L, N	F	18–60% gut contents	T		47, 51, 71, 72
C. auripes	H	F	12% gut contents	T		51
C. austriacus	I	O	4.4–6.4 bites min^{-1}	T	Acr, Fav, Monti, Poc, Por, Ser, Sty	71, 73–75

Figure D.29: Part 3 of list of species that consume coral. Listed, studied and categorised by Rotjan and Lewis (2008). Region numbers can be compared with Figure C.1. Feeding mode consists of corralivores who are fully dependent on live coral consumption; 'obligate' (O) and 'facultative' (F), who also eat coral but also eat other products. The Style indicates what part of corals is consumed. T = Tissue, M = Mucus, S = Skeleton. The coral prey indicates what species are prone to consumption per corallivore (Rotjan & Lewis, 2008) See for corresponding references; Appendix 2 of the same article.

Taxa	Region	Feeding mode	Consumption rate	Style	Coral prey	Literature cited
C. baronessa	E, F, G, H	O		T	Acr	47, 51
C. bennetti	D, E, F, G, H, L, M	O		M, T		47, 51
C. capistratus	A	F	5.4 bites min^{-1}	T	Aga, Sid, Mad, Myc	69, 71
Chaetodon citrinellus	C, D, E, G, H, L, M, N	F	15–19% gut contents	T		47, 51, 71, 72
C. ephippium	C, D, E, G, H	F	19–26% gut contents	T		51, 71, 72
C. falcula	L	F	0.26 bites min^{-1}	T	Pav, Poc, Por	52, 71
C. flavirostris	D, E, F	F		T		47, 48
C. guttatissimus	L	F		T		71
C. kleinii	C, E, G, H, I, L, N	F	3% gut contents	T		47, 51, 71
C. larvatus	I	O	10 bites min^{-1}	T		76
C. lineolatus	E, G, I, L, N	F		T		47
C. lunula	E, F, G, L, N	F	0.2 bites min^{-1}	T	Pav, Poc, Por	47, 52, 71
C. lunulatus	C, E, F, G, H, O	O		T		48
C. madagascariensis	L	F		T		71
C. melannotus	E, F, G, H, I, L, N	F	42% gut contents	T		47, 51, 71
C. mertensii	D, E, F, G, H, L	F		T		71
C. mesoleucos	I	F	6 bites min^{-1}	T		76
C. meyeri	F, G, H, L, M, N	O		T		47, 48
C. multicinctus	C	F	21.8 bites min^{-1}	T	Poc, Por	71, 77
C. ocellatus	A	F		T	Acr	31
C. octofasciatus	G, H	O		T	Acr	78
C. ornatissimus	E, F, G, N, O	O	2.08–5.62 bites min^{-1}	M, T	Monti, Poc, Por	51, 71, 79
C. oxycephalus	G, N, O	F		T		47
C. pelewensis	D, E, F	F	58.9% gut contents	T		47, 71, 72
C. plebeius	E, G, H, O	O		T	Acr	47, 51, 71
C. punctatofasciatus	M, N	F		T	Poc	47, 80
C. quadrimaculatus	C, D, E, G, H	F	27.5% gut conents	T	Poc	48, 71, 72
C. rafflesii	E, F, G, H, N	F	10% gut contents	T		47, 51
C. rainfordi	F	F		T		71
C. reticulatus	E, F, G, H	O		T		47, 71
C. semilarvatus	G, H, I, N	O	6 bites min^{-1}	T		76
C. smithi	D	F		T		48
C. speculum	E, F, G, H, N, O	F	75% gut contents	T		47, 51
C. striatus	A	F		T	Acr	31
C. triangulum	N	O		T		71
C. trichrous	D	F		T		48
C. trifascialis	C, E, G, H, I, L, M	O	4.58–10.74 bites min^{-1}	T	Acr, Poc, Por, Monti	51, 71, 78, 81
C. trifasciatus	C, D, E, G, H, I, L, M	O	1.1–3.1 bites min^{-1}	T	Acr, Pav, Poc, Por, Monti	47, 51, 52, 71, 79
C. ulietensis	E, G, H	F	10–69% gut contents	T		51, 72
C. unimaculatus	C, D, E, G, H, L, N, O	–	4.9–7.2 bites min^{-1}	T	Monti, Poc	47, 51, 71, 82
C. vagabundus	E, G, H, L, M, N	F	8–18% gut contents	T		51, 71, 72
C. xanthocephalus	L	F		T		71
Forcipiger flavissimus	B, E, L	F	6.2% gut contents	T		72
Heniochus chrysostomus	D, E, F, G, H, O	F	7.1% gut contents	T		47, 48, 72
H. intermedius	I	F	1.3 bites min^{-1}	T		76
H. singularus	E, G, H	F		T		48
H. varius	E, F, H, N, O	F		T		48

Figure D.30: Part 4 of list of species that consume coral. Listed, studied and categorised by Rotjan and Lewis (2008). Region numbers can be compared with Figure C.1. Feeding mode consists of corralivores who are fully dependent on live coral consumption; 'obligate' (O) and 'facultative' (F), who also eat coral but also eat other products. The Style indicates what part of corals is consumed. T = Tissue, M = Mucus, S = Skeleton. The coral prey indicates what species are prone to consumption per corallivore (Rotjan & Lewis, 2008) See for corresponding references; Appendix 2 of the same article.

E

Glossary

abiotic	Components that do not exhibit life. These types of components influence habitat functions towards self-sustaining ecosystems.
anthropogenic	Covering human influences on nature.
biotic	Involves living organisms.
budding	extra tentacular splitting off of new polyps.
cold water corals	Corals that thrive in deeper colder waters, without the need for sunlight (deep water corals).
colonisation	Settlement and establishment of larvae on substratum, leading to the formation of polyps.
coral development	Coral evolution starting with larvae recruitment, spat, towards juveniles and the formation of adult corals. Including growth in length, biomass and in spatial sense.
coral propagation	Reproduction of coral
coral propagation techniques	Reproduction of coral through human interventions.
deep water corals	Corals that thrive in deeper colder waters, without the need for sunlight (cold water corals).
fines	Sediment particles with small sizes ($\leq$ 0.063 mm)
fission	intra tentacular splitting off of new polyps
framework	A structured display that assists in following the right approach (Roadmap)
gardening	Maintaining coral nursery (ex- or in- situ).
greenfield	(Subsea) land that has not yet been built on but will be used to place a construction on.

juvenile corals	Coral development stage between recruits and coral adults. juveniles < 50 mm (Babcock, 1985).
larvae	postembryonic stage of corals; fertilized gametes.
marine infrastructural works	Hydraulic structures that are used for social purposes.
marine protected areas (MPAs)	Protective management of natural areas according to management objectives.
mitigation	The action of reducing negative impacts of projects on ecosystems, including recovery measures.
nursery	A coral restoration/regeneration unit, belonging to one of the coral propagation techniques. can be placed in- or ex-situ and is maintained by coral gardening.
polyps	Organisms consisting of soft tissue which cover limestone skeletons. They maintain healthy and functioning corals and contain coral genes.
recruitment	Establishment of coral larvae on substratum.
recruits	Established larvae on substratum (<10 mm (Babcock, 1985; Sato, 1985), before turning into juveniles (spat).
rehabilitation	The optimization of functioning of an ecosystem by replacement or repairing interventions of an ecosystem where structural or functioning characteristics are reduced or lost.
reproduction	(A)sexual formation of new polyps by spawning of gametes, budding or fragmentation.
remediation	The action of reversing or stopping ecosystem damage.
restoration	Restoration comes in useful when an ecosystem is degraded. By this human intervention, an attempt is made to ’restore’ the (coral) ecosystem to its original state.
roadmap	A structured display that assists in following the right approach (Framework)
sedimentation	Settlement of suspended solids to form a deposition layer on the bottom surface.
settlement	The process in which floating larvae establish on substratum.
shallow water corals	Corals living in warmer waters, which are dependent on e.g. Sunlight.
spat	Established larvae on substratum (<10 mm (Babcock, 1985; Sato, 1985), before turning into juveniles (recruits).

spawning	The natural process of corals releasing gametes in the water colomn for coral propagation.
suspended sediment (plume)	Cloud of small particles resulting from dredging works or other sediment disturbances.
Suspended Sediment Concentration (SSC)	Non dissolved fine sediments, occurring in the water column.
threshold	Maximum levels coral can tolerate before impacts become apparent.
tolerance value	Maximum levels coral can tolerate before impacts become apparent.
trigger value	Early warning levels that are set below threshold levels.
tropical corals	Corals living in warmer waters, which are dependent on e.g. sunlight.
turbidity	Suspended fine particles causing cloudiness in the water column.
zooxanthellae	Single celled organisms, living in polyps by symbiosis with corals.