Sustainable Port Infrastructure

An interdisciplinary design study of nature friendly banks made of residual material to enhance biodiversity in a port

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Cover image:
Impression of project "De Groene Poort" in the Port of Rotterdam
Magazine Land+Water, volume 10, October 2014, p. 12-14

Sustainable Port Infrastructure

An interdisciplinary design study of nature friendly banks made of residual material to enhance biodiversity in a port

By

S.J. Sangster

in partial fulfilment of the requirements for the degree of

Master of Science
in Civil Engineering

at the Delft University of Technology,
to be defended publicly on Wednesday June 17th, 2015 at 15:00 PM

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Summary

Port locations are often selected to optimize access to land and navigable water. Many ports are therefore situated at the mouth of an estuary or along a coastline. Besides being economically important these locations are also often valuable from a biodiversity point of view. Human interventions along the coast such as port development often do not agree with local environmental processes. These interventions may be a threat to the existence of ecosystems on which our society depends in many ways. Therefore, there is an urging need for port development which is in harmony with nature and that contributes to the functioning of ecosystem services. Sustainable port development is widely regarded as 'the answer'.

This study focusses on two opportunities that can contribute to the sustainability of a port: enhancing biodiversity and the circular economy within a port and its surroundings. Generally, higher biodiversity ensures increased functioning of an ecosystem and thus supports the services an ecosystem provides. Without these services life could not exist. Enhancing the circular economy can help in mitigating the environmental pressure of a port by producing less waste and using less raw material.

A promising measure to enhance both biodiversity and the circular economy at the same time within a port is constructing nature friendly banks made of residual material. Since this is not common practice in ports, it is a relatively unknown topic. The aim of this research is, therefore, to broaden the knowledge base of constructing nature friendly banks made of residual material in a port. Therefore, insight must be gained into:

- stakeholders and their interests in order to understand the system;
- critical design aspects in order to be able to identify criteria for a suitable design.

Interviews with important stakeholders with different backgrounds (Rijkswaterstaat, Port of Rotterdam, Municipality of Rotterdam and WWF) are conducted to gain insight into their interests. The interviews resulted in an increased understanding and knowledge in constructing nature friendly banks made of residual material within a port. Four critical design aspects were identified during these interviews:

1. stability of the design;
2. functioning of the port and its surroundings;
3. circular economy;
4. ecological performance.

Profound insight into the critical design aspects is gained by inspecting them further by obtaining a case study research and a design study. Project "De Groene Poort" in the Port of Rotterdam has been identified as a suitable case for this study. This project aims at establishing nature friendly banks in the Nieuwe Waterweg by using residual material from the port and its surroundings. The Nieuwe Waterweg is unique because of the open connection between the river and the sea, making it an important area for migratory fish. A design concept of a nature friendly bank of project "De Groene Poort" has already been developed. The main elements of this concept are a dam parallel to the bank and a nourishment between the dam and the existing bank. The dam is made of coarse residual material and aims to create sheltered conditions at the shore. The gently sloping nourishment is made of dredged material and creates intertidal area that allows more room for nature compared to the existing, steep banks.

The stability is the first critical design aspect. It applies to the dam, nourishment and subsoil of the design. The port area is a dynamic environment; the governing loads are ship-induced water movements and a semi-diurnal tide. The design of the nature friendly bank has to withstand these loads and integrate with the surrounding functions of the port; the second critical design aspect. The requirements with respect to the functioning of the port and its surroundings apply to the functions: shipping, flood safety and nature and recreation. The design of project "De Groene Poort" must not impose limitations on these functions. In order to define requirements for the third and fourth critical design aspects in-depth research is required as limited information and knowledge is available on ecology in a port and the circular economy in general.

One of the main objectives of project "De Groene Poort" is to enhance the circular economy of the port and its surroundings; the third critical design aspect. The project can enhance the circular economy by acting as a valuable destination for residual material and thereby reducing waste flows and the use of raw materials in the port. Project "De Groene Poort" aims to use two types of residual material as a construction material:

1. coarse residual material (e.g. debris) as a construction material for the dam;

2. dredged material as a construction material for the nourishment.

Besides enhancing the circular economy, using residual material can also benefit the business case of the project by reducing expenses on dumping fees and the purchase of construction material. However, there is a high uncertainty in the availability of coarse residual material. Therefore, the final design must be flexible and adaptive to uncertainties on the fluctuating and underdeveloped market of coarse residual material. With respect to dredged material it is expected that the project imposes a small demand relative to the supply. Therefore, it is not a limiting factor for the design.

Another main objective of project "De Groene Poort" is increasing biodiversity in the port and its surroundings by enhancing the living conditions of migratory fish in the area; the fourth critical design aspect. The Port of Rotterdam is situated in an estuary; an important stepping stone for migratory fish that need time and space in this area to adapt to the changing salinity between the sea and the river. Potentially, this area could be filled with fish like salmon, sturgeon and trout. However, the existing banks in the area are designed to withstand unnatural loads that are the result of intensive shipping, leaving little space for nature to develop. The area is, therefore, lacking food sources and areas for shelter. Project "De Groene Poort" can add value to the port in terms of biodiversity by providing food sources and areas of shelter for migratory fish. In order to define requirements for the final design, habitat requirements of the following groups of indicator species are, therefore, studied:

1. migratory fish;
2. food sources for migratory fish; crustacean/molluscs/polychaetes;
3. shelter for migratory fish; riparian vegetation.

By improving the habitat of these indicator species, the project is expected to improve the overall ecological state of the port. The design requirements with respect to ecology affect the following factors:

1. water movement;
2. substrate;
3. salinity.

Based on the requirements with respect to the critical design aspects, five alternative designs based on the existing design concept have been developed and evaluated in this study. These include a zero state model, three alternatives with dams with a varying crest level and an alternative with only a nourishment along the bank of the Nieuwe Waterweg. It has been investigated if the alternatives enable the conditions suited for the desired ecological state. This has been done by simulating the performance of each alternative with respect to every critical design aspect. The optimum design seems to be a trade-off between the objectives of enhancing the circular economy and the ecological performance. The higher the dam, the better the ecological performance but at the same time the higher the uncertainty in the availability of material. In case a lot of material is available the highest possible dam is the preferred alternative. When less material is available a lower dam is also acceptable in terms of ecological performance. These alternatives are also expected to be stable and impose no limitations on the functioning of the port and its surroundings.

It has been concluded that the project imposes a relatively small demand of dredged material compared to the availability. It is, therefore, expected that using dredged material as a construction material will have limited impact on the circular economy of the Port of Rotterdam. Overall, it can be concluded that the impact of using residual material as a construction material in a nature friendly bank on the circular economy depends on the dimensions and on the scale at which a nature friendly bank is constructed. This is also related to the space that is available along the river or channel at which the nature friendly bank is constructed.

Furthermore, it has been concluded that a nature friendly bank can improve the overall ecological state of a port. Results in this study prove that the (hydraulic) loads on the bank can be dissipated in favor of local ecological conditions. This can be of high value in industrial areas like ports where every ecological development is a large benefit according to ecologists. Depending on their size and scale, nature friendly banks can also add value on a regional scale. A systems approach is thereby necessary, linking different projects in order to achieve benefits on a larger scale.

Overall, it is concluded that a nature friendly bank made of residual material can enhance the circular economy and the biodiversity of a port. However, the execution of approaches and methods from this study are only applied to one case. Therefore, the body of evidence is limited. It is therefore recommended to further investigate the impact of nature friendly banks for example in other ports and on locations other than along a channel.

Preface

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering at Delft University of Technology. The research was carried out in cooperation with Hydronamic B.V.; the engineering department of Boskalis.

The aim of the research presented in this report is to broaden the knowledge base of constructing nature friendly banks made of residual material in a port. This is done through an interdisciplinary design study based on a case in the Port of Rotterdam.

An interdisciplinary research approach requires the combination of several disciplines. Combining disciplines is increasingly becoming important and relevant because of increased environmental consciousness and the need for development that is in harmony with nature and the environment. Linking environmental, economic and social aspects in the engineering practice is, therefore, in my opinion one of the most important challenges for the coming generation of engineers. This was also the main challenge in this thesis.

I would like to like to thank my graduation committee for their feedback and guidance throughout my research. Their experience and knowledge made me aware of the relevance of sustainable port infrastructure and increased my enthusiasm for the subject.

Furthermore, I would like to acknowledge my colleagues of Boskalis in Papendrecht. They were always available to answer my questions and endorse me in my research. In particular, I would like to thank Stefan Aarninkhof and Jaap van Thiel de Vries for welcoming me at Boskalis and making me so enthusiastic on the subject. I also owe a special word of thanks to my fellow students at Boskalis with whom I have shared valuable moments of reflection and distraction.

Finally, for the interesting conversations and their additional support I would like to acknowledge: Dries Hof (Boskalis), Stefanie Ross (Boskalis), Piter Hiddema (Rijkswaterstaat), Joep van Leeuwen (Municipality of Rotterdam), Wim Zwakhals (Port of Rotterdam), Gijs van Zonneveld (WWF), Arjenne Bak (Bureau Waardenburg), Marcel Klinge (Witteveen+Bos) and Barend de Jong (Witteveen+Bos).

Sarah Joy Sangster
Papendrecht, June 2015

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1. Introduction

1.1 Context

Ports are central points in the transport network: they act as an essential interface between seaborne and land-based modes of transport. They are also increasingly becoming centres of energy production and points of departure for the growing offshore industry [Vellinga, De Craene, & Rijks, 2014]. Obviously, port locations are often selected to optimize access to land and navigable water. Therefore, many ports are situated at the mouth of an estuary or along a coastline.

Not only are estuaries and coastlines a suitable location for ports: they are also attractive for living, working, tourism, recreation, water resources and food supply. It is therefore not a surprise that 80% of the largest population centres are found in coastal areas, as is illustrated in Figure 1.1. Besides being economically important, these areas are also valuable from a biodiversity point of view and often contain vulnerable ecological sites like intertidal areas, wetlands and bird nesting areas [Waterman, 2010]. Port areas thus generally need to combine a large amount of functions and values in a narrow strip of land which is making design, construction and maintenance of ports a challenge.

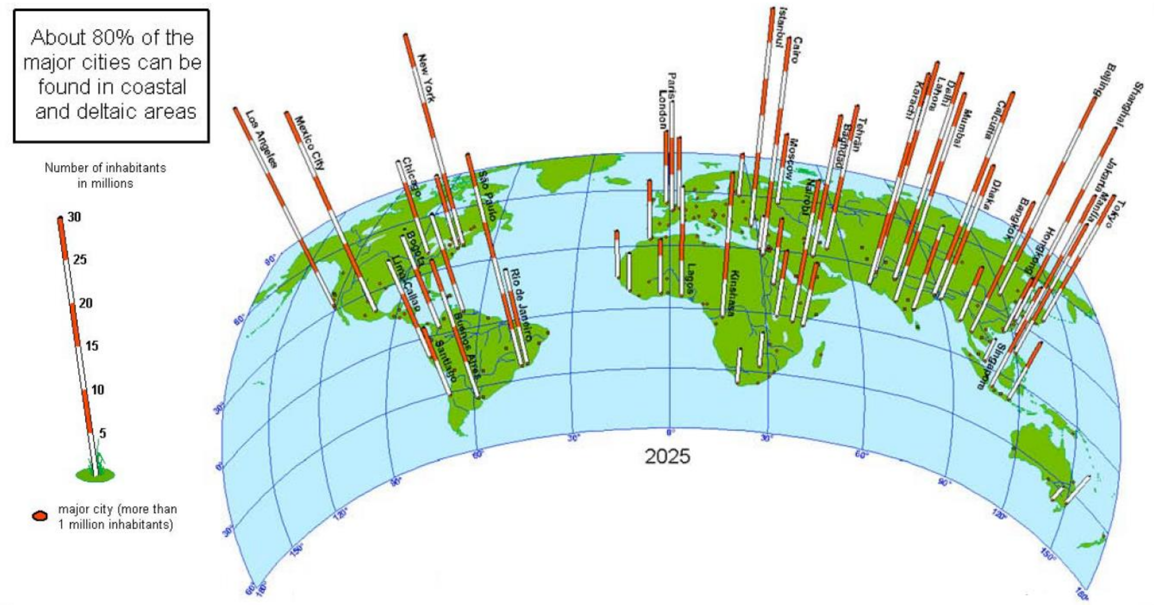


Figure 1.1 Largest population centres of the world [Waterman, 2010]

The human interventions along the coast often do not agree with local environmental processes [Bollman, 2010]. Coastlines and estuaries are shaped by natural forces, often changing greatly in response to changing environmental conditions. Humans influence the environmental conditions along a coast, amongst others by port development. These interventions may be a threat to the existence of ecosystems, on which our society depends in many ways. Consequently, there are a lot of environmental considerations in coastal development, including port development.

There is an urging need for developing ports that are more in harmony with nature and that contribute to the functioning of ecosystems. The challenge is to combine the pressure on coastal regions, as explained above, and increasing environmental awareness. Making designs that integrate port infrastructure with nature and the environment is the key. If environmental considerations are not taken into account, the existence of ecosystems, on which we rely so greatly, can be in danger. In the context of port development, 'Sustainable Ports' or 'Green Ports' are widely regarded as 'the answer' to this challenge.

1.2 Opportunities

As explained, there is a need for innovative solutions aimed at sustainable port development that is more in harmony with its environment. There is a wide range of possibilities to improve the sustainability of a port. As we look into the future, the world is facing challenges like meeting the needs of a growing world population (especially along the coast) with a finite resource base on a planet that is already under stress [Rabobank & Port of Rotterdam, 2012]. These challenges also present opportunities. This study focusses on combining two promising opportunities that can contribute to the sustainability of a port: enhancing both the biodiversity as well as the circular economy within the port.

In the port a promising opportunity for enhancing biodiversity lies at the interface between land and water. In a port, this interface is usually unnatural. The banks are shaped by steep, rock revetments or big quay walls made of concrete [CUR, 1999b]. This leaves little space for intertidal areas which can attract a high diversity of species [Bolier, 2006].

Besides making space for nature, another opportunity that can contribute to sustainable port development lies in reducing the human impact on our planet by enhancing the circular economy within the port and its surroundings. The circular economy is an economic system that is designed to maximize reusability of products and raw materials and minimizing value destruction [Oegema & Wurpel, 2012]. The circular economy can thus be enhanced by reusing residual material for port development projects. In general, ports produce a lot of residual material. Therefore a lot of types of residual material are usually readily available in ports. In many cases residual material is regarded as waste and it is therefore deposited (against a fee) and thereby being a possible threat to the environment. On the other hand ports also use a lot of material in development and maintenance projects, of which the production and transport can be expensive and harmful for the environment. Residual material can be seen as waste in one project, but also as a commodity for another project. By using residual material, money can be saved on dumping fees and on the purchase of raw materials, while at the same time reducing emissions and waste.

Constructing nature friendly banks made of residual material in a port is an opportunity to enhance both biodiversity as well as the circular economy at the same time within the port. This study focusses on this subject.

1.3 Case study

Combining the two objectives of enhancing the circular economy and biodiversity by constructing nature friendly banks is one of the aims of project "The river as a tidal park" in the Port of Rotterdam. This project aims at integrating the city of Rotterdam and the river that runs through it by creating nature and recreational areas at the interface of the river and the city: the riverbank. This project involves several pilot projects within the port that are related to constructing nature friendly banks. The aim of constructing these nature friendly banks is creating circumstances that are suitable for the desired ecological state for nature in the port, while at the same time enhancing the circular economy within the port.

Nature friendly banks offer opportunities for nature and are considered as an effective measure to improve the ecological functioning of waters [Sollie, Brouwer, & de Kwaadsteniet, 2011]. A more natural transition from land to water accommodates both plants and animals that live in water and on land, which may create a diverse and species-rich riparian zone. Therefore, constructing nature friendly banks is a promising measure for improving the ecological functioning of ports, and when made of residual material also for enhancing the circular economy of the port. However, since constructing nature friendly banks is not common practice in ports, this is a relatively unknown topic. It is thus uncertain which considerations are important when designing and constructing nature friendly banks made of residual material in a port area.

In order to gain more insight in the important considerations in constructing and designing nature friendly banks, an analysis has been made of two possible cases within project "The river as a tidal park". The analysis is based on stakeholder and expert interviews. The Port of Rotterdam, Rijkswaterstaat, World Wildlife Fund and the Municipality of Rotterdam are the main stakeholders of the projects. Their main strategic goals in constructing nature friendly banks are:

1. to enhance the biodiversity by improving the living conditions for migratory fish (especially sturgeon and salmon) and migratory birds and;
2. using residual material for the construction of the nature friendly banks in order to enhance the circular economy within the port and its surroundings and in order to finance the project.

The stakeholder interviews resulted in increased understanding and knowledge in constructing nature friendly banks made of residual material in the Port of Rotterdam. Constructing nature friendly banks made of residual material in a port is a promising measure to enhance biodiversity and the circular economy within the port. However, there are several critical design aspects that require extra attention. These critical design aspects affect both the success of the project, as well as the functioning of the port and its surroundings. The following four critical design aspects are considered to be of importance:

1. Ecological performance of the design;
2. Circular economy: the availability and applicability of residual material;
3. Integration of the design with respect to surrounding functions;
4. Stability of the design.

This research focusses on these critical design aspects. Project "De Groene Poort" in the Port of Rotterdam is used as a case study throughout the research. This project aims at constructing nature friendly banks made of residual material in the Nieuwe Waterweg.

1.4 Problem description

New trends in port development bring about new standards for designing infrastructure within a port, as was also concluded from the case study analysis. These new ways of designing aim at reducing emissions and increasing biodiversity in the port and its surroundings. However, the knowledge about nature in a port as well as reusing residual material as a construction material is limited [Bolier, 2006]. Furthermore, new ways of designing generally impose uncertainties on the impact and therefore may also impose risks. These risks can have an effect on the success of an infrastructure project and, even more important, on the functioning of the port and its surroundings.

Although there are opportunities for the Port of Rotterdam to improve sustainability in terms of enhancing both the biodiversity as well as the circular economy within the port by constructing nature friendly banks made of residual material, very little is known about this subject. This lack of knowledge may limit the chance of success of enhancing biodiversity and the circular economy in the port and its surroundings. This lack of knowledge is limiting the sustainable port development in general and therefore is a problem for the port and its surroundings.

1.5 Research objectives and questions

The research objectives and questions are associated with the results of the case study analysis.

The main objective of this study is to broaden the knowledge base of constructing nature friendly banks made of residual material in a port. This is done by:

- Gaining knowledge on important stakeholders and their positions;
- Gaining knowledge on the several critical design aspects.

The main research question associated with this objective is:

Will nature friendly banks made of residual material enhance the functioning of a port and its surroundings by enhancing the biodiversity and the circular economy?

This question can be divided into sub questions, based on the critical design aspects that were identified in stakeholder interviews. The sub questions will serve as a guide throughout the project. The sub questions are:

1. Is the envisaged construction, as proposed in the case study design, stable?
2. Does the envisaged design fit with ongoing activities and functions of the port and its surroundings?
3. Will the envisaged design enable opportunities to enhance the circular economy within the port by using residual material?
4. Will the envisaged design of a nature friendly bank enable conditions suited for the desired ecological state?

1.6 Report and research structure

For this research, a staged approach is adopted. This implies that insights and questions obtained from early data collection and analysis provide the basis for later research stages. The structure of the research is consistent to that of the report structure and divided into three parts: A, B and C, shown in Figure 1.2. As can be seen from the figure, part A has a broad focus on port development in general. Subsequently, the focus is narrowed down to the case study Port of Rotterdam in part B. Eventually, the focus is widened again in part C of the report to port development in general.

Part A comprises chapters 2 and 3. Chapter 2 explains the methods and research approach used in order to achieve the research objectives. Chapter 3 focusses on the context of sustainable port development, in which the concept of sustainable port infrastructure and its relation to nature friendly banks is explained. The focus lies on enhancing biodiversity and the circular economy within ports in general.

In part B of the report the focus is narrowed down to a case study in the Port of Rotterdam. Chapter 4 presents an analysis of the case study. More insight in the use of residual material is presented in chapter 5. Chapter 6 discusses the ecological performance of the design. In chapter 7 different alternatives are developed and evaluated based on the requirements set in chapter 4, 5 and 6.

In the third and last part of the research, part C, the focus is broadened again. This part of the report comprises chapters 8 and 9, and is a reflection on the case study and the overall research. Parts A and B are reflected upon and validated using the results of the case study research, own interpretation and expert views. This part of the report tells us what can be learned from the case study for sustainable port development in general. The aim of this part of the report is to answer the research questions and give recommendations with respect to the case project and future research.

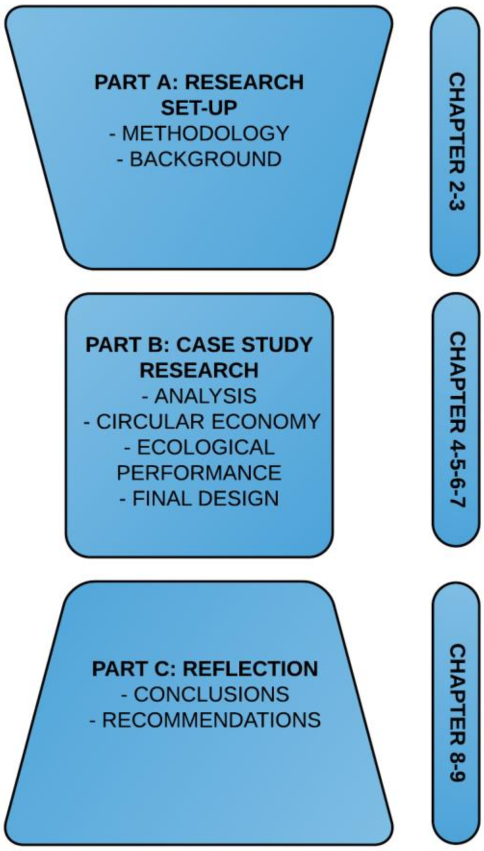
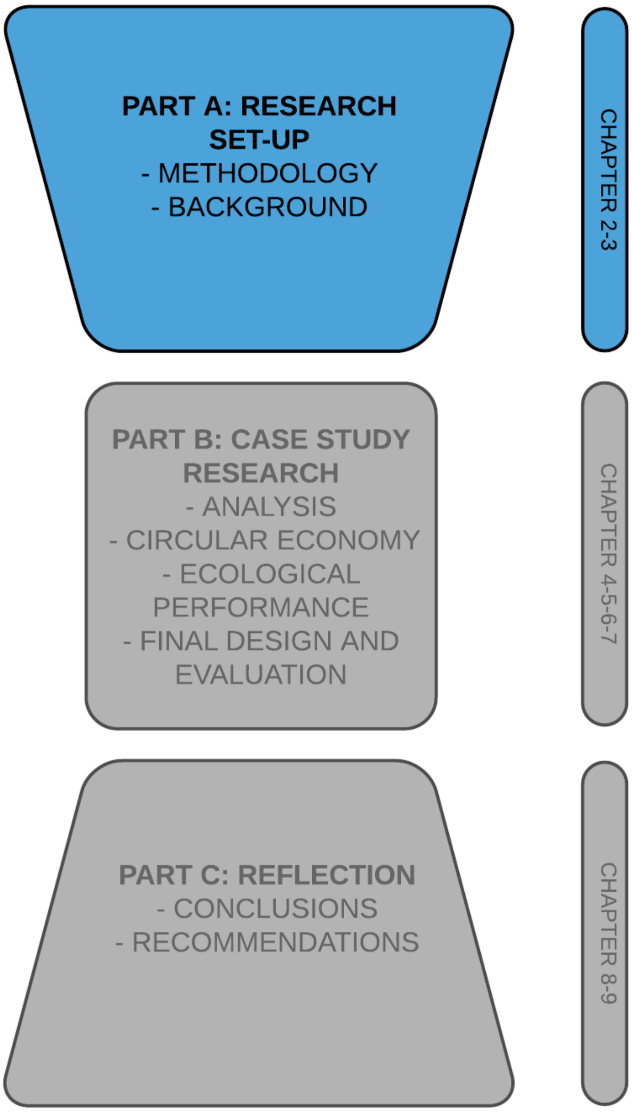


Figure 1.2 Structure of the report


PART A: RESEARCH SET-UP
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2. Methodology

This chapter presents the methods that are used in order to achieve the research objectives and answer the research questions. Section 2.1 presents the overall research approach, section 2.2 presents the interview methodology and section 2.3 explains the case study methodology.

2.1 Research approach

The main objective of this study is to broaden the knowledge base of constructing nature friendly banks made of residual material in a port. This is done through a design study in which emphasis is put on gaining insight in:

- stakeholders and their interests;
- critical design aspects.

The approach of this research is thus based on a design study. A design study involves several processes. This section explains these processes and explains on which of these processes emphasis is placed throughout this research.

2.1.1 Design study

A design study is a cyclical process that runs from the first exploration of a problem to having a solution. It is a creative process in which the decisions to be taken are preceded by several processes including feedbacks. Several design cycle theories exist; one is the elementary design cycle as shown in Figure 2.1.

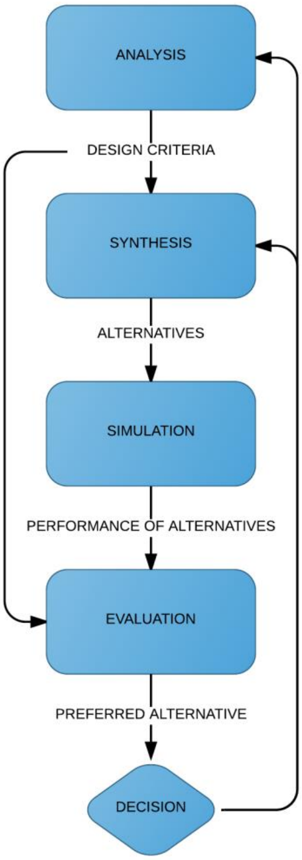


Figure 2.1 Elementary design cycle [Hertogh & Bosch-Rekveldt, 2014]

The elementary design cycle has five general design steps that are involved in a cyclical process of generating designs:

1. Analysis: understand the system and define design criteria;
2. Synthesis: identify realistic alternatives that use and/or provide ecosystem services;
3. Simulation: evaluate the qualities of each alternative and preselect an integral solution;
4. Evaluation: fine-tune the selected solution (practical restrictions and the governance context);
5. Decision: prepare the solution for implementation in the next project phase.

As can be seen in Figure 2.1 the elementary design cycle includes feedbacks. If it is decided that the proposed solution is not acceptable (because the solution does not meet the design criteria), the cycle must be followed again. There are three possibilities:

1. through the synthesis with the aim to generate new effects;
2. through the analysis with the aim to develop new, improved criteria;
3. through both the analysis and synthesis aiming at developing new, improved criteria and the generation of new effects.

2.1.2 Building with Nature approach

The Building with Nature approach is integrated in the steps of the elementary design cycle. This approach aims at achieving goals within an environment rather than assessing the consequences of a predefined project design. The focus should be on win-win instead of minimizing ecological harm [Waterman, 2010].

Traditional engineering design studies have a "reactive" approach: the intent is to minimize negative impacts and compensate for residual or secondary negative effects. "Building with Nature" has a "proactive" approach: the intent is to utilize nature processes and natural materials and providing opportunities for nature development in infrastructure [De Vriend & Van Koningsveld, 2012].

The aim of doing this is to develop integrated solutions that:

- are flexible and adaptable to changing circumstances;
- help to safeguard the economy and ecology;
- are both cost effective and sustainable;
- make the environment safer and more attractive as a place to live.

Constructing nature friendly banks made of residual material in a port aims at providing opportunities for nature development in the infrastructure of the port by utilizing the environment. Thus, the focus does not only lie on enhancing port infrastructure but also on enhancing biodiversity and the circular economy. This research is therefore consistent with the 'Building with Nature' philosophy.

2.1.3 Focus

This study is focussed on broadening the knowledge base of the critical design aspects identified in the interviews, in order to create alternatives suited for enhancing circular economy and biodiversity in a port. Therefore, emphasis is placed on the first phase of the elementary design cycle: the analysis.

As explained in the previous section, the analysis involves understanding the system and defining design criteria. Therefore, insight must be gained into:

- stakeholders and their interests in order to understand the system;
- the critical design aspects in order to be able to define the design criteria.

Gaining insight in the positions and interests of stakeholders is done by conducting interviews. It is expected that through these interviews more insight is gained in important considerations and critical design aspects of constructing nature friendly banks made of residual material in a port. The interview methodology is explained in section 2.2 of this chapter.

Profound insight into the critical design aspects is then gained by inspecting them further by obtaining a case study research and a design study. Case study research is a practice-oriented research methodology which is suitable for generating knowledge on relatively new and undiscovered subjects [Dul & Hak, 2008]. Therefore it is a suitable research methodology in this case since constructing nature friendly banks in a port area is not common practice. The case study research methodology is explained in section 2.3 of this chapter.

To be able to define the design criteria, it is necessary to understand the system. Therefore an analysis is made of the following aspects:

- Project area and environment (presented in chapter 4);
- Circular economy (chapter 5);
- Ecology (chapter 6).

The subsequent phases of the design cycle (synthesis, simulation, evaluation and decision) are also presented in this report as a first impression of a possible design. It is however expected that these phases must be followed again multiple times in order to come to an appropriate final design. These phases are presented in chapter 7 of this report. This chapter presents several alternatives for a proper design (synthesis). Subsequently, the performances of these alternatives are assessed using several methods. Based on these performances the alternatives are finally evaluated based on the design criteria. The evaluation method is explained in the following section.

2.1.4 Evaluation method

A lot of standard evaluation methods exist, often ranking alternatives based on weighting factors and scores of the alternative's performance. Based on the ranking of the alternatives the most preferable alternative can be identified. However in this case the objective of simulating the performance of the alternatives is not to identify the most preferable alternative. The objective is rather to get insight in the degree of flexibility of the design.

Therefore, a method is obtained that allows an evaluation based on several perspectives: a 'balanced score card method'. The idea behind the balanced scorecard method is that several factors can be weighted differently. It is a hierarchical performance measurement framework for strategy implementation aimed at balancing short- and long-term goals [Wurpel, 2014]. The key to this method is a multi-perspectives framework where in this case the performance is measured based on the four critical design aspects:

1. Stability;
2. Functioning of the port and surroundings;
3. Circular economy;
4. Ecological performance.

The alternatives are thus evaluated based on the performance regarding every specific critical design aspect. Three qualification categories have thereby been distinguished based on colours:

1. Red: if the design requirement is not met;
2. Orange: if the design requirement is sometimes met and sometimes not met;
3. Green: if the design requirement is met.

Working with colours is a very subjective method of evaluation. However, it gives a clear, straightforward and visible insight in the trade-off between the different requirements.

2.2 Interviews

One of the objectives of this research is to broaden the knowledge on important stakeholders and their positions regarding nature friendly banks made of residual material in a port. This is done by conducting interviews with the stakeholders of two pilot projects within the port that aim at constructing nature friendly banks:

1. project "De Groene Poort";
2. project "Shoaling of old city harbours".

2.2.1 Method

Several interview methods exist. In this case a semi-structured interview technique is used, in which more or less open-ended questions are brought to the interview situation in the form of an interview guide. The main challenge is to get the participant to expand upon their answer, give more details and add additional perspectives [Stewart, 2008]. In this way, a profound insight can be gained in the different considerations in constructing nature friendly banks made of residual material in a port.

2.2.2 Interviewees

Interviews are conducted with stakeholders and experts in the fields of ecology. It is thereby aimed to gain insight on the positions of every part of the so-called "golden triangle": government, businesses and non-governmental organizations. All of these "parts" are required to participate in a project in order to generate and promote innovation [De Vriend & Van Koningsveld, 2012], as is illustrated in Figure 2.2.

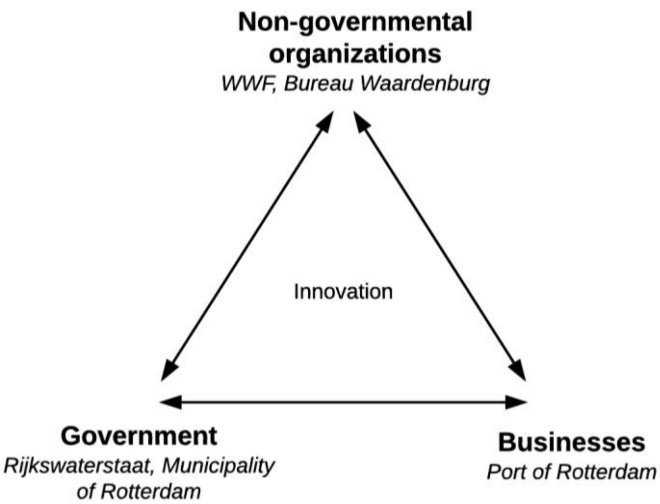


Figure 2.2 "Golden triangle" of innovation

An overview of the interviewees and their function is presented in Table 2.1. Based on their background, it is expected that all stakeholders have a slightly different interest in the project. It is therefore expected that their expectations and the goals of the project differ. To gain more insight in the ecological aspects and to get an objective view on the project an ecologists of Bureau Waardenburg are interviewed. Bureau Waardenburg has a lot of experience in designing nature friendly banks in several different environments and is therefore expected to provide valuable insight in the subject.

Role	Company	Person	Function
Stakeholder	Rijkswaterstaat	Ir. Piter Hiddema	Project engineer
	Port of Rotterdam	Ing. Wim Zwakhals	Project manager sustainable development
	Municipality of Rotterdam	Ir. Joep van Leeuwen	Senior advisor urban development
	World Wide Fund for nature (WWF)	Ing. Gijs van Zonneveld	Project manager
Independent expert	Bureau Waardenburg	Drs. Arjenne Bak	Manager aquatic ecology

Table 2.1 Overview of the conducted interviews

2.2.3 Interview analysis

In order to make optimum use of the stakeholder and expert interviews an extensive analysis is required. An analysis method has been developed to make optimum use of the interview results. A top-down, manual, qualitative analysis method is used. This means that prior to the interviews, a few subjects have been chosen to be relevant and the interviews are analysed based on these subjects. The subjects are based on a theoretical framework, illustrated in Figure 2.3 that was developed for this research.

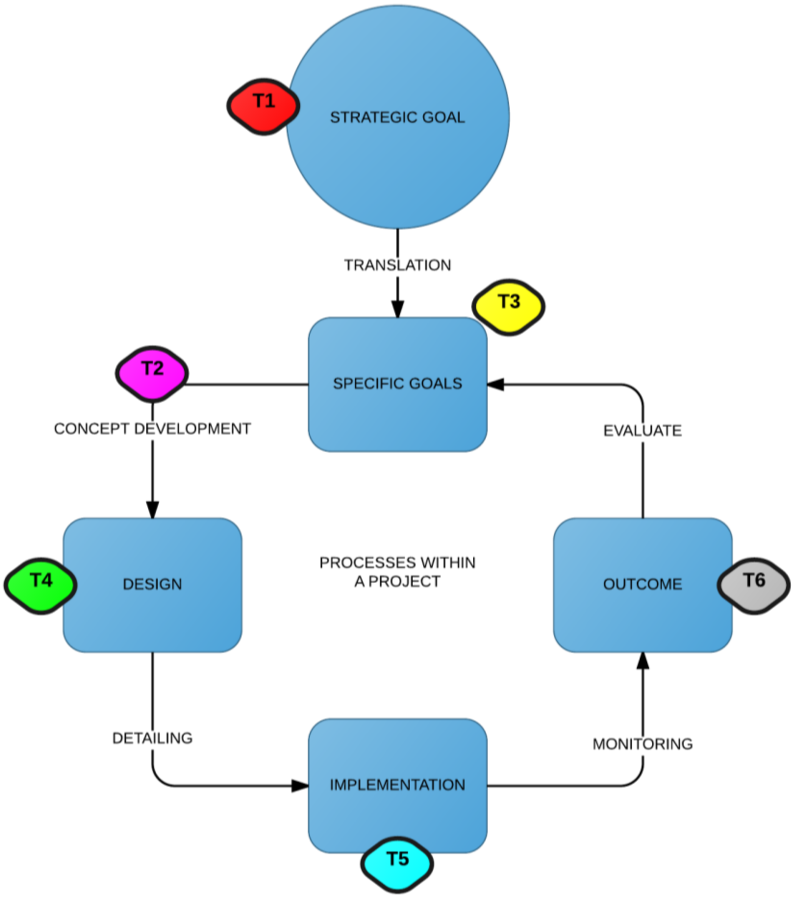


Figure 2.3 Theoretical framework with labels

The framework shows the processes that take place within a project. Every project has a strategic goal which is the underlying reason a project started. This strategic goal is translated into specific goals of the project. These goals are translated into a project design. After a detailed design has been made, the project can be implemented. After the project has been implemented the created situation is monitored to determine the outcomes of the project. These outcomes are then evaluated based on the specific goals of the project to see whether the project is successful or not.

Prior to the interviews, theoretical labels have been defined that fit the theoretical framework and that are based on the information that is required from the interviews. An overview of the labels and their significance can be found in Table 2.2.

Right after the interviews have taken place, a verbatim transcript is made of every interview. In this verbatim transcript all necessary information from the interview is written down. The information in the verbatim transcripts of the interviews is schematized based on the labels. The verbatim transcript is then analysed, using colours to highlight the information based on the theoretical labels. All the highlighted information is then put into excel, in such a way that the information can be arranged by label and by stakeholder. Consequently, a clear and visual overview of the interview data is created and the information can be easily interpreted and analysed.

Predefined code	Place within theoretical framework
T1	Strategic goal
T2	Initiation of the project
T3	Specific goals
T4	Design
T5	Implementation
T6	Risk

Table 2.2 Overview of the predefined theoretical labels

2.3 Case study research

This section explains the relevance of case study research in general and how it can be applied to this research.

2.3.1 General

Case study research can be used for exploratory phases of investigation [McCutcheon & Meredith, 1993]. This type of research is also obtained in innovative programs like 'Building with Nature'. Since not a lot of theory is available on constructing nature friendly banks made of residual material in ports this subject is in its exploratory phase. Therefore, case study research is an appropriate approach in this study. An in-depth case study research enables the identification and investigation of the critical design aspects of nature friendly banks made of residual material in a port.

2.3.2 Data collection

Any case study finding or conclusion is likely to be more convincing and accurate if it is based on several different sources of information. The important advantage of the use of multiple sources of data in case studies is the development of converging lines of inquiry: a process of triangulation. Through the use of triangulation the validity and reliability of the research is enlarged [Yin, 2009]. The need for triangulation arises from the ethical need to confirm the validity and reliability of the case study research. In case studies this can thus be achieved by using multiple sources of data [Yin, 2009]. Throughout the research it is therefore aimed to use various methods and sources for gathering data to realize an in-depth and validated research. The following data sources are used:

- Interviews;
- Expert views in the field of:
    - ecology;
    - residual material;
    - structural design;
- Project documentation and literature;
- Hydrodynamic model (XBeach).

Figure 2.4 illustrates the data sources that are used per research step.

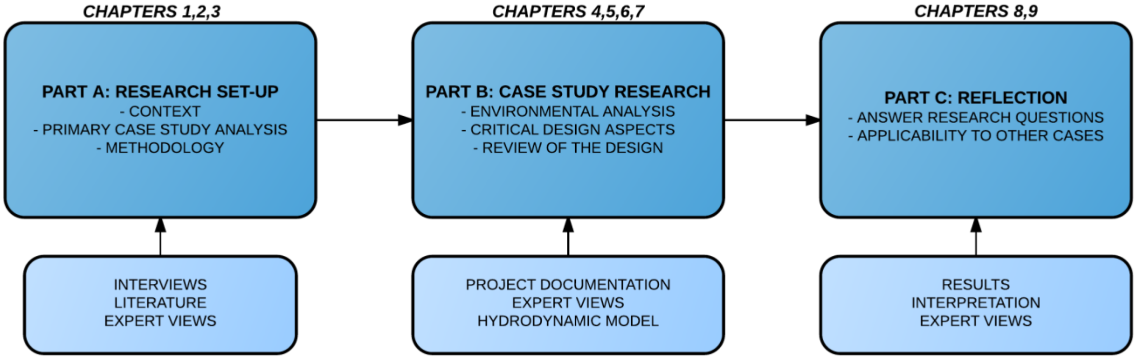


Figure 2.4 Data sources throughout the research

2.3.3 Case selection

As explained before, two potential case studies in the Port of Rotterdam have been analysed that are related to constructing nature friendly banks:

1. Project "De Groene Poort" involving the construction of nature friendly banks in the Nieuwe Waterweg;
2. Project "Shoaling of old city harbours' involving the redevelopment of old city harbours that have lost their port function.

One of the projects has to be chosen as a case study for this research. The case is selected based on the following criteria:

- the stakeholders must be approachable;
- information on the case must be readily available;
- the case must be widely applicable.

Based on the project analysis and the criteria stated above, project "De Groene Poort" was chosen to be the most suitable for this research. Firstly, Boskalis has close connections with the stakeholders of project "De Groene Poort". Therefore it is easy to approach the stakeholders for questions and information. Furthermore, the stakeholders have a different background which generally yields a wide range of information from different disciplines. Furthermore, project "De Groene Poort" is in its implementation phase. This means that a lot of information is available on the project which gives a good research basis. Finally, it is expected that this is case is applicable to a wide range of ports. The Port of Rotterdam is located at an obvious location for a port: in a large estuary, at the outflow of the river Rhine and along the coast of the North Sea. Because many ports are located in similar areas, it is expected that the conclusions and recommendations for project "De Groene Poort" are also applicable to a large extend to other cases of nature friendly banks made of residual material in port area.

Project "Shoaling of old city harbours" is not thought to be suitable to serve as a case study for this research. There are many uncertainties in when, how and by whom the old city harbours will be redeveloped.

3. The sustainable port

In chapter 1 the context of the need for sustainable port development was explained. Nature friendly banks made of residual material are identified as a promising measure supporting sustainable port development by enhancing the biodiversity and the circular economy in a port. This chapter explains what sustainable port development comprises of and how it relates to biodiversity and the circular economy. Section 3.1 gives insight in sustainable port design in general and its relevance. Section 3.2 explains about biodiversity and its relevance in ports. In section 3.3 the term circular economy is explained. Section 3.4 explains how that all relates to the case study used in this study: project "De Groene Poort" in the Port of Rotterdam.

3.1 Sustainable port design

3.1.1 Sustainability in general

Over the past decades our environmental awareness has steadily increased. This is not surprising, since everything we need for our survival and well-being depends, either directly or indirectly, on our natural environment. Sustainability aims at making sure that we have and will continue to have water, materials, and resources to protect human health and our environment. Sustainability is defined by the World Commission on Environment and Development as follows:

"Sustainability is to meet the needs of the present without compromising the ability of future generations to meet their own needs [Brundtland, 1987]."

This definition of sustainability supports strong economic and social development but at the same time underlines the importance of protecting the natural resource base available from the natural environment. The idea is that economic and social well-being on the long term cannot be improved with measures that destroy the environment. Solidarity for next generations therefore demands that all developments take into account the impact on the resource base [Jacobs, Dendoncker, & Keune, 2014].

In order to achieve a sustainable society, sustainable project designs are required, which aim at economic and social development while at the same time taking care of the environment. The sustainability of a design can be measured by using the Triple Bottom Line theory, which encompasses three interests: "people, planet, and profit" [Bridges, 2011]. Integrating these social ("people"), economic ("profit") and environmental ("planet") considerations into decision making will eventually result in solutions for growth that are more socially acceptable, viable, equitable and, ultimately, more sustainable, as illustrated Figure 3.1. When a project's design encompasses the three "P's", the design is considered to be sustainable.

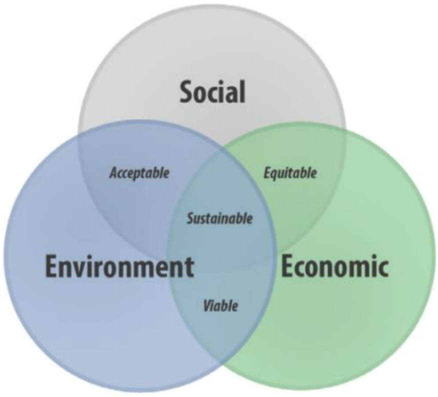


Figure 3.1 Social, economic and environmental considerations in designing [Bridges, 2011]

3.1.2 Ecosystem services

Thus, sustainability aims at making sure that we have and will continue to have water, materials and resources to protect human health and our environment. These (primary) resources are brought to us by the services provided by ecosystems. Every living being in the world depends completely on earth's ecosystems and the services they provide: without ecosystems (human) life could not exist. The convention on Biological diversity provided the following definition of an ecosystem:

"An ecosystem is a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit."

Ecosystem services are the benefits people obtain from these ecosystems, they can be divided into four basic categories [Zakri & Watson, 2005]:

- Supporting services (e.g. nutrient cycles, photosynthesis and crop pollination);
- Provisioning services (products supplied from ecosystems such as food, water, timber, and fiber);
- Regulating services (benefits provided by ecosystems by regulating water, erosion, flooding, climate and air quality);
- Cultural services (recreational, aesthetic, and spiritual benefits).

The ecosystem services have several functions. The three "P's" (people, planet, profits), as explained in the previous section, can be assigned to each function-category of the ecosystem services. This is illustrated in Figure 3.2.

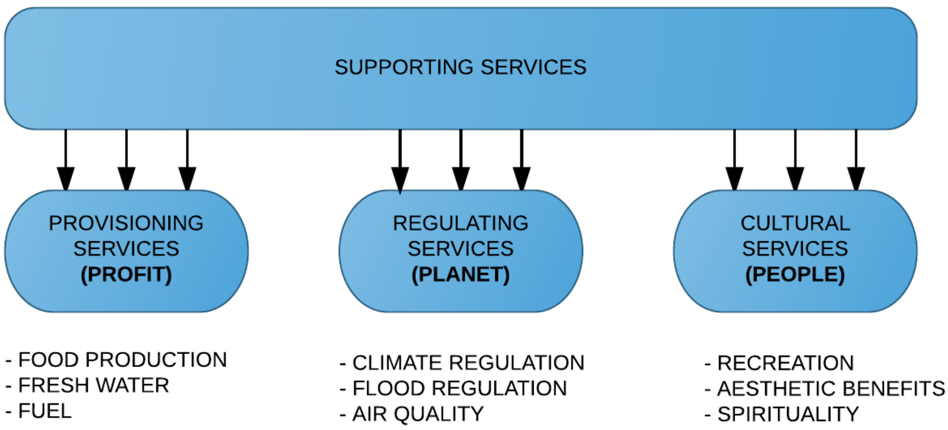


Figure 3.2 Ecosystem services [Zakri & Watson, 2005]

Many ecosystems and the services they provide are at risk. This is because often human interventions do not fit ongoing geological and biological processes [Bollman, 2010]. Over the past 50 years, the planet's ecosystems have been changed by human intervention more rapidly and extensively than in any comparable period of time in human history. This transformation of the planet has contributed to our prosperity and economic development [Vellinga et al., 2014]. However, to ensure further socio-economic development it is evident that these ecosystems need to be protected.

3.1.3 Sustainable/green port

In chapter 1 it was explained that port areas are valuable in terms of economy but also in terms of the environment. Therefore, there is an urging need for developing ports that are more in harmony with nature and that contribute to the functioning of ecosystems. 'Sustainable Ports' or 'Green Ports' are widely regarded as 'the answer' to this challenge.

The World Association for Waterborne transport Infrastructure defines a sustainable port as follows:

"A sustainable port is one in which the port authority together with port users, proactively and responsibly develops and operates, based on an economic green growth strategy, on the building with nature philosophy and on stakeholder participation, starting from a long term vision on the area in which it is located and from its privileged position within the logistic chain, thus assuring development that anticipates on the needs of future generations, for their own benefit and the prosperity of the region that it serves [Vellinga et al., 2014]."

The 'economic green growth strategy', mentioned above in the definition of a sustainable port, is based on green growth being used as an economic driver. By accommodating the growth of ports in harmony with the environment (cities and nature), where space is limited and development is desired, green growth can be adopted as an economic driver [Vellinga et al., 2014]. By using sustainable policies, ports will get more acceptance which leads to less resistance of stakeholders against port development projects. Sustainable policies can thus save valuable time and money. Ports that do not obtain sustainable policies will continue to fight for permits and against environmental legislation. Ports that do obtain sustainable policies therefore are at least one step ahead of their competition and act beyond legislation.

This definition of a sustainable port stresses the importance of stakeholder involvement. For port development stakeholder involvement is important because water-related infrastructure projects are likely to affect the interests of a variety of stakeholders, especially in densely populated areas that usually surround a port. Stakeholder involvement can dismiss resistance against projects and it can inspire surprising new solutions [De Vriend & Van Koningsveld, 2012]. The building with nature philosophy mentioned in the definition, aims at a clear shift in the design cycle from replacing nature by building with nature. This shift also includes a change in the design cycle from the aim at a functional design into a multifunctional design: creating value for stakeholders by making a value-added design.

Both in the definition of sustainability in general and the definition of a sustainable port it is mentioned that the needs of future generations should be taken into account. Needless to say, this requires a long-term vision. By including the long-term vision in a project, measures that relate to the conservation of ecosystem services can be taken into account. On the short-term, the conservation of ecosystem services is of less importance.

3.1.4 The need for sustainable ports

Within the three "P's" framework (people, planet, profit) most ports are mainly focused on the economic aspect of making a profit, instead of taking care of social and environmental aspects. Therefore, as in many industries, a lot of port authorities approach sustainability in a negative way: port development and economic activities in general regularly conflict with the desire to conserve the vulnerable environment ("planet") that usually surrounds a port. However, environmental consciousness in the port industry is growing and the pressure of environmental legislation on port development is increasing. Also, having a "social license to operate and grow" ("people") may be a necessity for certain major ports if their environmental performance is seen as problematic for their surroundings.

3.1.5 Opportunities

Opportunities for sustainable port development lie in making use of the ecosystems services, but ensure their functioning in the future such that future generations can also benefit. An indicator for the functioning of an ecosystem is biological diversity or: biodiversity. Generally, higher biodiversity ensures increased functioning of an ecosystem and therefore assures the ecosystem services [Wilson, 1988]. Thus enhancing the biodiversity in a port can contribute to ensuring the surrounding ecosystem services.

Besides enhancing the biodiversity in the port by making space for nature, another possibility that can contribute to sustainable port development lies in reducing the human impact on our planet by enhancing the circular economy within the port and its surroundings. The circular economy is an economic system that is designed to maximize reusability of products and raw materials and minimizing value destruction. The circular economy can thus be enhanced by reusing residual material for port development projects.

In the following sections the opportunities to enhance biodiversity and the circular economy in a port are discussed.

3.2 Biodiversity

3.2.1 General

As mentioned before, an indicator for the functioning of an ecosystem is biological diversity, or: biodiversity. Generally, higher biodiversity ensures increased functioning of an ecosystem and therefore assures the ecosystem services [Wilson, 1988]. The most widely used definition for biodiversity is formulated within the convention on biological diversity organized by the United Nations in 1992:

"Biodiversity or biological diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems [Jacobs et al., 2014]."

The term biodiversity thus describes the number of species, the amount of genetic variation or the number of community types present in an area. However, most studies focus on species diversity. All relations between biodiversity and ecosystem services generally point to increased functioning of an ecosystem with higher biodiversity. Generally, ecosystem functions are thus stabilized and diversified by a higher biodiversity. This implies that ecosystem service delivery by these functions is ensured. Thus, by increasing the biodiversity in an area the ecosystem services are enhanced and thus a sustainable environment can be created [Jacobs et al., 2014].

3.2.1 Biodiversity in ports

Biodiversity can thus be seen as a measure to enhance the functioning of ecosystems and thereby sustaining the services they provide for the current and future generations. Therefore, biodiversity within a port can attribute to its sustainability. Ports are often located at valuable sites in terms of biodiversity: along a coastline or in an estuary, that house vulnerable ecological sites like intertidal areas, wetlands and bird nesting areas. On the one hand, the developments of industrial port areas often do not agree with the ecological processes in the surroundings. On the other hand, port development may create possibilities to add value to nature in the port. The ecological processes that are characteristic for many port areas because of their location can be included in the design process. In this way, biodiversity within a port can be increased and the port will become more sustainable.

Many ports are located at the mouth of a river and thus in an estuary. An estuary is a transition zone between fresh water from rivers into marine water from the sea. The hydrological regime depends on tide and river discharge. These circumstances often cause special aquatic ecosystems. The gradual transition in salinity makes the area an essential stepping stone for migratory fish which commute back and forth from fresh to salt water. In this area, the fish can adjust to the changing circumstances of the hydrological regime. Fish need time and space for this adjustment, as was concluded from a research of the WWF that studied the migration of the Atlantic sturgeon from the river towards the sea [de Kok & Meijer, 2012].

Thus a great opportunity for many ports is to enhance the biodiversity by creating space for migratory fish. In the port a promising opportunity for creating space for nature lies at the interface between land and water. In a port, this interface is usually unnatural: the banks are generally shaped by steep, rock revetments or big quay walls made of concrete [CUR, 1999b]. This leaves little space for intertidal areas which can attract a high diversity of species [Bolier, 2006].

3.3 Circular economy

Enhancing the circular economy was identified as an opportunity that can contribute to sustainable port development. This section explains the concept of a circular economy and how that relates to sustainable port development.

3.3.1 General

Our current use of the planet's resource base is based on the 'take, make and dispose' premise in which waste is produced at the end of the cycle, as can be seen in Figure 3.3. This is a linear pattern that assumes an infinite supply of low cost inputs and also assumes that waste can be assimilated at the environment at no cost. This system will reach its limits in terms of resources sooner or later [Van den Akker, Betsema, Oegema, & Wurpel, 2013].

Figure 3.3 The linear economy principle [Ellen MacArthur Foundation, 2013]

However, in the 1970s the realization dawned that by extracting raw materials the subsoil was being exhausted. It was concluded that there is no such thing as an infinite supply of raw materials and that our use of the planet's resource base was not sustainable. Furthermore, the negative effects of rapid industrial growth were increasingly becoming noticeable. Suddenly, pollution of air, water and soil had to be dealt with [Boskalis Dolman bv, 2008].

A growing recognition that the world is moving beyond planetary boundaries, along with short-term challenges posed by resource scarcity, consequently mean businesses need to start thinking and acting differently. Moving to a circular economy may provide an important potential solution. The circular economy is an economic and industrial system that aims at maximizing the value retention of products and raw materials and minimizing value destruction [Loppies, 2015].

As can be seen in Figure 3.4, the circular system has two cycles of materials at which this can be achieved:

1. a biological cycle, in which residual materials safely flow back into nature after use;
2. a technical cycle, in which products or parts of products are designed such that they can be reused at a high quality level [Van den Akker et al., 2013].

Figure 3.4 The circular economy principle [Ellen MacArthur Foundation, 2013]

Enhancing the circular economy can thus help in mitigating environmental pressure by producing less waste and using fewer raw materials: it takes care of the "planet" within the three "P's" framework.

3.3.2 In a port

Ports can only maintain their societal value and deliver more value by responding to global challenges. Another vision on the use of raw materials, the production of waste and residues is necessary in the development of a clean, green and sustainable port [Rabobank & Port of Rotterdam, 2012]. Enhancing the circular economy within a port is therefore necessary to reduce the human impact on our planet. This adds to the sustainability of a port, according to the definition of a sustainable port.

Ports are an ideal place to start building pathways towards a circular economy: they have many advantages to offer to a region. The scale and diversity of economic activities and the (international) connections of the ports mean a vast array of opportunities [Rabobank & Port of Rotterdam, 2012].

Ways of moving from the linear economy into a circular economy is to reduce the use of resources, to recycle waste and, in the ideal case, eventually replace 100% of the resources used with waste, as illustrated in Figure 3.5. The ideal circular economy is a closed environment in which no waste is produced and no external resources are needed.

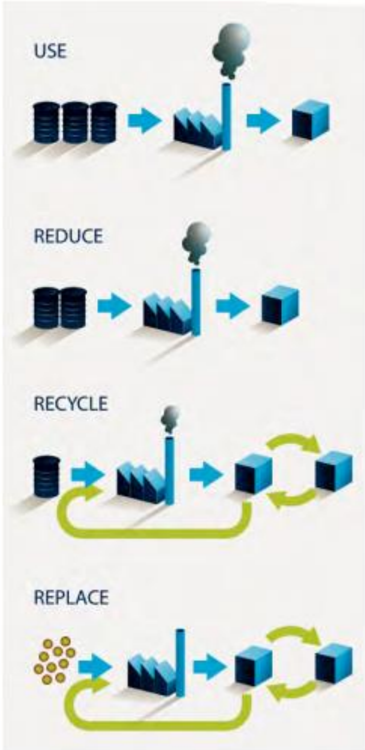


Figure 3.5 Basic principles of the circular economy [Port of Rotterdam, 2011]

On the one hand, ports produce a lot of residual material that is normally deposited and is a possible threat to the environment. On the other hand, ports use a lot of material in development projects, of which the production can be expensive and harmful for the environment. Residual material can be seen as waste in one project, but also as a commodity for another project. Recycling and replacing raw materials with residual material is therefore a promising option for the port to start moving towards a circular economy.

3.4 Port of Rotterdam

In the previous sections, the need for sustainability in ports was discussed, and how that is related to a circular economy and biodiversity. In this section, opportunities are presented to combine these two within the Port of Rotterdam.

3.4.1 General

The Port of Rotterdam is one of the main ports and the largest logistic and industrial hubs in Europe. With an annual throughput of 450 million tons of cargo a year the Port of Rotterdam is by far the largest seaport of Europe [Port of Rotterdam, 2014]. The port is the gateway to a European market of more than 350 million consumers. The Port of Rotterdam thanks its position to the excellent accessibility via sea, the hinterland connections and the many companies and organizations that are active within the port. The port stretches out over 40 kilometres and has an area of about 12.500 ha [Port of Rotterdam, 2011].

The Port of Rotterdam has the following two main functions [Port of Rotterdam, 2014]:

1. Hub for global, intra-European and local cargo flows (dry bulk, liquid bulk, containers and break bulk) of which an overview of the annual throughput can be seen in Figure 3.6;
2. Petrochemical and energy complex.

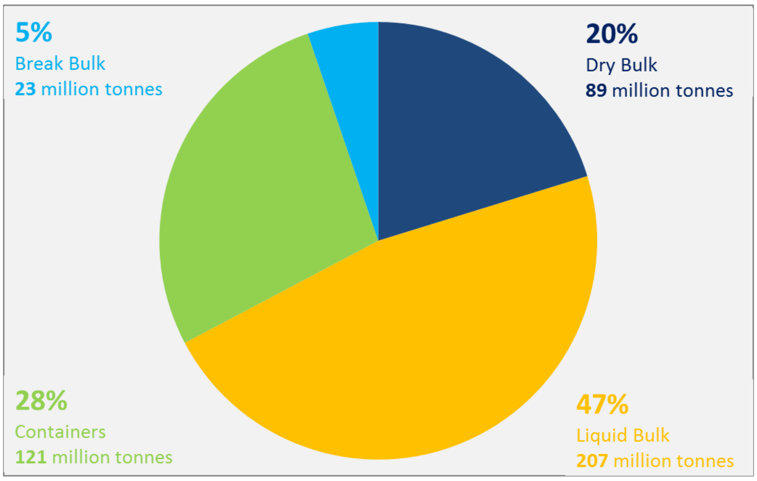


Figure 3.6 Throughput in the Port of Rotterdam in 2013 (based on information obtained from the website of Port of Rotterdam)

Not only does the port have infrastructural and industrial functions, it is also increasingly becoming a place for recreational activities, renewable energy production and nature development. Consequently, an increasing number of stakeholders is becoming active within the port and its surroundings. According to the Building with Nature philosophy, all these functions and values need to be considered and involved within port development processes in order for the Port of Rotterdam to be a "Sustainable Port".

3.4.2 Sustainability in the port

A growing recognition that the world is moving beyond planetary boundaries, along with short-term challenges posed by resource scarcity, mean businesses like the Port of Rotterdam authority need to start thinking and acting differently towards their environment. Obviously, the port works within the laws and regulations, but it also has its own code of conduct which everyone working in the area (including customers) must keep to. The ambition of the Port of Rotterdam is to become the port with the smallest ecological footprint per ton-kilometre in the world in 2030.

In order to achieve this, the port has initiated several projects [Port of Rotterdam, 2013]. These include:

- Cutting emissions by producing ' clean energy' and encouraging the use of it by:
    - Supporting sustainable energy (wind turbines in the port area);
    - Supporting biofuels (the largest plants for the production of bio fuels are located in Rotterdam);
    - Introducing an environmental ship index that grants discounts for clean sea-going shipping;
- Enhancing biodiversity by initiating and funding projects for nature in the port;
- Enhancing the circular economy within the port by:
    - Recycling plastic, metal and glass into new raw materials;
    - Refining oily sludge and residue to produce diesel and bitumen;
    - Incinerate household waste from ships and use the released heat.

3.4.3 Circular economy

The Port of Rotterdam aims to be an active player in the so-called circular economy principles. In other words, the port has the ambition to minimize waste streams by reusing as much material as there is available in order to create new value. Being the largest port and distribution hub in Europe, the Port of Rotterdam is a place where material flows meet. The Port of Rotterdam is therefore an ideal place to start building pathways towards a circular economy in Rotterdam and its surroundings.

There are many sources of residual material in the port that can be recycled. A few examples are:

- Industrial activity:
    - CO_2;
    - Heat;
- Vessels:
    - Cargo-associated waste (including all material left on board as waste after the stowage and handling of the cargo, e.g. packing material and pallets);
    - Ship-generated waste (fuel oil residues/sludge, used engine oil, bilge water, garbage, maintenance waste);
- Infrastructure projects:
    - Soil/dredged material;
    - Coarse material (e.g. from old quay walls or other terminal facilities).

This research focusses on the latter two types: dredged materials and coarse material. They are considered to be most suitable to be combined with the objective of enhancing biodiversity within the port.

3.4.4 Biodiversity

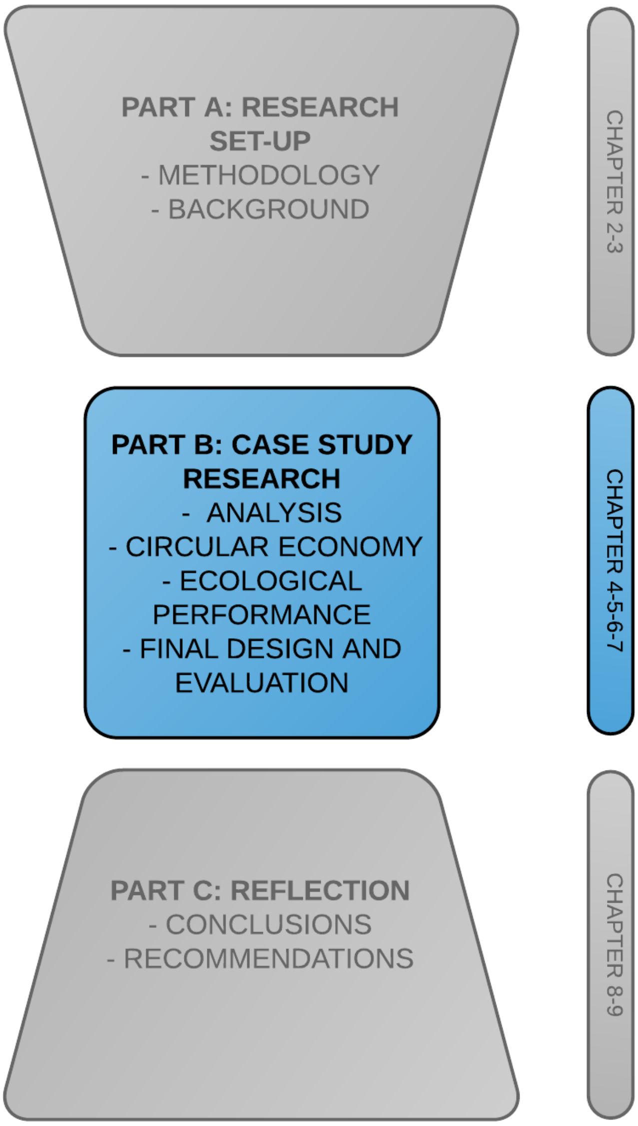
An ideal opportunity to increase the biodiversity within the port is to improve the living conditions for migratory fish. The Port of Rotterdam is in potential an ideal hub for migratory fish. Before the Port of Rotterdam emerged the Dutch Delta was filled with migratory fish like salmon and sturgeon. Because of the development of industrial areas upstream and the accompanying explosive growth of the Port of Rotterdam this situation changed drastically. Because of shipping, industrial and constructional activities the water quality in the Delta worsened and the natural, “soft” banks were replaced by “hard” banks and quay walls [Rijkswaterstaat, 2008].

The Port of Rotterdam is part of the estuary between the rivers Rhine, Meuse, Nieuwe Waterweg and the North Sea. An estuary is a transition zone between fresh water from rivers into marine water from the sea. The hydrological regime depends on tide and river discharge. These circumstances often cause special aquatic ecosystems. The gradual transition in salinity makes the area an essential step stone for migratory fish, when commuting back and forth from fresh to salt water. In this area, the fish can adjust to the changing circumstances of the hydrological regime. Fish need time and space for this adjustment, as was concluded from a research of the WWF that studied the migration of the Atlantic sturgeon from the river towards the sea [de Kok & Meijer, 2012]. Now that the chemical quality of water has been improved significantly over the past decade [Rijkswaterstaat, 2008] chances for ecological restoration of the hub for fish are improving.

3.4.5 Conclusions

Both enhancing the circular economy as well as enhancing biodiversity within the Port of Rotterdam can contribute to the strategic goal of the Port of Rotterdam to become a sustainable port. Especially alongside the banks a lot of ecological benefits can be achieved that can be combined with enhancing the circular economy. Nature friendly banks made of residual material offer opportunities for nature and the circular economy. It is considered as an effective measure to improve the ecological functioning of waters [Sollie, Brouwer, & de Kwaadsteniet, 2011] and when made of residual material they can add value to the circular economy of the port and its surroundings. A more natural transition from land to water accommodates both plants and animals that live in water and on land, which may create a diverse and species-rich riparian zone.

Nature friendly banks thus are a promising measure to contribute to a sustainable port by enhancing biodiversity and the circular economy within the port and its surroundings. However, in-depth research is needed on both disciplines as limited information and knowledge is available on the two subjects.


PART A: RESEARCH SET-UP
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- ECOLOGICAL PERFORMANCE
- FINAL DESIGN AND EVALUATION
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- CONCLUSIONS
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CHAPTER 8-9

4. Case study analysis

A design study based on project "De Groene Poort" will be executed in order to broaden the knowledge base of nature friendly banks made of residual material in a port area.

As explained in chapter 2 the emphasis of the design study is placed on the analysis phase of the elementary design cycle. This chapter presents the analysis of the project based on stakeholder interviews in section 4.1. As was also explained in chapter 2 the output of this analysis are the design criteria. The design criteria form the basis of design and in include:

- Assumptions (section 4.2);
- Functional boundary conditions (section 4.3);
- Physical boundary conditions (section 4.4);
- Critical design requirements (section 4.5).

An assumption is a qualification or quantification of an uncertainty in the design. A boundary condition is an external limit imposed by the environment. The designer has no influence on the boundary conditions. Requirements are internal limits and are imposed by the wishes and demands stakeholders. A design has to comply with the assumptions, boundary conditions and requirements [Hertogh & Bosch-Rekveldt, 2014].

4.1 Project and stakeholder analysis

4.1.1 Project description

Project "De Groene Poort" is a cooperation between Rijkswaterstaat, Port of Rotterdam, the Municipality of Rotterdam and the World Wildlife Fund. It aims at establishing nature friendly riverbanks in the Nieuwe Waterweg by reusing residual material from the port and its surroundings.

The Nieuwe Waterweg is an open connection between the river (fresh water) and the sea (marine water). This is quite unique in Western Europe since few of these open connections still exist. The gradual transition in salinity makes the area an essential stepping stone for migratory fish, which commute back and forth from fresh to salt water. In the area of the Port of Rotterdam, the fish can adjust to the changing circumstances of the hydrological regime [Rijksinstituut voor Kust en Zee, 1999]. However, because of port related activities, the situation in the Nieuwe Waterweg is far from desirable for ecology in general. Currently, the riverbanks in the Nieuwe Waterweg are made of steep, blocked revetments and are exposed to currents and waves from ships passing by, leaving little space for nature development [Hiddema, Van Leeuwen, Van Zonneveld, & Zwakhals, 2013].

Project "De Groene Poort" aims at creating foreshores made of coarse residual material in order to create a protected environment: free from ship-induced currents and waves. Between the foreshore and the existing riverbanks the riverbed will be nourished in order to create intertidal area. The intertidal areas between the groynes in the river should become living and foraging areas for migratory fish such as sturgeon and for migratory birds. All the material used for construction is recycled from nearby, in order to minimize transport costs and emissions as much as possible. This project thereby aims to be a sustainable and cost-effective project. Figure 4.1 gives an artist impression of the project.

Figure 4.1 Artist impression of project "De Groene Poort": a busy port and nature go hand-in-hand [Hiddema, Van Leeuwen, Van Zonneveld, & Zwakhals, 2014]

4.1.2 Stakeholders analysis

In order to gain more insight in the project and the interests of the stakeholder's interviews were conducted with stakeholders and experts in the fields of ecology. These interviews resulted in increased understanding in stakeholders and their positions.

The stakeholders have different backgrounds: governmental institutions, non-governmental institutions and businesses. This results in different types of interests in project "De Groene Poort". Rijkswaterstaat's aim is based on European guidelines to enhance aquatic life in rivers and coastal waters. The municipality's ultimate goal is to improve the city's working and living environment, in which ecology and a green environment plays a significant role. It is WWF's aim to reconstruct the natural processes within the Delta amongst others by increasing the biodiversity. The ultimate goal of the Port of Rotterdam is to achieve the goals that were set in the "Port Vision 2030" in which the Port of Rotterdam states that it wants to become the most sustainable port of the world in 2030.

Besides the increased insight in the stakeholders and their interests, the interviews exposed four critical design aspects of the project:

- the stability of the design;
- the integration of the design with respect to surrounding functions;
- the availability and applicability of residual material;
- the ecological performance of the design.

Based on the interviews it is concluded that with respect to the framework it would benefit the project if more emphasis is placed into:

- translating the strategic goals of the design into specific goals and;
- translating the specific goals into a final design.

This is illustrated in Figure 4.2.

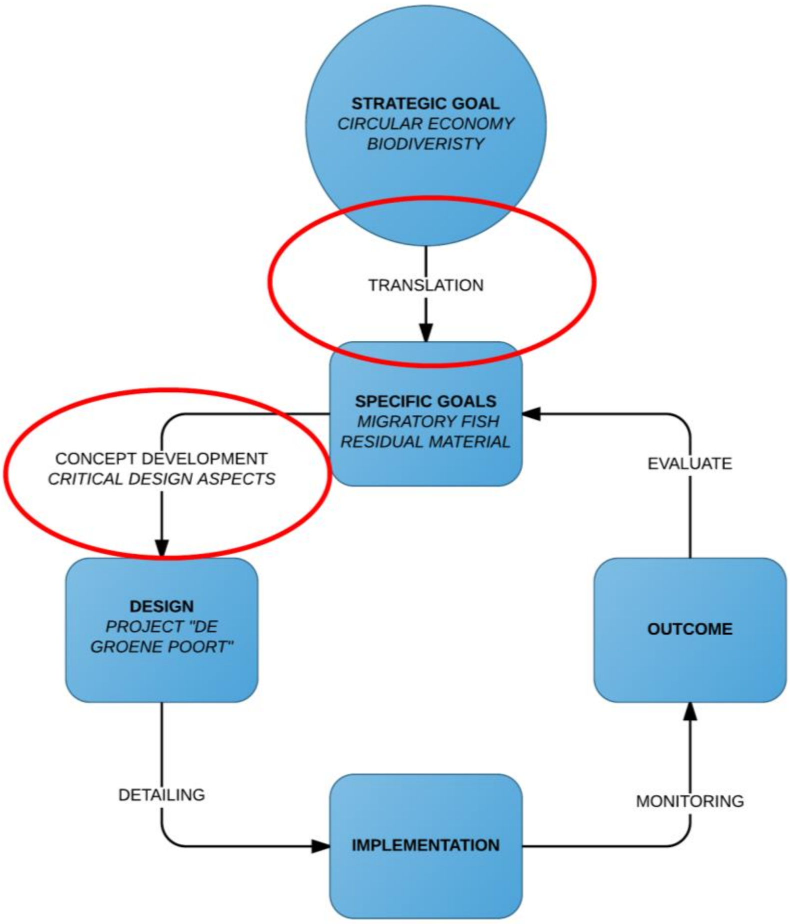


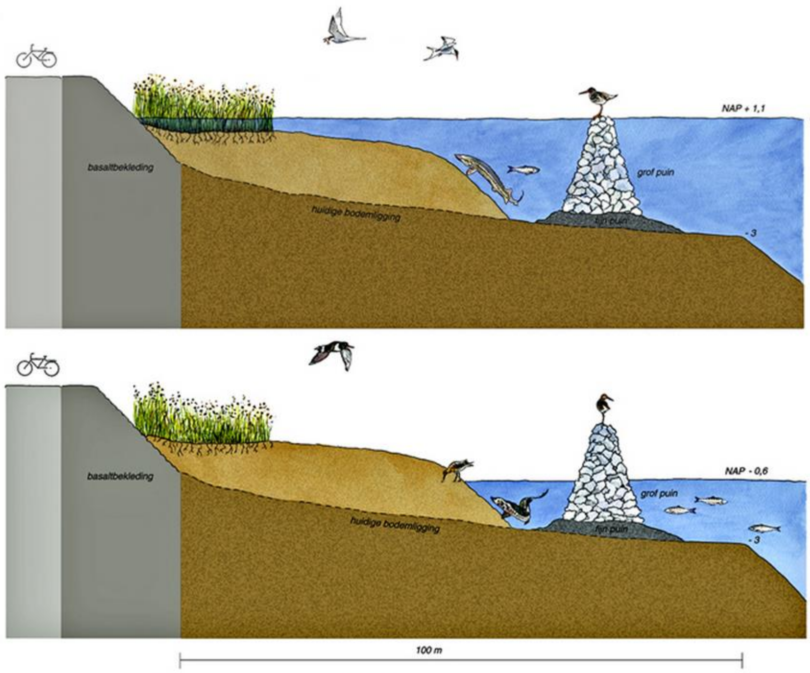
Figure 4.2 Uncertainties in the case study design with respect to the analytical framework

The main conclusions of the stakeholders interviews is thus that more emphasis must be placed on gaining knowledge on the critical design aspects and translating them in a proper design. A more comprehensive overview of the interview results can be found in Appendix A.

4.2 Assumptions

One of the specific goals of project "De Groene Poort" is to increase the biodiversity of migratory birds in the port and its surroundings. It is assumed that when the aquatic biodiversity is enhanced, a diversity of migratory bird species will also be attracted. This is because aquatic life is a major food source for migratory birds [Bak, A., personal communication, November 13th 2015]. Therefore, the design study will focus on the 'wet' part of the design rather than the 'dry' part of the design.

The design of the 'wet' part consists of three main components: the dam, the nourishment behind it, and the wet strip between the dam and the nourishment as can be seen in Figure 4.3. The assumptions made for each of these components are discussed in this section.



GHW = Gemiddeld hoog water GLW = Gemiddeld laag water

Figure 4.3 Artist impression of the design concept of project "De Groene Poort" (not to scale) [Hiddema et al., 2013]

4.2.1 Dam

As explained before, the design of project "De Groene Poort" consists of a parallel dam between the existing groynes. The purpose of the dam is to create a protected area between the groynes for fish to shelter and for the nourishment behind the dam to be stable. The roughness of the concrete elements or rocks creates possibilities for mussels, algae, weeds etc. to establish. The pores between the elements give room for shrimp, crabs, etc. The following assumptions are made with respect to the dam:

- The dam is made of concrete elements or rocks.
- The dam is located 25m behind the existing groyne heads, at a depth of -2.5m NAP.
- In the preliminary design the crest of the dam is located at Mean High Water (MHW).

Because the dam is located at Mean High Water (MHW) there is no water exchange between the wet strip and the channel during low water conditions if no additional measures are taken. Stagnant water is not desirable for the ecological performance in general [Ross, S., personal communication, February 22nd 2015] so it is necessary to make openings in the dam to allow the water behind the dam to be refreshed. Moreover, these openings make it possible for fish and other species to migrate to and from the nature friendly bank during both low and high water conditions. The openings in the dam must meet the following requirements:

- The opening should be large enough to "feed" the hinterland with fresh water;
- Fish are able to pass through the openings during low water conditions;
- Wave penetration through the openings must be minimized.

Based on previous studies of openings in nature friendly banks it is concluded that the wetted area of the openings should be 10 m^2 during MWL [Hiddema et al., 2013]. This is not studied further in this research.

4.2.2 Nourishment

The parallel dam creates a sheltered area between the groynes. Behind the dam a sand/silt mixture is nourished to shallow the area such that an intertidal area is created. The intertidal area is a gradual, sandy transition between low and high water created by a gentle slope. During high water conditions, this area is flooded. During low water conditions, the area falls dry.
It is assumed that a slope of 1:10 is able to create an intertidal area suitable for ecological conditions [Bak, A., personal communication, November 13th 2015].

4.2.3 Wet strip

To allow fish to forage in the sheltered area between the bank and the parallel dam, enough water depth must be available during low tide for the fish to swim. A space of 5 m wide between the dam and the nourishment is assumed to be sufficient for fish to forage.

4.3 Functional boundary conditions

The functional boundary conditions follow from an analysis of the project site and its surrounding area. These functional boundary conditions are related to three important functions in the project area:

1. shipping function;
2. flood safety ;
3. nature and recreation.

4.3.1 Area analysis

Project "De Groene Poort" is situated in the Port of Rotterdam, between the city of Rotterdam and the North Sea. The project site is located in the Nieuwe Waterweg between the Maeslantkering and the village of Rozenburg. An overview of the area is shown in Figure 4.4.

Figure 4.4 Area overview (left) and project site (right, highlighted in green) (images obtained from Google Earth)

The Nieuwe Waterweg (indicated by the red line in Figure 4.4) is a man-made, estuarine water connection between the city of Rotterdam and the North Sea. Construction of the channel started in 1863, when Rotterdam had already established itself as an important port for North-West Europe. To be able to maintain its important position the Port of Rotterdam initiated the construction of the Nieuwe Waterweg to allow for larger ships in the port and a better connection between the city harbours (Botlek, Waalhaven, etc.) and the North Sea. It is an important connection for the Port of Rotterdam and can be seen as a "highway for ships" [Rijkswaterstaat, 2011b]. The Nieuwe Waterweg has a length of 20.5 km and connects the lower parts of the river Rhine ("Het Scheur" and "Nieuwe Maas") to the outflow to the North Sea ("Breeddiep"). The width of the channel varies from 480 m to 675 m, and the depth varies from -14.5 m NAP to -16.0 m NAP [Rijkswaterstaat, 2009].

During the construction of the Nieuwe Waterweg groynes were added to the design. Groynes ensure a uniform flow distribution in the mainstream, which involves a certain flow velocity and sediment transport. This keeps a channel at depth and in position. Furthermore, the groynes cause turbulence at the groyne heads, as illustrated in Figure 4.5. This leads to mixing of marine and fresh water which reduces the intrusion of marine water towards the inland. Thus, the groynes in the Niewe Waterweg nowadays have two main functions [Rijkswaterstaat, 1980];

- maintaining the channels position by minimizing erosion and sedimentation;
- reducing the salt intrusion by causing a mixing effect due to the extra turbulence (as illustrated in Figure 4.5).

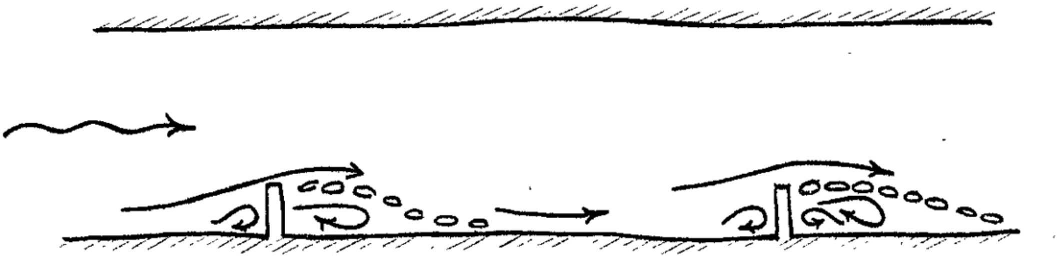


Figure 4.5 The mixing effect of groynes [Rijkswaterstaat, 1980]

As can be seen in Figure 4.4 the project site is located between the Maeslantkering and the city of Rozenburg. The Maeslantkering is the largest moveable flood barrier in the world. It can close off the Nieuwe Waterweg from the North Sea, making it an important element in the Dutch Flood protection system. Rozenburg is a small village with approximately 13.000 inhabitants that is situated on a spit called "Landtong Rozenburg". It is located between the Nieuwe Waterweg and the Callandkanaal. Over the past few years a large nature development project has taken place and turned "Landtong Rozenburg" into a large nature and recreation area.

As can also be seen in Figure 4.4 the project site is divided into two locations:

- Southern area;
- Northern area.

The Southern area contains intertidal area. This intertidal area was created by a nourishment that was part of a nature development project. This intertidal area remains in place because of the sheltered conditions caused by a ferry dock just upstream of the area. The sheltered conditions facilitate conditions for sedimentation and less impact of hydrodynamic loads, allowing vegetation to develop, as illustrated in the right part of Figure 4.6. This is the desired situation for project "De Groene Poort".

The riverbanks at the project site are made of steep, blocked revetments, as can be seen in the left part of Figure 4.6. The banks are exposed to currents and waves from ships passing by. This situation can be considered nature unfriendly. During ebb tide the banks run dry for a short period of time. The area is characterized by relatively high flow rates and ship waves. The intertidal zone is littered with stones and there is no vegetation present. The nature is limited to hard substrate types and species in sediment life [Gemeente Rotterdam, 2012].

Figure 4.6 Current situation (left) and desired situation (right) [Gemeente Rotterdam, 2012]

4.3.2 Shipping

A very important function that should be considered in this area is that of the Port of Rotterdam. As mentioned before, the Nieuwe Waterweg, alongside which the project is situated, can be considered as a “highway for ships”. In general, ships can be divided into three main groups:

1. inland ships;
2. seagoing ships;
3. recreational ships.

This study focusses on inland and seagoing ships since it is expected that these types of ships generate the governing loads on the banks. In 2010, there were over 135.000 commercial ship passages in total (inland and seagoing ships combined). This number is expected to grow continuously over the following decades as is shown in Table 4.1 in which high growth and low growth scenarios of shipping in the future are shown.

Type	2010	2050 (low growth scenario)	2050 (high growth scenario)
Seagoing ships	57.504	60.076	87.802
Inland ships	76.691	90.169	153.309
Total	*134.195*	*150.245*	*241.111*

Table 4.1 Commercial shipping in the Nieuwe Waterweg [Ecorys, 2012]

In Europe, inland shipping channels are divided in CEMT classes. The maximum allowed sizes of the inland vessels in a channel are established per class. The Nieuwe Waterweg has the classification ‘VIb’ which means ships pass with maximum dimensions as shown in Table 4.2 below.

Class [CEMT]	Length [m]	Beam [m]	Draught when laden [m]	Speed [kn]
VIb	185-195	22.8	2.5 – 4.5	8 - 10

Table 4.2 Dimensions of the governing inland vessel in the Nieuwe Waterweg [Rijkswaterstaat, 2011b]

For sea-going ships no specific classes are defined. The available width and depth of the channel are governing for the maximum admitted sea-going ships. An overview of the governing dimensions of the admitted sea-going ship in the Nieuwe Waterweg is presented in Table 4.3.

Length [m]	Beam [m]	Draught when laden [m]	Speed [kn]
360	60	13	4-5

Table 4.3 Dimensions of the governing sea-going vessel in the Nieuwe Waterweg [Port of Rotterdam harbourmaster, personal communicaton, April 28th 2015]

As can be expected, this important shipping function imposes conditions for the design of the nature friendly banks. The design may not impose limitations for shipping.

4.3.3 Flood safety

The area around the Nieuwe Waterweg is very important in terms of flood defence. Along the Nieuwe Waterweg dikes are situated that are part of a primary flood defence of the first category. This means that the flood defence belongs to the system that directly encircles a dike ring area and retains outside water. A dike ring area is defined in the Dutch law as 'an area that has to be protected against flooding by a system of dikes, especially in case of high storm surges, high water conditions in one of the major rivers, the Ijsselmeer or Markermeer, or a combination of all these factors'. The dikes alongside the Nieuwe Waterweg are part of dike ring area 14 (province South-Holland) and dike ring area 19 (Rozenburg) [Ministerie van Verkeer en Waterstaat, 2007].

As mentioned before, the Maeslantkering is located just downstream of the project site. It is also a very important component in the flood protection of The Netherlands. It is part of the Delta Works that protect The Netherlands against high water, especially the southern, low-lying provinces Zeeland, Zuid-Holland and Noord-Brabant. The Maeslantkering is an important component in protecting the area of Rotterdam against high water.

Summarizing, the area around the Nieuwe Waterweg is very important in terms of flood defence. The design of project "De Groene Poort" may not impose limitations on the flood safety of this area.

4.3.4 Nature and recreation

Although the Nieuwe Waterweg is a man-made channel it is a valuable site in terms of nature. It is an estuary with a moderate tidal range, which makes it a dynamic environment with changes in both salinity as well as in water level. This attracts all kinds of species that are unique for this hydrodynamic regime [Rijkswaterstaat, 2009].

Along the Nieuwe Waterweg, near the project site, a spit called "Landtong Rozenburg" is situated. "Landtong Rozenburg" is a nature compensation project initiated as a result of the construction of Maasvlakte 2. It included the removal of desolate industrial sites, the planting of trees, grazing meadow for wild horses and the construction of a cycle and skating path. The design of project "De Groene Poort" may not impose limitations for the further development of this area.

4.4 Physical boundary conditions

The environment of the Nieuwe Waterweg is dynamic with changing water levels and salinity gradients and ship-induced water movements. The design of the banks must be able to withstand this dynamic environment. In order to be able to make a good design, more insight is required in the governing conditions. This section discusses the physical boundary conditions of the project site. The research focusses on one groyne field; however physical boundary conditions might vary per groyne field.

4.4.1 Bathymetry

The bathymetry of one groyne field is plotted by making use of data obtained from Rijkswaterstaat and data obtained from soil tests near the shore. The plots are presented in Figure 4.7.

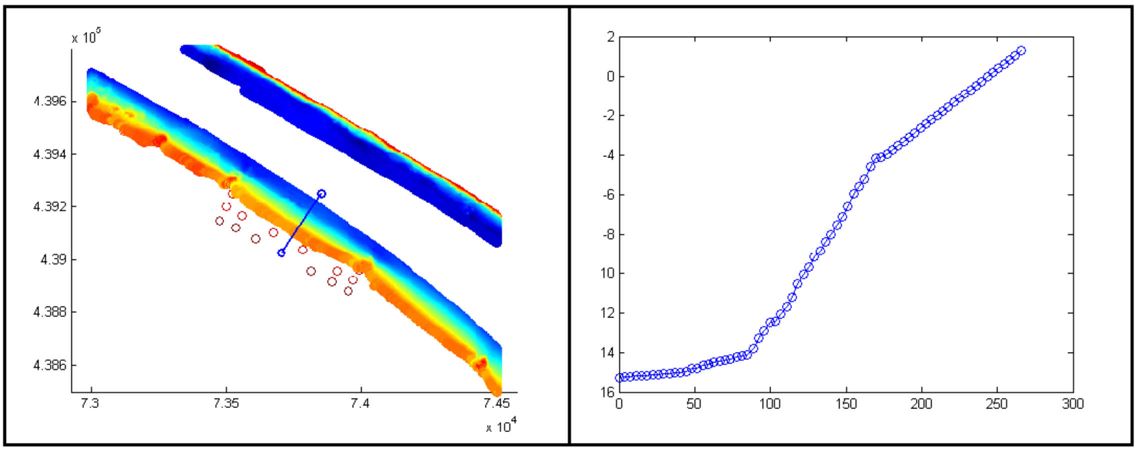


Figure 4.7 Bathymetry of a groyne field in the Nieuwe Waterweg (right) and an overview of the location of the cross-section (left) (based on data obtained from Rijkswaterstaat)

4.4.2 Tide

The water levels in the Nieuwe Waterweg are influenced by the tide, as illustrated in Figure 4.8 and Table 4.4.

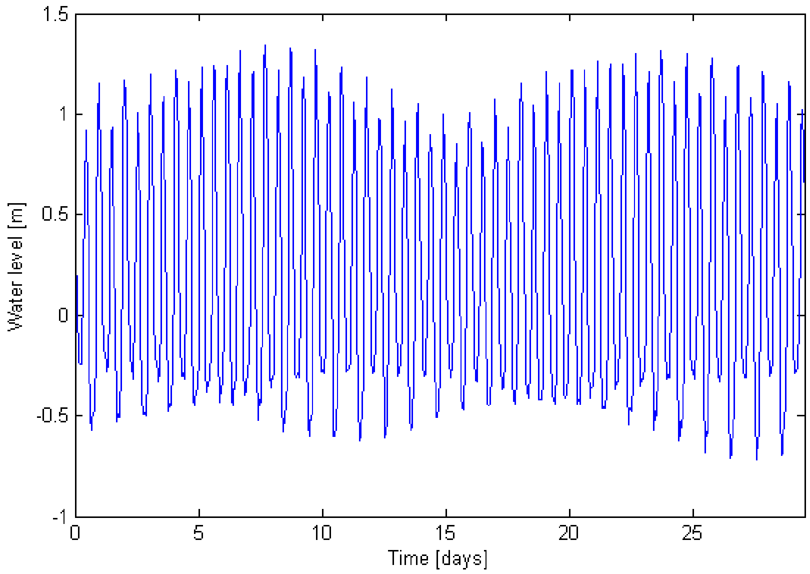


Figure 4.8 Water levels influenced by the tide in the Nieuwe Waterweg (based on data obtained from Rijkswaterstaat)

As can be seen in Figure 4.8 the amplitude of the low water levels and high water levels vary with two extreme high water levels and three extreme low water levels during the time duration of 29.5, which is exactly one lunar month. When sun, earth and moon are in one line the solar and lunar tides reinforce each other. The tide then has a relatively large amplitude. This effect is called spring tide. When the solar and lunar tides are out of phase, their effects cancel each other and consequently the tide gets a smaller amplitude. This effect is called neap tide. The spring and neap tide cycle varies with moon phase and therefore with the lunar month of 29.5 days [Bosboom & Stive, 2010]. This can be clearly seen in Figure 4.8 in which the water levels in the Nieuwe Waterweg are plotted for one lunar month. The effects of the neap tides and spring tides can clearly be seen.

Water level	Abbreviation	Value
Very high water	HHW	+1.9m NAP
Mean High Water	MHW	+1.1m NAP
Mean Water	MW	+0.27m NAP
Mean Low Water	MLW	-0.6m NAP
Very low water	LLW	-2.7m NAP

Table 4.4 Relevant water levels [Witteveen+Bos, 2011]

4.4.3 Ship induced waves and water movements

As mentioned before, the banks in the Nieuwe Waterweg are made of steep, blocked revetments and are exposed to currents and waves from ships passing by. These ship induced water movements are generated by moving vessels and can be divided into three main components:

1. a primary wave;
2. a secondary wave;
3. a propeller jet.

The primary wave is the result of water flowing around the ship. It consists of a front wave, a water level depression and a stern wave as illustrated in Figure 4.9 and Figure 4.10. The secondary wave is formed by a number of periodic waves: a wave train. These periodic waves are formed by the pressure pattern that is caused due to the discontinuities in the ship's hull profile. The secondary waves consists of transverse and diverging waves that meet at so-called 'interference peaks' (see Figure 4.9) [Schiereck, 2012]. The propeller jet can induce high current velocities if the ship is manoeuvring. This can be ignored in this case since the Nieuwe Waterweg is not a location where ship manoeuvring is often taking place.

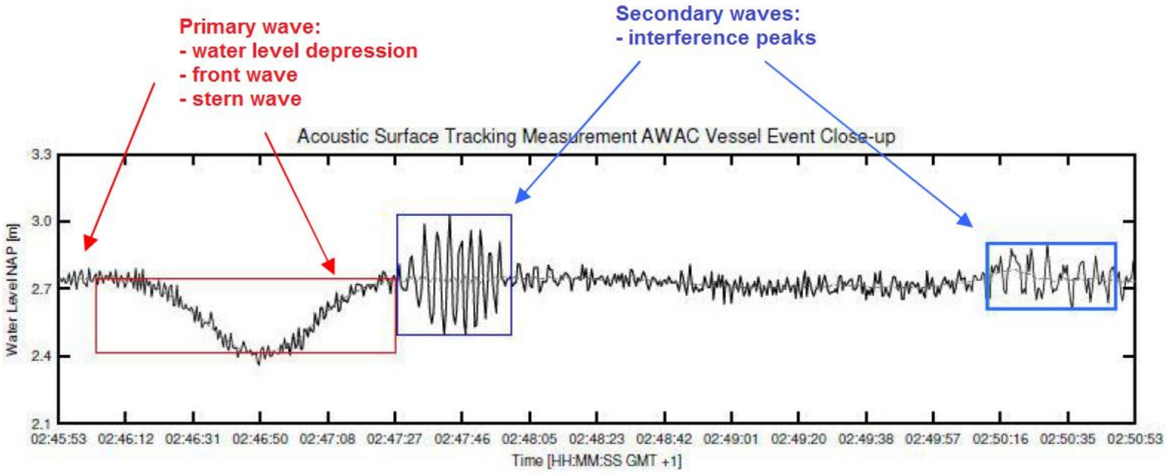


Figure 4.9 Wave signal of an ocean-going vessel [Schroevers & Van der Wal, 2011]

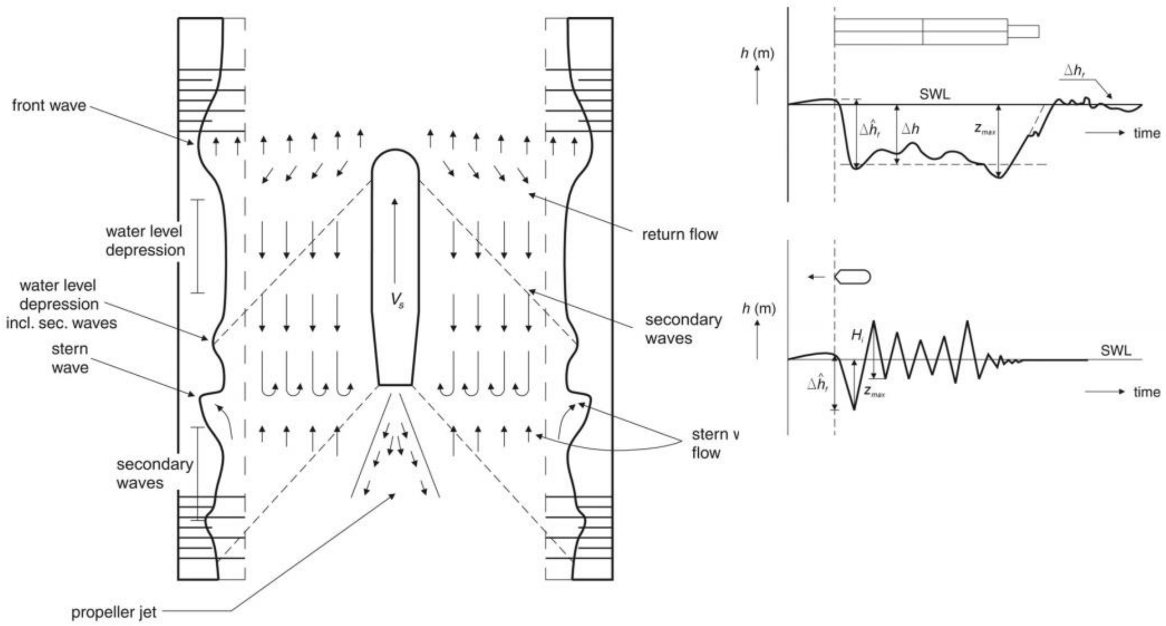


Figure 4.10 Top view of ship-induced waves [CIRIA, CUR, & CETMEF, 2007]

The available literature is divided on the governing component of the ship induced water movement and thus the governing conditions in the Nieuwe Waterweg. Therefore a deterministic analysis is performed using several methods to calculate the governing ship-induced movement. The results are then compared with statements from literature. The calculations and results of the several methods are presented in Appendix B. Results of the calculations of the governing conditions of ship-induced water movements in the Nieuwe Waterweg are shown in Table 4.5.

Relevant wave component	Height [m]	Period [s]
Water level depression	0.5	40
Stern wave	0.75	3
Secondary wave	1	2.7

Table 4.5 Relevant ship induced water movements

From observations in the "marine traffic app" it is estimated that approximately every 10 minutes a ship of considerable size passes. The "marine traffic app" is an application that shows in near real time the position of ships and yachts worldwide. The application covers most major ports and shipping lanes because it is connected to the largest network of AIS (Automatic Identification System) receivers.

4.4.4 Wind waves

The governing wind direction at the project site is WNW (West North West) and has a maximum fetch of 2.5 km and a maximum speed of 10 m/s [Rijkswaterstaat, 2009] the significant wave height according to the Bretschneider formula is 0.36m, as is determined with the Cress application of which the result is illustrated in Figure 4.11.

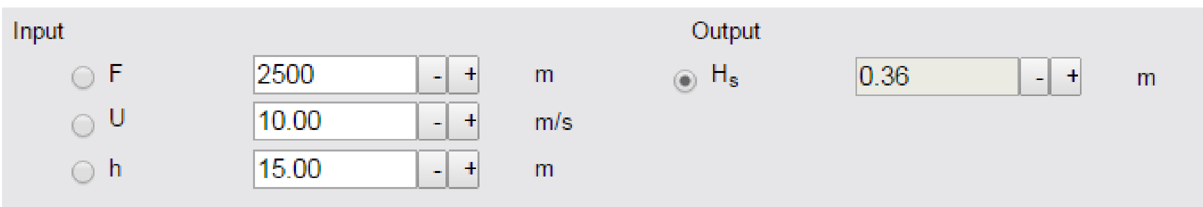


Figure 4.11 Wind wave calculated with the Bretscheinder formula in CRESS

When ship waves and wind waves are compared it can be concluded that the ship waves are significantly higher. Therefore, the wind waves in the Nieuwe Waterweg are considered to be insignificant [Rijkswaterstaat, 2009].

4.4.5 Subsoil composition

The soil of the project site has been investigated by studying existing cone penetration tests and taking soil samples. The shallow subsurface until a depth of -13m NAP consists of clay embedded with sand layers. The vertical permeability of this layer is poor. Below -13m NAP a layer of mainly sand, alternating with thin layers of clay, found. A more extensive elaboration on the subsoil composition can be found in appendix E

4.4.6 Salinity

As can be seen in Figure 4.12 the Nieuwe Waterweg has varying conditions in terms of salinity. The variation in salinity in time can be explained by the influence of the tide. As was already mentioned, the Nieuwe Waterweg has a semi-diurnal tide with two low tide and two high tides during a day. This variation is also applicable to the salinity, having two high and two low values of concentration every day. In Figure 4.12 the salinity concentrations in the Nieuwe Waterweg are plotted for five consecutive days (data is obtained from Rijkswaterstaat that only provides salinity concentration datasets of five consecutive days).

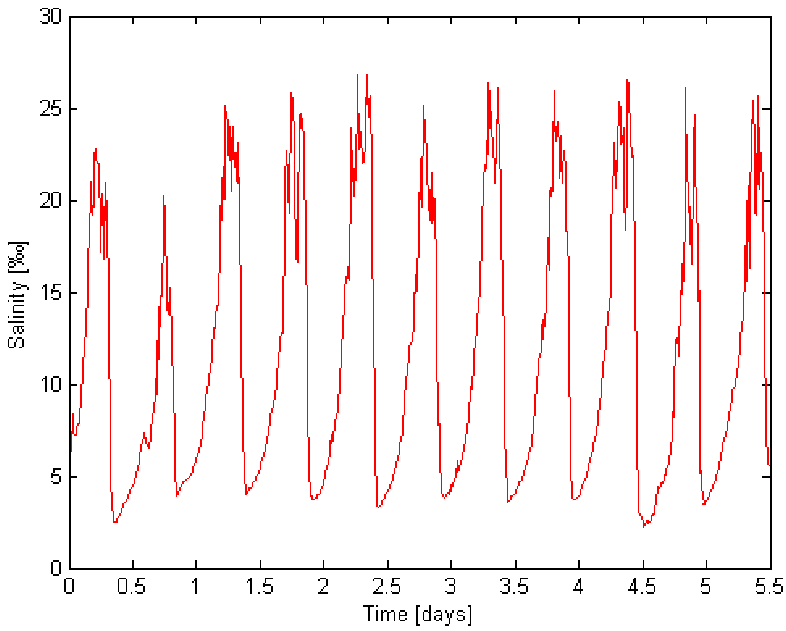


Figure 4.12 Varying salinity in the Nieuwe Waterweg (based on data obtained from Rijkswaterstaat)

4.5 Critical design requirements

As was concluded from the stakeholder analysis: there are four critical design aspects in designing nature friendly banks made of residual material in a port. These critical design aspects affect both the success of the project as well as the functioning of the port and its surroundings.

In this section the requirements set by the stakeholders are presented.

4.5.1 Stability

The design of the dam and the nourishment must be stable. The stability requirement applies to the following elements of the design:

- Dam: no loss or movement of blocks is allowed;
- Nourishment: minimize erosion/sedimentation;
- Subsoil: scour and settlements due to the additional loads must be minimized.

4.5.2 Functioning of the port and surroundings

The requirements with respect to the functioning of the port and surroundings apply to the following functions:

- shipping;
- flood safety;
- nature and recreation.

The design must not impose limitations for shipping. Therefore:

- the increased wave reflection caused by the dam must be minimized (order of magnitude 5-10%);
- no obstruction of the waterway may occur, therefore the nourishment and the dam must be stable, in other words: no loss of material may occur.

The design of project "De Groene Poort" must not impose limitations on the flood safety of this area.

The design of project "De Groene Poort" must not impose limitations for the further development of the nature and recreational area around "Landtong Rozenburg".

4.5.1 Circular economy

One of the main objectives of the project is to enhance the circular economy by reusing residual material.

In order to specify clear requirements with respect to this objective, more insight must be gained in the opportunities of project "De Groene Poort" in terms of adding value to the circular economy of the port and its surroundings. Chapter 5 provides insight information in the reuse of residual material and the project's business case. Subsequently design requirements with respect to the circular economy can be specified.

4.5.1 Ecological performance

Another main objective of the project is to enhance the biodiversity in the port by improving the living conditions of migratory fish in the area.

In order to specify clear requirements with respect to this objective more insight must be gained in the opportunities of project "De Groene Poort" in terms of adding value to the habitat of migratory fish. Chapter 6 provides insight information in the ecological objectives of the project and the habitat requirements of migratory fish. Subsequently design requirements with respect to the ecological performance of the design can be specified.

5. Circular economy

5.1 Introduction

Enhancing the circular economy of the Port of Rotterdam and its surroundings is a requirement of project "De Groene Poort", as can be read in chapter 4. As was already concluded in chapter 5 enhancing the circular economy can contribute to the strategic goal of the Port of Rotterdam to become a sustainable port. The aim of project "De Groene Poort" is to enhance the circular economy in the port and its surroundings by using residual material as a construction material.

Residual material can be seen as waste in one project but also as a commodity for another project. By reusing waste material in ports, value chains of different companies or clusters of companies are connected. In project "De Groene Poort" the aim is to use residual material from other projects in port and its surroundings as a construction material instead of dumping it as waste. This is consistent with the principle of a circular economy in which (in this case technical) nutrients are seen as a construction material rather than as waste (see Figure 5.1). In this case the focus lies on two types of residual material that can be used in the project:

1. dredged material;
2. coarse residual material.

Figure 5.1 Residual material as a commodity instead of waste [Port of Rotterdam, 2011]

Besides enhancing the circular economy, using residual material can also benefit the business case of project "De Groene Poort" by reducing project expenses by:

1. saving the dumping fee of getting rid of residual material;
2. not having to purchase construction material.

This chapter gives insight in the opportunities of project "De Groene Poort" with respect to the circular economy. Insight is given in the reuse of residual material and the project's business case. This is done by:

1. specifying the objectives of the project concerning the circular economy (section 5.2);
2. making an analysis of the current practices, legislation and opportunities with respect to dredged material (section 5.3);
3. making an analysis of current practices, legislation and opportunities with respect to coarse residual material (section 5.4);
4. Assessing the feasibility of the project in terms of the specified objectives, availability of material and the business case (section 5.5);
5. specifying requirements for the final design (section 5.6).

5.2 Circular economy in the Port of Rotterdam

To gain more insight into the possible added value of this project to the circular economy of the Port of Rotterdam the level of detail on which the project can add value must be taken into account.

5.2.1 Level of detail

In any project it is possible to discern various levels of detail. It is important to be aware of the level of detail one is working on and to keep an eye on the adjacent levels. An example of levels than can be distinguished is [Schiereck, 2012]:

1. System (Macro level)
2. Components (Meso level)
3. Parts (Mini level)
4. Elements (Micro level)

Table 5.1 gives an overview of the division of levels with respect to the circular economy in the Port of Rotterdam and project "De Groene Poort".

Level	Interpretation	Objective
1. System	Circular economy of the Port of Rotterdam and its surroundings	Contribute to the objectives of a sustainable port
2. Component	Different clusters of residual material	Reducing waste flows and the purchase of raw materials
3. Part	Project "De Groene Poort"	Valuable destination for several types of residual material
4. Element	a. Dam b. Nourishment	Valuable destination for: a. coarse residual material b. dredged material

Table 5.1 Level of detail of project "De Groene Poort" in the circular economy

The system comprises the entire circular economy of the Port of Rotterdam and its surroundings. The objective of the circular economy is to enhance the sustainability of the Port of Rotterdam and thereby helps reaching the goals of the Port of Rotterdam in terms of sustainability (as laid out in the "Port Vision 2030") [Port of Rotterdam, 2011]. The circular economy can be divided on the component level into different clusters of residual material flows, for example clusters of:

- energy (e.g. carbon, gas);
- metals;
- chemicals;
- dredged material;
- coarse residual material (e.g. debris).

Project "De Groene Poort" can function as a part of the two latter clusters. The two main elements of the nature friendly bank (the dam and the nourishment) can both serve as a valuable destination for a specific type of residual material.

5.2.2 Objectives project "De Groene Poort"

The objective of the project is to enhance the circular economy within the port. As can be concluded from the previous section this can be done by serving as a valuable destination for several types of residual material (see Table 5.1). The project can be valuable to the circular economy in the Port of Rotterdam because of two main reasons:

- the location of the project site is favourable;
- the project adds value to the functioning of the port and surroundings.

Project "De Groene Poort" is centrally located within the port and easily accessible by water and by land. This central location of project "De Groene Poort" means that residual material from the port and its surroundings will not have to be transported over a long distance. Therefore transport costs and C02 emissions can be reduced. Besides that, the project site is located alongside a wide and deep channel (The Nieuwe Waterweg) which makes it easily accessible for ships. Besides its favourable location, the project is a valuable destination for residual material because added nature values are generated that improve the functioning of the port in terms of sustainability.

Summarizing, project "De Groene Poort" can contribute to the larger system of the circular economy in the Port of Rotterdam by making efficient use of resources by using residual material from nearby, thereby reducing transport costs and emissions and adding value to the port in terms of sustainability.

However, using residual material as a construction material in project "De Groene Poort" must be feasible and profitable for the stakeholders that are involved. Therefore, the feasibility of the project is further investigated. This is done by gaining insight on current practices in the port with respect to these materials, legislation on the use of these materials as a construction material and on the preferred composition of the material.

5.3 Dredged material

It is the aim to use dredged material dredged material as a construction material for the nourishment behind the dam. Dredged material is soil that has become available from the subsurface through the surface water or space intended for the surface water. Soil is a solid material and is composed of mineral parts with a maximum grain size of 2 millimetres and organic matter in a ratio and having a structure such as naturally found in the subsurface material [Boskalis Dolman bv, 2008].

This section discusses the current practices in the port with respect to dredged material, the legislation involved when using dredged material as a construction material and the preferred composition of the used material in project "De Groene Poort".

5.3.1 Current practices

A lot of dredged material is produced in the Port of Rotterdam because of ongoing maintenance dredging on the waterways. Furthermore, a lot of soil is becoming available from construction works in the city of Rotterdam. Depending on the degree of pollution and the composition this material is either being dumped or reused. The material flows with respect to dredged material are illustrated in Figure 5.2.

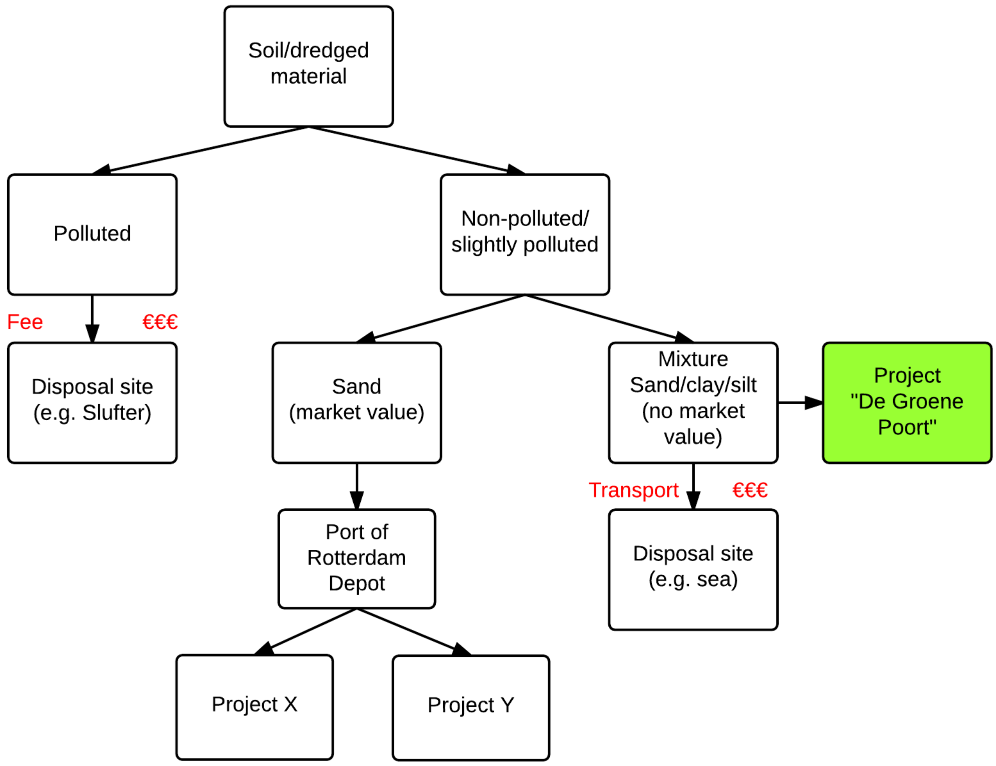


Figure 5.2 Soil and dredged material flows in the Port of Rotterdam

As can be seen in the diagram (heavily) polluted material is dumped on a disposal site for which a fee has to be paid to the administrator of that particular disposal site. This material is too polluted to be re-used in any project. Therefore, this type of material cannot add value to the circular economy of the Port of Rotterdam. Non-polluted or slightly polluted material is, depending on its composition, reused in a project or dumped at a disposal site (often at the North Sea). Material that mainly consists of sand has a considerable market value and is stored in a depot before it is redistributed over projects in the port (for example Maasvlakte 2). Material that consists of a mixture of sand, clay and silt has no considerable market value and is generally transported towards sea. This material is also suitable to be used in project "De Groene Poort", which is therefore added to the diagram in Figure 5.2. Using this type of material can enhance the circular economy by cutting the costs and emissions induced by the large distances over which the material normally has to be transported (to the sea).

5.3.2 Legislation

Legislation on the use of dredged material is inter alia fixed in the Decree of Soil Quality [Boskalis Dolman bv, 2008]. According to the rules batches of dredged material may be used only in case of a "useful application". A list of "useful applications" has been provided by the Decree. It is assumed that project "De Groene Poort" is a "useful application" because of its objective to enhance ecological conditions within the port. Thus it is assumed that it is legally allowed to use dredged material as a construction material for the project.

5.3.3 Preferred composition

Two types of distinctions can be made with respect to the composition of dredged material:

1. constructive and non-constructive soil;
2. degree of pollution.

Dredged material usually consists of a sand/clay/silt mixture, several mixtures are illustrated in the "soil texture triangle" presented in Figure 5.3. The "soil texture triangle" specifies the composition of several types of soil.

The smaller the sand fraction of the mixture, the smaller the level of constructivity and thus the smaller the market value. It is advised to use constructive material that remains in place under all circumstances. This means that the soil that is used has a significant sand fraction. Furthermore, it is advised to use a soil mixture with a 10-20% silt fraction, which enhances the growth of plants [Slinger, J.H., personal communication, April 1st 2015]. A suitable type of soil is sandy clay loam of which the composition is illustrated in Figure 5.3.

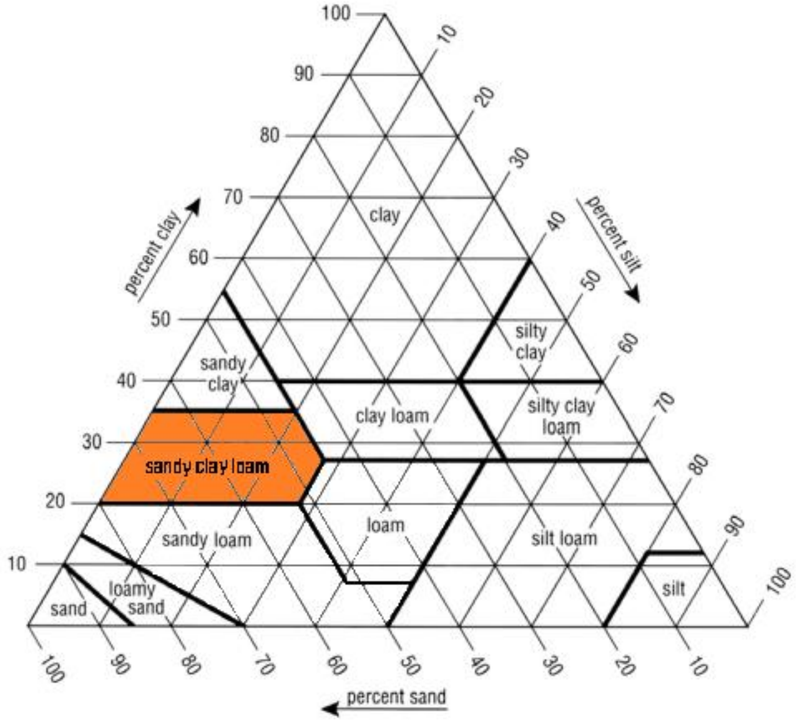


Figure 5.3 Preferred soil composition [Schiereck, 2012]

Although it would benefit the business case, it is not advised to use (slightly) polluted material within the nature friendly bank. This has two main reasons:

1. it would threaten the ecological objectives of the project;
2. it may lead to bad imaging of the project and its stakeholders.

The ecological objectives of the project may be threatened when polluted material is used because organisms can be very sensitive to polluted soil and polluted water [Hermans, A., personal communication, December 12th 2014]. Using polluted residual material may also lead to bad imaging for the project and its stakeholders because the public might see the project as a huge waste disposal opportunity.

5.4 Coarse residual material

In project "De Groene Poort" it is the aim to use coarse residual material as a construction material for the dam. This section discusses the current practices in the port with respect to coarse residual material, the legislation involved when using this type of material as a construction material and the preferred composition and element size of the used material in project "De Groene Poort".

5.4.1 Current practices

Coarse residual material (e.g. debris) becomes available from the port and surroundings from a variety of projects. This material usually becomes available on the market in large batches at a time for example because of the demolition of old quay walls. Depending on the uniformity of the grading this material is either being stored in a depot or taken to a crusher. The material flows with respect to coarse residual material and debris is illustrated in Figure 5.4.

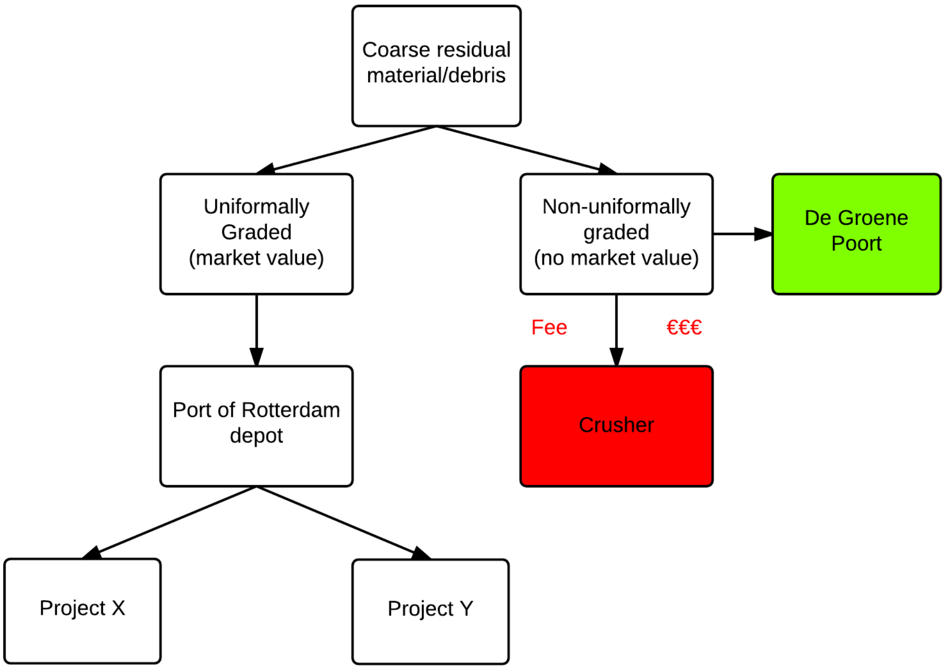


Figure 5.4 Coarse residual material flows in the Port of Rotterdam

As can be seen in Figure 5.4 uniformly graded material has a considerable market value and is therefore stored in a depot of the Port of Rotterdam awaiting a suitable destination within the port. Non-uniformly graded material has no considerable market value and is usually brought to a crusher for which a fee has to be paid. The crusher generally crushes the material to a product that is as fine as possible, after which the fine material is put on the market for sale. This material is generally used as a base cover underneath roads. The process of crushing is polluting and energy guzzling, therefore this alternative has a red colour in the diagram: indicating its negative impact on the environment. This negative impact has the following reasons:

- CO_2 is emitted during transport of the coarse residual material to the crusher;
- a lot of energy is needed to crush the material;
- potentially dangerous particulate matter is released in the atmosphere during the crushing process [Stigter, H., personal communication, October 10th 2014].

Besides the negative environmental impact of crushing, the demand for the final product of the process is decreasing since relatively few road construction projects are being planned in The Netherlands [Hof, D., personal communication, April 3rd 2015]. Conclusively, coarse material would be a suitable material source for project "De Groene Poort". It can thus add value to the circular economy by reducing the negative impacts of taking this type of material to the crusher. Therefore, the project is indicated with a green colour in the diagram.

5.4.2 Legislation

Legislation on the re-use of construction material is inter alia fixed in the Decree of Soil Quality [Boskalis Dolman bv, 2008]. This decree is not only applicable to soil but also to "rocky" material like concrete and asphalt. The decree sets out rules for the use of construction material, and also has a section especially dedicated to the reuse of construction material.

The rules that are involved when residual material is used as a construction material mainly apply to guarantee the material's quality. The quality of the building material does not need to be re-examined if the following four conditions are fulfilled:

- the construction material does not change of ownership;
- the construction material is not altered;
- the construction material is used under the same conditions as originally intended;
- the application is notified five days in advance with the authorities.

In case of project "De Groene Poort" it is most likely that one or more of the above conditions are not fulfilled. In that case there is an obligation of quality inspection of the residual material. This obligatory quality test usually consists of a leaching test.

Performing these quality tests might lead to high costs of inspection and an administrative burden that is disproportionately large with respect to the benefits of re-using residual material in the first place. An investment has to be made to perform the tests and besides that it is uncertain whether a batch of coarse residual material will pass the quality test. This leads to a high uncertainty in the ultimate costs and benefits of using coarse residual material in project "De Groene Poort".

5.4.3 Element size

The required element size of the coarse residual material follows from the stability requirement. The elements used in the dam must be stable: no displacement of the elements due to waves or currents may therefore occur. The stability of randomly placed elements is depends on the following factors:

- the governing load;
- the gradient of the slope;
- the sizes of the elements;
- the crest width.

Several methods exist to determine the required element size of the blocks used in a partly submerged dam like the dam in project "De Groene Poort". However, all available methods are not 100% applicable in the case of using concrete elements as a bank protection in the Nieuwe Waterweg. Usually, in situations like the Nieuwe Waterweg, quarry stone is used in the construction of the bank protections. The use of concrete blocks in The Netherlands is generally only economical in case very large elements are required, for example at a sea defence [Van den Bos, J., personal communication, December 10th 2014]. Formulas used to calculate the required size of the concrete elements usually apply to large wind and storm waves rather than ship induced waves. Therefore an assessment is done based on different methods, using formulas that apply to both ship waves and wind waves, and dimensions of quarry rock and concrete elements. The results are compared and it is expected that a combination of several methods gives an appropriate impression of the required element size. Appendix D contains an extensive elaboration of this assessment.

The results vary between a required element sizes of 0.42 m to 0.56 m, with varying weights of 182 kg to 478 kg. In a sample of coarse residual material there will always be a range of block weights. In this case, a standard grading of 300 – 1000 kg is assumed to be suitable to account for the stability of the dam. This is associated with a maximum element diameter of 0.75 m. This standard grading has also been applied on the groynes in the area, which are known to be stable [Hiddema et al., 2013]. This confirms the assumption that using a 300 – 1000 kg grading ensures a stable dam.

5.5 Feasibility

Using residual material as a construction material in project "De Groene Poort" must be feasible and profitable for the stakeholders. The feasibility and profitability of the project depend on respectively:

- the availability of material, discussed in section 5.5.1;
- the business case, discussed in section 5.5.2.

5.5.1 Availability and impact on circular economy

The approximated required amounts of coarse residual material and dredged material are specified in Table 5.2 These amounts are based on the original design of project "De Groene Poort" with a dam crest level at Mean Water Level +1,1m NAP.

Type of material	Per meter nature friendly bank [m^3/m]	Entire project (6 km) [m^3]
Coarse residual material	29.5	147.500
Dredged material	11.2	56.000

Table 5.2 Required amounts of residual material for construction of project "De Groene Poort"

Dredged material
The required amount of dredged material is approximately 56.000 m^3 which is about the same amount as can be carried by two large hoppers. Dredged material is readily available in the port and its surroundings [Zwakhals, J.W., personal communication, May 5th 2015] [Hiddema, P.W., personal communication, May 6th 2015]. It is therefore expected that with the dredged material from ongoing maintenance works the project can be executed.

Furthermore, the Port of Rotterdam has the intention to carry out a very large dredging project in 2016: the deepening of the Nieuwe Waterweg over a large stretch including the main shipping channels of the ports in the Botlek area. This will produce a major amount of dredged material with an order of magnitude of 1-2 million m^3 [Ministerie van Infrastructuur en Millieu, 2014].

Taking into account the amounts of dredged material already available in the port and the large-scale dredging project that is planned, it is expected that the availability of dredged material is not a limiting factor for the feasibility of project "De Groene Poort". However, this also means that the use of dredged material in project "De Groene Poort" will not have a substantial impact on the circular economy of the port. Because of the small demand that the project imposes compared to the large supply in the port it is expected that still a lot of dredged material will have to be deposited at sea whether project "De Groene Poort" will be executed or not.

Coarse residual material
Compared to the amount of required dredged material the amount of required coarse material is relatively large. The availability of coarse material that can be used in the dam is uncertain and expected to be limited [Zwakhals, J.W., personal communication, May 5th 2015] [Hiddema, P.W., personal communication, May 6th 2015]. In section 5.4.3 it was concluded that relatively large blocks are required. These type of blocks do not often become available in and around the Port of Rotterdam. The availability of these blocks for project "De Groene Poort" is therefore not guaranteed.

As a destination for residual material, project "De Groene Poort" is entirely dependent on suppliers of coarse residual material. As large projects in the Port of Rotterdam and surroundings are awarded to contractors, the project depends on these contractors and available projects. The supply of coarse residual material thus highly fluctuates in time because of:

- the dependency on few suppliers;
- a lot of material becoming available at once because of large projects.

An example of a project in which coarse material becomes available is shown in Table 5.3. This project, for which a large breakwater has to be demolished, is expected to be executed in the near future [Zwakhals, W., personal communication, May 5th 2015]. A large amount of coarse residual will then become available that is possibly suitable for project "De Groene Poort".

Project	Amount of coarse residual material [m3]	Distance to project "De Groene Poort"
Project 'Widening of the Breeddiep channel'	40.000 – 60.000	7 km

Table 5.3 Project Breeddiep [Zwakhals, J.W., personal communication, May 7th 2015]

The high fluctuations of the supply of coarse residual material can be explained because the market is underdeveloped. This is because:

- users are not aware of using coarse residual material as a construction material;
- suppliers are stuck in old habits of bringing coarse residual material to the crusher.

Summarizing, there is a large uncertainty in the availability of coarse residual material. Furthermore, for every available party it is unsure whether it meets the legislation of being used as a construction material, as explained in section 5.4.2. There is an obligation of quality inspection of the residual material. This might lead to high costs of inspection and an administrative burden that can be disproportionately large with respect to the benefits of re-using residual material as a construction material in the first place.

Summarizing, the availability of coarse residual material is highly uncertain because of:

- dependency on few suppliers;
- uncertainty if the material meets legislation;
- relatively large demand of coarse material on an underdeveloped market.

5.5.2 Indicative business case

This section presents an indicative business case for project "De Groene Poort". As mentioned before, using residual material as a construction material can benefit the business case of project "De Groene Poort". The indicative business case is based on first order expenses of the project. It is indicative because not all expenses are treated: it is only indicated where expenses/costs can be saved/reduced for the project by making use of residual material. Benefits for stakeholders individually or society in general are not considered; it is however recommended to study this further in the future.

As was already identified, project expenses can be reduced by:

1. saving the dumping fee of getting rid of residual material;
2. not having to purchase construction material.

Saving the dumping fee applies to both the dredged material as well as the coarse residual material. It is estimated that by reusing dredged material approximately 2 €/m^3 can be saved on dumping fees [Hof, D., personal communication, April 3rd 2015]. It is estimated that by reusing coarse residual material approximately 8 €/m^3 can be saved on dumping fees [Hof, D., personal communication, April 3rd 2015].

It is the intention of the stakeholders to finance the project with these saved expenses. However, to give an impression of the costs of construction using conventional construction materials these costs are also considered in this section. The costs of conventional construction material are [Witteveen+Bos, 2010]:

- Soil: 8 €/m^3;
- Coarse material: 36 €/m^3.

Table 5.4 gives an overview of the expenses that can be saved based on the original design.

Type of material *(original design)*	Per meter nature friendly bank [m³/m]	Saved expenses (dumping fee)		Conventional construction material		Entire project (5 km) [m³]	Saved expenses (dumping fee) €	Conventional construction material €
		€/ m3	€/ m3/m	Bulk costs €/m3	Project costs €/ m			
Coarse residual material	29.5	8	236	36	1062	147.500	$1.18*10^6$	$5.31*10^6$
Soil/dredged material	11.2	2	22.4	8	90	56.000	112.000	448.000

Table 5.4 Overview indicative business case project "De Groene Poort"

As can be concluded from Table 5.4 the use of coarse residual material can result in large benefits for the project compared to the use of dredged material. This is caused both by saving the dumping fee as well as by not having to purchase conventional construction material.

However, there are large uncertainties in the business case because of:
1. Uncertainties in availability;
2. Costs of inspection.

There is an obligation of quality inspection of the coarse residual material. This might lead to high costs of inspection and an administrative burden that is disproportionately large with respect to the benefits of re-using residual material in the first place.

5.6 Conclusions and requirements for the final design

One of the two main objectives of project "De Groene Poort" is to enhance the circular economy of the Port of Rotterdam and its surroundings. It was concluded in section 5.2 that this can be achieved by acting as a valuable destination for coarse residual material and dredged material.

5.6.1 Dredged material

As was concluded from the previous section, the availability of dredged material is not a limiting factor for the execution of project "De Groene Poort": the project requires a small amount of material which is furthermore readily available in the port. This however also means that using dredged material as a construction material in project "De Groene Poort" has a very limited impact on the circular economy of the port and its surroundings and on the project's business case.

It would benefit the circular economy and the business case if more dredged material could be used as a construction material in the project. Options to do so should be investigated further. However, since there is little space alongside the banks of the Nieuwe Waterweg, it is still expected that using dredged material in project "De Groene Poort" will not substantially enhance the circular economy of the Port of Rotterdam and its surroundings.

5.6.2 Coarse residual material

The availability of coarse residual material is highly uncertain because of:
- the dependency on few suppliers;
- the uncertainty if the available material meets the legislation;
- the relatively large demand of coarse material on an underdeveloped market.

Thus, with respect to the use of coarse residual material as a construction material, the design should be flexible and adaptive to uncertainties on the fluctuating and underdeveloped market of coarse residual material. The design must be able to adapt to the changing circumstances in the market. The project must have the opportunity to change the design according to the availability of coarse residual material. It should be investigated if alternatives that require less coarse residual material than the original design enable conditions that are suited for the desired ecological state.

Besides that, possibilities of using alternative materials should be investigated to supplement the availability of coarse residual material for the project. One of the options is to make large blocks out of finer, residual material. These blocks would preferably have a density similar to concrete (≈ 2400 kg/m^3). Possibilities of making these blocks are being investigated and very little is known about the costs that are involved. This should be investigated further, however it is outside the scope of this research.

6. Ecological performance

6.1 Introduction

Enhancing biodiversity in the Port of Rotterdam is one of the main objectives of project "De Groene Poort". The aim is to do so by enhancing the living conditions for migratory fish; in particular the Atlantic Sturgeon. However, the conditions that enable the desired ecological state for migratory fish are not known a priori. Therefore, this topic is studied in more detail in this chapter.

Potentially, the area around the Port of Rotterdam could be filled with fish like salmon, trout and eels. However, the area lacks sources of food and places for the fish to shelter during their migration [Rijkswaterstaat, 2008]. The Port of Rotterdam consists of a network of harbours connected by long, wide stretches of waterways. Large ocean going vessels and inland barges navigate through the channels to reach a certain harbour basin or to leave the port towards the sea or an inland route. The banks of these channels are designed to withstand the unnatural loads that are a result of the intensive shipping. The large water depths and little available space in this busy, industrial area generally do not allow nature development [CUR, 1999b].

Nature friendly banks can improve the ecological performance of a waterway [Sollie et al., 2011]. In this chapter, the ecological performance of the nature friendly bank design of project "De Groene Poort" is assessed in detail by making use of a four step approach, these steps include:

1. specifying the ecological objectives of the project (section 6.2);
2. identifying the important ecological parameters and the indicator species (section 6.3);
3. specifying the habitat requirements of the indicator species (section 6.4);
4. specifying design criteria (section 6.5).

6.2 Objectives

In order to assess the ecological performance of the design the ecological objectives must be clearly specified. It is therefore important to consider the level of detail of the project, since it determines the potential influence the project can have on a larger scale.

6.2.1 Level of detail

A very important consideration is how project "De Groene Poort" can add value to the living environment of migratory fish in general and sturgeon in particular. This consideration eventually determines the input and requirements for the final design. To get more insight in the possible value of this project, the level of detail must be taken into account.

In any project it is possible to discern various levels of detail. It is important to be aware of the level of detail one is working on and to keep an eye on the adjacent levels. An example of levels than can be distinguished is [Schiereck, 2012]:

1. System (Macro level)
2. Components (Meso level)
3. Parts (Mini level)
4. Elements (Micro level)

All levels have their own specific goals. In this case a division of levels can be made as presented in Table 6.1.

Level	Interpretation for migratory fish in general	Interpretation in this case	Objective
1. System	Ecological infrastructure for migratory fish	Migratory route along the River Rhine	Facilitate living environment for migratory fish (Atlantic Sturgeon in particular)
2. Component	Stepping stone in the estuary	Estuary in Rotterdam (Project "The river as a tidal park")	Create space for migratory fish to adjust to changing environment in brackish water
3. Part	Configuration of the stepping stone in the estuary	Stretch of nature friendly banks (Project "De Groene Poort")	Enhance the living environment of migratory fish in the port
4. Element	Bank, intertidal area, etc.	Element of the design (dam, nourishment, etc.)	Add value to the living environment of migratory fish

Table 6.1 Level of detail of project "De Groene Poort" in the ecological infrastructure

The system includes the entire ecological infrastructure of migratory fish, which in this case is their migratory route along the river Rhine. This ecological infrastructure consists of a trajectory along the river Rhine and several stepping stones along that trajectory where there is space and food for the fish to forage. Migratory fish need these stepping stones to be able to migrate from the upstream portion of a river towards the sea downstream, and vice versa.

6.2.2 Stepping stone in the estuary

One of the required stepping stones along the migratory route of fish is the estuary, in which the fish forage for a while to adapt to the changing salinity of the water. Studies have shown that the Atlantic sturgeon stays in the area around the Port of Rotterdam for approximately 14 days to adjust to the changing circumstances, before swimming to open sea [de Kok & Meijer, 2012]. It is assumed that migratory fish in general need a certain adaptation time in this area in order to adapt to the changing circumstance. Therefore, extra space and food sources are required for the migratory fish in the estuary. Project "the river as a tidal park", of which project "De Groene Poort" is part of, aims at creating space in this area where there is a natural, gradual transition of fresh to marine water.

However, it can be concluded that the area of project "De Groene Poort" on its own is too small to have a substantial impact on the living conditions of migratory fish in the port and its surroundings. Project "De Groene Poort" can, however, contribute to the living conditions of migratory fish by creating optimum circumstances that fit their habitat. This can be achieved by providing food sources and space for the fish to shelter, both of which the area is currently lacking [Rijkswaterstaat, 2009]. It is assumed that local species that have the estuary around Rotterdam as their fixed habitat can provide the sheltered conditions and the food required for the habitat of migratory fish. This means that the focus of the design should be on local species like vegetation and small organisms that typically live in the intertidal area (mussels, shrimp, little crabs, etc.) rather than on migratory fish. The objective of project "De Groene Poort" to enable conditions that suit the living environment of migratory fish can thereby be reached by adding to their habitat.

6.3 Parameters

Thus, the project can enhance the living environment of migratory fish by focussing on the habitat of local species and vegetation. Thus more insight in the habitat requirements of these species is needed. In this section, the important ecological parameters of a habitat are discussed and indicator species are identified. The ecological parameters and the indicators will eventually determine the requirements for the final design.

6.3.1 Habitat requirements

A habitat includes all the sites where a species appears because the abiotic and biotic factors of these sites meet the requirements and tolerances that allows the organism to survive, grow and reproduce [Baptist, Van der Meer, & De Vries, 2007]. The abiotic factors are the non-living components of an organism's environment that affect the substrate (soil), water and climate. The biotic factors are the living components that affect another organism, including the existing vegetation, plants and other animals [Bolier, 2006]. These abiotic and biotic factors form the requirements of the ecosystem. The specification of these requirements follows from the choice of indicator species.

Abiotic factors
The most important abiotic factors that affect the distribution of species in an estuary are [Burcharth, Hawkins, Zanuttigh, & Lamberti, 2007]:

1. Water movement:
    a. Wave attack;
    b. Tidal influence;
    c. Current velocity;
2. Substrate:
    a. Type of material (sand, concrete, rock);
    b. Grading (fine – coarse);
    c. Orientation (steep – gentle slope);
3. Salinity.

Biotic factors
The biotic boundary conditions in this case apply to:

1. Food sources;
2. Vegetation for shelter.

In reality, the ecological performance depends on a lot more factors than can be included in this (or any) study. Predicting which species certain conditions attract is therefore impossible. However, these factors give a good idea of the suitability of a habitat for a certain species. Water quality parameters, like visibility and oxygen concentration, are thereby of secondary importance [Bolier, 2006].

6.3.2 Indicator organisms

An important tool that assesses the impact of new developments within an ecosystem is the assessment based on indicator organisms. Indicator organisms are organisms that are characteristic to certain ecosystems and often play an important role in the food chain of that system. The requirements and tolerances that allow the indicator organisms to survive, grow and reproduce form the requirements of the final design.

Three levels of indicator organisms have been specified for this study:

1. Level I: migratory fish;
2. Level II: crustacean/molluscs/polychaetes;
3. Level III: riparian vegetation.

The habitat of migratory fish is the primary starting point in enhancing the ecological performance of the design. Therefore, level I of the indicator organisms includes the migratory fish. The second level applies to the main food sources of these migratory species: crustacean, molluscs and polychaetes. The third level includes riparian vegetation, which can serve as shelter for the other organisms.

An overview of the (biotic and abiotic) factors that form the habitat of migratory fish is illustrated in Figure 6.1.

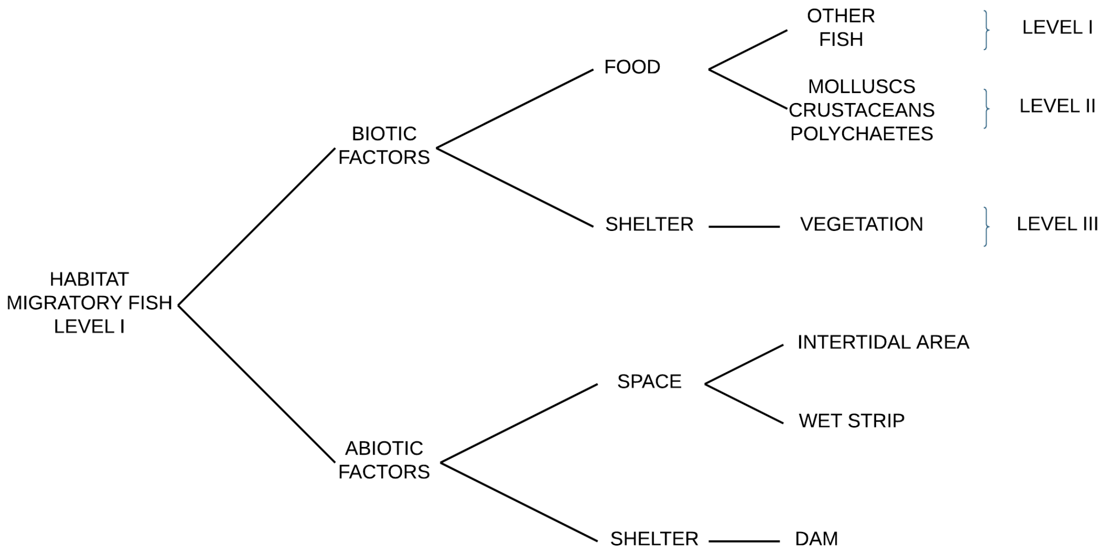


Figure 6.1 Habitat components of the design

As can be seen from the diagram in Figure 6.1 the indicator species apply to the biotic factors of the habitat. The abiotic factors apply to the several elements of the design: the intertidal area that is created by the nourishment, the wet strip behind the dam and the dam itself.

For each of the levels of indicator organisms several types of species are identified in order to be able to define the requirements for the final design. In identifying these indicator species the following requirements are kept in mind:

- the species has to be able to thrive in (the surroundings of) the Nieuwe Waterweg;
- the species is representative for a larger group of species;
- the species has to generate added value for the project;
- enough information on the habitat requirements of the species is available;
- the species preferably appeals to a larger public.

Level I: migratory fish
Based on the basic requirements for identifying indicator species the migratory fish species are chosen as presented in Table 6.2. It is assumed that this group is characteristic for the environment and that it represents a larger group of migratory fish. This group can add value to the biodiversity of the port and its surroundings since all these species are either threatened or have disappeared in the Dutch waters according to a database of the Association of Sport Fishing in The Netherlands [Sportvisserij Nederland, 2015].

Common name	Scientific name	Status of appearance in The Netherland	Main food sources
Atlantic sturgeon	Acipenser sturio	disappeared	Worms (mainly polychaetes) Molluscs Crustacean Other (small) fish
River lamprey	Lampetra fluvialis	threatened	Remains of other fish
European smelt	Osmerus eperlanus	threatened	Crustacean Other (small) fish
Sea lamprey	Petromyzon marinus	threatened	Remains of other fish
Twait shad	Allosa fallax	disappeared	Crustacean Other (small) fish
Allis shad	Allosa Allosa	disappeared	Crustacean Other (small) fish
Atlantic salmon	Salmo Salar	threatened	Crustacean Other (small) fish

Table 6.2 Level I indicator species: Migratory fish

Level II: Molluscs/crustaceans/polychaetes
In order to define species for level II, the food preferences of the indicator migratory fish were investigated. As can be concluded from Table 6.2 macro fauna like crustacean, worms and molluscs are a very important food source for migratory fish in general. For each of this category two indicator species have been chosen based on their occurrence in the Nieuwe Waterweg [STOWA, 2012]. It is assumed that this group, as presented in Table 6.3, represents a larger group of crustacean, molluscs and polychaetes.

Category	Common name	Scientific name
Molluscs	Common mussel	Mytilus edulis
	Razor shell	Ensis ensis
Crustaceans	Common/brown shrimp	Crangon crangon
	Common marine hermite crab	Pagurus bernhardus
Polychaetes	Catworm	Nepthys hombergii
	Lugworm/sandworm	Arenicola marina

Table 6.3 Level II indicator species: Molluscs, Crustaceans & Polychaetes

Level III: riparian vegetation
There is no wide variety of riparian vegetation species that is able to thrive in the Nieuwe Waterweg. However, the area is suitable for different types of eelgrass [Ross, S., personal communication, February 22nd 2015]. Therefore two types of eelgrass have been chosen to serve as indicator species for the riparian vegetation, presented in Table 6.4.

Common name	Scientific name
Dwarf eelgrass	Zostera Noltii
Common eelgrass	Zostera Marina

Table 6.4 Level III indicator species: Riparian vegetation

6.4 Habitat requirements of the indicator organisms

In the previous section indicator organisms have been chosen. This section specifies the habitat requirements of all these organisms.

6.4.1 Interpretation of habitat suitability indexes

Several databases exist in which information is described on the abiotic living conditions of several species. For this research information from the databases of Deltares (HABITAT) and MarLIN (BIOTIC) is used.

Information on the abiotic living conditions usually comes in the form of habitat suitability indices that assume a relation between the quality of a habitat for a specific species and certain abiotic parameters. The habitat suitability indices give an insight in the ranges in which the species might occur. These ranges in fact are limits: outside these ranges the species do not occur, inside these ranges they might occur but it is not ensured they will. Furthermore, these ranges are in reality often also time-dependent: if certain extreme values within the range occur during a long period of time or if the values in time are highly dynamic, the habitat might not be suitable, even though the index implies it is. For example, a mussel can withstand very low salinity conditions, but only for small periods of time. This time dependence is often not embedded in the habitat suitability index. Therefore, these habitat suitability indexes should be seen as a rough indication for the probability of occurrence of a certain species rather than as a proof of the occurrence of the species.

6.4.2 Level I: migratory fish

The habitat requirements of the level I indicator species can be found in Appendix C.1. There is not a lot of literature available on the abiotic requirements of migratory fish. However, the species were selected based on the requirement that they would potentially be able to thrive in the Nieuwe Waterweg and its surroundings. Based on the literature, this can be considered to be true so it is assumed that the abiotic factors are satisfying the living conditions of the migratory fish. It can be concluded that the biotic factors are critical for the occurrence of migratory fish in the Nieuwe Waterweg. As was already concluded, the area mainly lacks food sources. It was found that the main food sources are other (small) fish and molluscs/crustaceans/polychaetes (level II of the indicator organisms). In section 6.2.2 it was also concluded that the focus of the design should be on local species like vegetation and small organisms that typically live in the intertidal area (mussels, shrimp, little crabs, etc.) that add to the habitat of migratory fish, rather than on the fish themselves.

6.4.3 Level II: molluscs/crustaceans/polychaetes

The habitat requirements of the level II indicator species can be found in Appendix C.2. Molluscs, crustaceans and polychaetes were identified as one of the main food sources of migratory fish. Since the area lacks food sources for migratory fish it is assumed that when the diversity and populations of these food sources increase the living conditions of migratory fish overall improve.

Most of the chosen species in this group are very tolerant with respect to wave attack: they can survive in very dynamic environments. However, some of the species require sheltered conditions. It is difficult to specify the requirements with respect to tidal influence since not a lot of information is available on this topic. However, most species prefer dynamic conditions: the occurrence of both wet as well as dry conditions. The optimum current conditions range between 0.5 – 1.5 m/s.

Habitat requirements with respect to the type and grading of the substrate vary per specie. Some species are very tolerant and survive on different types and gradings of substrate, others have more specific requirements. Overall it can be concluded that the wider the variety of substrates in the design is the higher the diversity of species it attracts.

Regarding salinity, the habitat requirements range between a concentration of 18‰ and 40‰. Overall it can be concluded that the optimum salinity ranges between 18‰ and 30‰.

6.4.4 Level III: riparian vegetation

It is difficult to specify the requirements of eelgrass with respect to water movement since not a lot of information is available on this topic. In general Eelgrass grows in very sheltered, moderate conditions, especially Dwarf Eelgrass [Ross, S., personal communication, February 22nd 2015]. It is therefore concluded that Dwarf Eelgrass grows in the higher parts of the intertidal area with respect to Common Eelgrass. Furthermore, Eelgrass is known for growing on a sandy subsoil. Both species occur between a salinity concentration range of 15‰ and 30‰.

6.5 Requirements for the final design

The output of section 6.4 are limits within which the indicator species can survive. These limits have to be converted into design requirements that the final design has to comply with. The requirements are based on the abiotic and the biotic parameters. The abiotic factors are the non-living components of an organism's environment that affect the substrate (soil), water and climate. The biotic factors are the living components that affects another organism, including the existing vegetation, plants and other animals [Bolier, 2006].

This section discusses the abiotic and biotic requirements for the final design that follow from the habitat requirements of the indicator species that were presented in the previous sections.

6.5.1 Abiotic design requirements

The overall abiotic habitat requirements of the selected indicator organisms confirm the common ecological rule of thumb: "the higher the diversity in parameters, the higher the diversity in species" [Bak, A., personal communication, November 13th 2014]. The overall abiotic requirements for the final design that follow from the habitat requirements of the selected indicator organisms are presented in Table 6.5.

Abiotic factor	Parameter	Requirement
Water movement	Wave attack	H_{max} = 0.4 m
	Tidal influence	lower part of the bank should be flooded >70% of the time
		upper part of the bank (top of the nourishment) is allowed to be flooded <70% of the time
	Current	just behind the dam: v = 0.1 – 1.5 m/s
		upper part of the bank: v = 0 – 0.25 m/s
Substrate	Type of material	high variety
	Grading	high variety
	Orientation	high variety
Salinity	Concentration	18 - 30‰

Table 6.5 Habitat requirements for the final design

6.5.2 Biotic design requirements

As was concluded in section 6.3 and illustrated in Figure 6.1 the biotic factors of a habitat mainly comprises food and shelter. The biotic requirement for the final design is therefore that the design must provide enough food and shelter for the indicator species. Level II and level III of the indicator species provide this food and shelter. It is assumed that when the abiotic design requirements are met the biotic design requirements are also met. The only condition is fish must be able to reach the area and therefore the project site has to be well-connected with other parts of the stepping stone in the Nieuwe Waterweg.

7. Final design and evaluation

The performance of several alternatives is simulated and evaluated in this chapter based on the requirements that were specified in chapters 4, 5 and 6. At first the developed alternatives are presented and the simulation approach is explained in section 7.1. Subsequently, the performances of the designs are simulated with respect to the critical design aspects:

1. Stability (section 7.2);
2. Functioning of the port and its surroundings (section 7.3);
3. Ecological performance (section 7.4);
4. Circular economy (section 7.5).

The chapter concludes with an evaluation of the alternatives in section 7.6 and a discussion of the results in section 7.7.

7.1 Modelling alternatives

In this section the alternatives are presented and the methods used to simulate their performance is described. The alternative designs are based on the requirements set in chapters 4, 5 and 6.

The objective of evaluating several alternatives is to get insight in the flexibility of the design. The output of this chapter is therefore whether or not different designs enable conditions suited for the desired ecological state.

7.1.1 Alternatives

As was concluded in chapter 5, the design must be flexible and adaptive to the fluctuating supply of coarse residual material. Therefore it is investigated if designs with different dimensions can enable the conditions suited for the desired ecological state. The following alternatives are evaluated in this chapter:

1. Zero state (do nothing);
2. Original design of project "De Groene Poort" (h_{crest}=+1.1m NAP);
3. Medium crest (h_{crest}=+0.70m NAP);
4. Low crest (h_{crest}=+0.27m NAP);
5. No dam, only a nourishment.

The zero state alternative always has to be considered. By evaluating the scenario of doing nothing the possible cost and benefits of intervening become clearer. Furthermore, in this case the zero state alternative is used as a calibration for the hydrodynamic model (XBeach) that is used to assess several design aspects of the design. This is further explained in section 7.1.3.

The second alternative, illustrated in Figure 7.1, is based on the original design of project "De Groene Poort". The top of the crest is located at Mean High Water level: +1.1m NAP. This is the highest possible level at which construction is possible; higher is not allowed by law for reasons of flood safety.

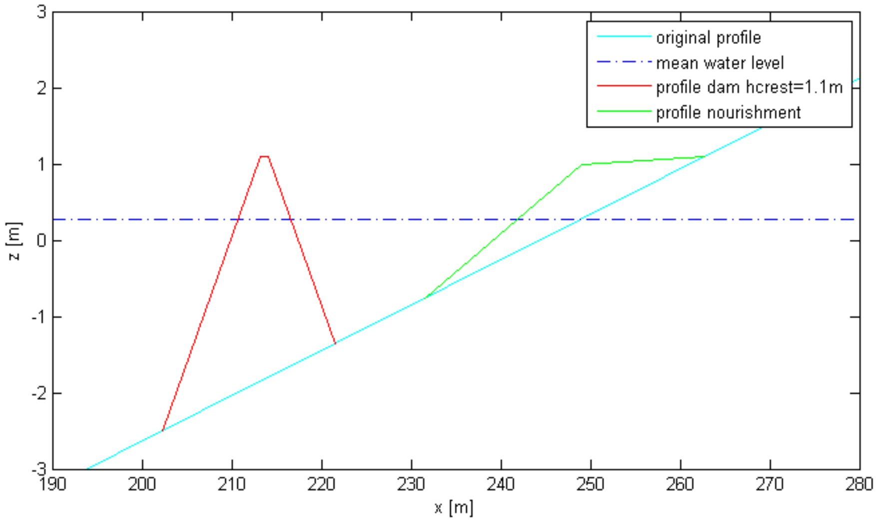


Figure 7.1 Overview of alternative 2 (not to scale)

Because of the uncertainties in the availability of coarse residual material alternatives are considered that require less coarse residual material. Furthermore, it is investigated if there are possibilities to store a larger amount of dredged material in the design. It is expected that alternatives with a lower crest require less coarse residual material and leave more space for the nourishment. Therefore two alternatives with lower crest than the original design are assessed.

The third and fourth alternatives thus have a lower crest than the original design of project “De Groene Poort” (alternative 2). Alternative 3, illustrated in Figure 7.2, has a crest level of +0.70m NAP, in between Mean High Water (+1.1m NAP) and Mean Water (+0.27m NAP). Alternative 4, illustrated in Figure 7.3, has a crest level of +0.27m NAP at Mean Water Level.

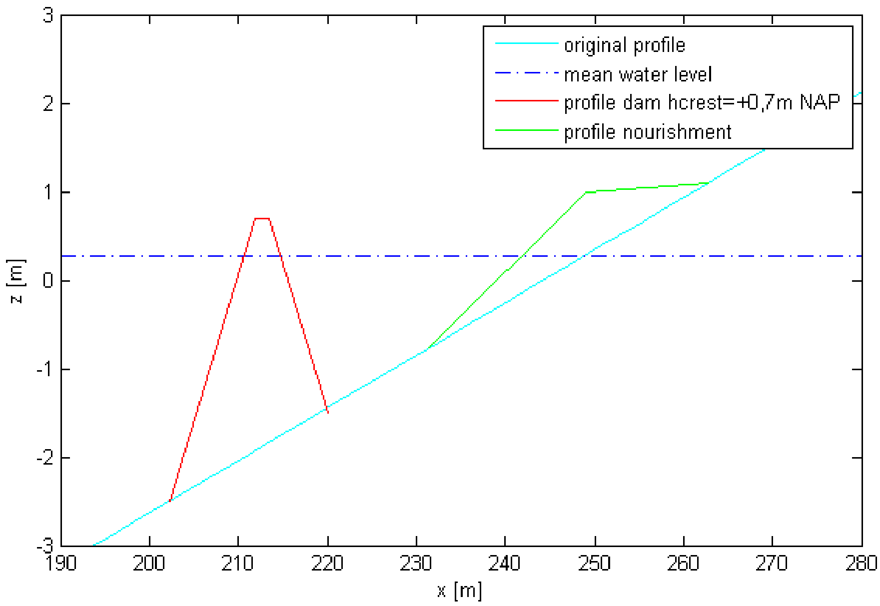


Figure 7.2 Overview of alternative 3 (not to scale)

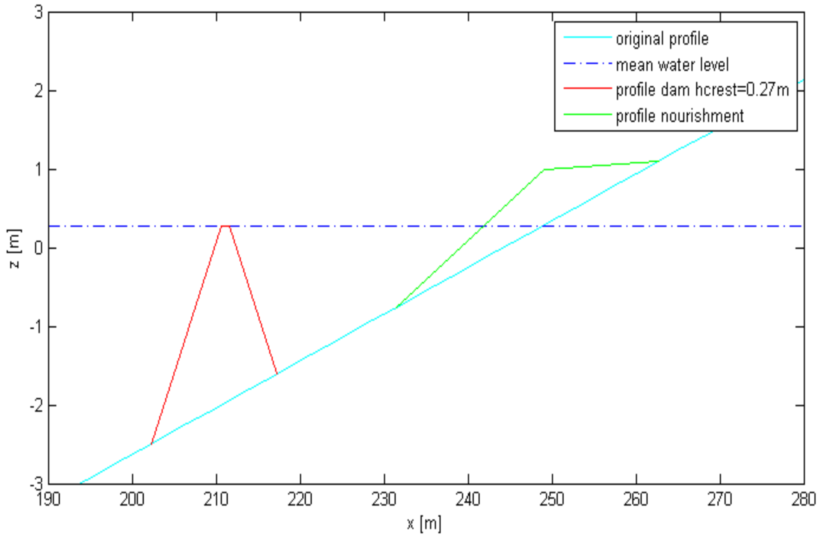


Figure 7.3 Overview of alternative 4 (not to scale)

The fifth and final alternative that is assessed consists of a nourishment only, as illustrated in Figure 7.4. The dam is left out in the design. This alternative gives insight in whether the dam is necessary to meet the design requirements.

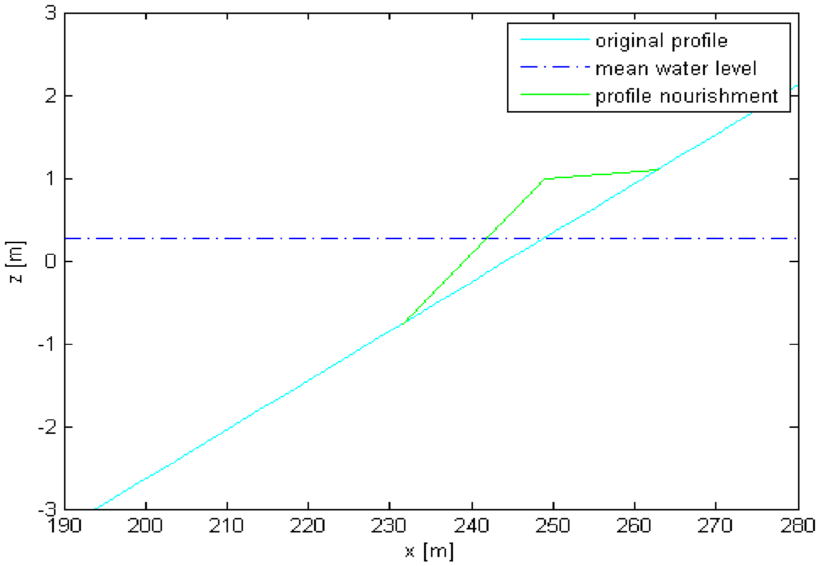


Figure 7.4 Overview of alternative 5 (not to scale)

7.1.2 Design requirements

The final design has to meet the requirements set by the stakeholders. To assess the alternatives the performances with respect to the design requirements are simulated. The design requirements are based on the four critical design aspects of a nature friendly bank made of residual material in a port and have been specified in chapters 4, 5 and 6. An overview of the design requirements and their method of assessment is shown in Table 7.1.

Critical design aspect	Type of requirement	Requirement	Method of assessment
Stability	Dam	No erosion	Literature study and calculations
	Nourishment	No erosion	Xbeach
	Subsoil	Minimize settlements	Literature study and calculations
		Minimize scour	Xbeach
Functioning of the port and its surroundings	Shipping	Wave reflection < 10%	Literature study and calculations
		No deposits of blocks and sand in the Nieuwe Waterweg	Xbeach
	Nature and recreation	No limitations for the further development of the nature and recreational area around "Landtong Rozenburg"	Qualitative research
	Flood safety	No limitations on the flood safety	Qualitative research
Ecology	Water movement	Hmax = 0.4m	Xbeach
		Current velocity v = 0 – 1.5 m/s	Xbeach
		Tidal influence	Qualitative research
	Substrate	High variety in type, grading and orientation	Qualitative research
	Salinity	18‰ - 30‰	Data research
Circular economy	Business case	Profitable for the stakeholders	Qualitative research
	Availability	Feasible	Qualitative research

Table 7.1 Overview of the design requirements based on the critical design aspects

As can be concluded from Table 7.1 the following different methods are used to evaluate the alternatives:

- Literature study and calculations;
- XBeach;
- Qualitative research;
- Data research.

The XBeach model objectives and processes are described in the following sections.

7.1.3 XBeach model objectives

XBeach is a two-dimensional (2DH) numerical model which is developed to simulate hydrodynamic and morphodynamic processes and impacts on shores [Roelvink et al., 2010]. The aim of the use of the XBeach model in this case is to partly assess the structural, hydraulic and geotechnical performance of the design of project "De Groene Poort". By making use of the results of the model, more insight should be gained in the following processes:

- Sedimentation and erosion patterns:
  - behind the dam to assess the stability of the nourishment;
  - in front of the dam to assess the geotechnical stability with respect to scour development;
- Water movement behind the dam to assess the ecological performance with respect to:
  - transmitted wave height;

- current velocities;
- tidal influence on different parts of the design.

It is the aim to keep the model as basic as possible, to show and understand the basic processes that take place within the system and to make it applicable to other cases. Therefore, the typical loads on a bank within a port, like ship waves and the influence of the tide, are modelled.

7.1.4 Model settings and calibration

An extensive description of the XBeach model set-up can be found in Appendix F. This section briefly describes the important settings and the calibration of the model.

The design of project "De Groene Poort" is evaluated partly in XBeach in the cross-shore. Therefore, a 1DH model is set up which evaluates the alternatives in the x-direction. It is generally strongly recommended to specify as few parameters explicitly as possible and rely on the XBeach defaults for the other parameters. However, for the proper functioning of the model several default settings are altered. The most relevant non-default settings are explained below.

All settings and input are calibrated with the zero-state model (alternative 1). The zero-state model represents the situation as it is before intervention. In the current situation the banks at the project site are known to be stable (no ongoing erosion or sedimentation is taking place) [Hiddema et al., 2013]. Therefore it is assumed that the settings of the model of a stable zero-state model are the correct settings. These settings are used in setting up the models of the different alternatives.

Non-erodible layer module
In order to keep the model as simple as possible it is assumed that the dam is non-erodible. In reality this is off course not true. However, the stability of the dam is not assessed in XBeach so in this case this is an acceptable assumption. The dam is specified as a non-erodible layer; the rest of the domain is specified as erodible.

Groundwater
By default, infiltration and exfiltration of groundwater is not accounted for in XBeach: the bathymetry is by default specified as a non-porous layer. However, in reality the dam in project "De Groene Poort" is porous. It is important to specify this in the model, in order to simulate the tidal influence behind the dam. This is done by enabling the groundwater module in XBeach and specifying the dam as a porous structure.

Sediment composition
The sediment input is based on the composition of the bed. As was concluded in chapter 5, the subsoil and nourishment in project "De Groene Poort" consist of a mixture of sand, clay and silt. This mixture of sand, clay and silt is modelled by specifying a porosity of 0.45 and an average bulk density of 2500 kg/m3.

Morfac
The morphological acceleration factor can speed up the morphological time scale relative to the hydrodynamic time scale. It means for example that a hydrodynamic simulation of 10 minutes with a morfac of 6 simulates the morphological evolution of an hour. In this case a morfac of 10 is specified.

Wave input
The governing waves in the Nieuwe Waterweg are ship-induced. The ship-induced waves consist of several components, of which it was concluded that the water level depression, stern wave and secondary wave are substantial. Therefore, these wave components are specified in XBeach.

The water level depression is specified in the offshore flow boundary conditions, by lowering the tidal conditions with 0.5m every fifteen minutes (= 1 ship passage) for 40 seconds. The stern wave zmax and the secondary wave are specified in a time-series as short wave energy. This yields a wave signal as illustrated in Figure 7.5.

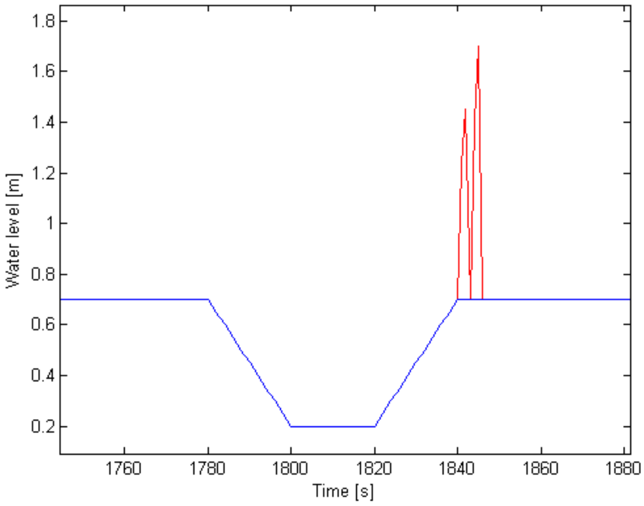


Figure 7.5 Imposed wave signal in XBeach

Flow input
With respect to the flow input, difference is made between the offshore boundary (=the Nieuwe Waterweg) and the landward boundary (the banks):

- Front: at the offshore boundary a time varying water level is specified influenced by the tide;
- Back: the landward boundary is specified as a reflective wall.

7.2 Stability

The stability of the alternatives is assessed with respect to the following design aspects:

- the dam;
- the nourishment;
- the subsoil.

7.2.1 Dam

The stability of the dam is mainly determined by the stability of the randomly placed elements which the dam consists of. The stability of randomly placed elements mainly depends on the following factors:

- the governing load;
- the gradient of the slope;
- the sizes of the elements;
- the crest width.

Generally, when hydraulic structures like the dam in project “De Groene Poort” are evaluated in terms of stability, standard failure mechanisms are considered. An overview of possible failure mechanisms is illustrated in Figure 7.6. In this case, the most relevant failure mechanisms can be categorized in:

- Macro instability: instability of the inner/outer slope;
- Micro instability: instability of individual elements;
- Settlement/erosion foreshore: instability of the subsoil.

These failure mechanisms are considered below. A more elaborate assessment of the stability of the dam is presented in appendix D.

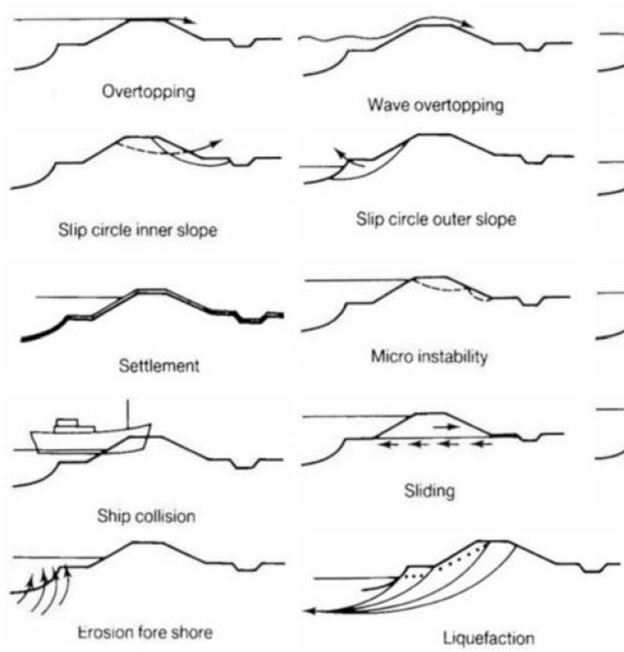


Figure 7.6 Failure mechanisms of rock structures [d'Angremond & Van Roode, 2001]

The macro instability mainly refers to stability of a slope as a whole. This is in contrast to the micro-stability which deals with individual grains/elements on a slope. Macro-stability is usually approached with a slip-circle analysis. In a slip circle approach the weight of the soil represents the load and the shear stress of the soil along the circle represents the strength. In a thorough study many slip circles must be considered. This is typically work for a computer. When no computercode for stability is available (in this case) an approach with micro-stability gives a safe slope angle [Schiereck, 2012]. The calculation methods for the assessment of micro instability use a slope of 1:1,5 – 1:3. It is therefore expected that a gradient of 1:3 ensures sufficient stability in this case [Van den Bos, J., personal communication, December 10th 2014].

Micro instability can be prevented by applying a suitable size of elements in the dam. When the elements are heavy enough, the waves are not able to lift nor move them. Based on several theories presented in Appendix D it was concluded that element sizes of a standard grading of 300 – 1000 kg are suitable for all alternatives to account for the micro stability of the dam. These elements have a maximum diameter of 0.75 m. The minimum crest width with respect to stability is two times the element diameter [d'Angremond & Van Roode, 2001]. Therefore, the minimum crest width of the dam is 1.5 m.

The instability of the subsoil in terms of settlement and scour/erosion of the foreshore is assessed in section 7.2.3.

7.2.2 Nourishment

The stability of the nourishment depends on erosion and sedimentation. This is evaluated in XBeach.

According to the XBeach results (presented in section F.4) the nourishment in alternative 2 is stable. In the model the nourishment of alternatives 3 and 4 are not 100% stable. However it is expected that when riparian vegetation starts to grow, the roots will trap the soil and increase the stability of the nourishment.

The nourishment of alternative 5 (without the dam) is far from stable. It is expected that this will eventually cause large deposits of sediment in the Nieuwe Waterweg.

Since the model in XBeach is a 1DH model it does not take into account the openings in the dam. However, these openings are expected to have an effect on the erosion and sedimentation patterns of the nourishment. The flow is expected to concentrate around the openings possibly causing local erosion. In order to investigate if extra measures to prevent erosion are required, it is recommended that this is investigated further.

7.2.3 Subsoil

A comprehensive assessment of the geotechnical stability (including data and caclulations) is presented in appendix E. In this section summaries of the scour and settlement assessments are presented. Furthermore, protective measures for the failure of the subsoil are discussed such as the application of an underlayer.

Settlement
The settlement is a result of the extra load on the subsoil imposed by the weight of the dam. The settlement is evaluated by making use of the formula of Koppejan. Alternatives 1 and 5 do not include the construction of a dam and thus settlement does not apply to these alternatives. For alternatives 2, 3 and 4 the settlements range between 0.18 m and 0.23 m as can be concluded from Table 7.2.

	Settlement Δh [m]
Alternative 1 *do nothing*	n.a.
Alternative 2 h_{crest}=+1.1m NAP	0.23
Alternative 3 h_{crest}=+0.70m NAP	0.21
Alternative 4 h_{crest}=+0.27m NAP	0.18
Alternative 5 *Nourishment only*	n.a.

Table 7.2 Settlement of the dam per alternative

Scour
In front of the dam scour is expected. Due to the presence of a structure, combined effects of waves and currents cause (an increase in) local erosion. The level of scour is evaluated for the alternatives with a dam (2, 3 and 4) in XBeach. The XBeach results show no development of a scour hole. However, on the long-term a scour hole is expected to develop in front of the dam.

Underlayer
As soon as artificial structures, like the dam in project "De Groene Poort", disturb the governing flow and wave attack fixation of the bottom by taking protective measures becomes necessary. The flow velocity and the turbulence of the flow can penetrate through the large stones of the dam. This can lead to the outwash of subsoil particles which may cause extra settlements and erosion near the toe. Therefore, it must be prevented that subsoil particles pass the pores of the upper layer. This can be prevented by constructing an underlayer consisting of either a granular filter or a geotextile [Schiereck, 2012].

Geotextiles can replace several filter layers, resulting in a thinner filter. However, in this case a very strong geotextile would be required because of the relatively heavy dam. Therefore, in this case it is chosen to apply a granular filter as a base layer for the dam.

7.3 Functioning of the port and surroundings

The requirements with respect to the functioning of the port and surroundings apply to the following surrounding functions:

- shipping;
- flood safety;
- nature and recreation.

7.3.1 Shipping

The shipping traffic might be disturbed by design in two ways:

1. increased wave reflection imposed by the dam;
2. deposits of elements from the dam or sediment from the nourishment.

Shipping traffic might be disturbed by waves reflected by the dam. Therefore, a requirement was made that the increased wave reflection caused by the dam must be minimized to an order of magnitude 5-10%. In appendix D.3.2 it is calculated that the alternatives 2, 3 and 4 (including a dam in the design) impose a maximum wave reflection of 12% of the incoming wave energy. This is slightly higher than the requirement but has the same order of magnitude.

Furthermore, deposits of elements from the dam or sediment from the nourishment may disturb the shipping traffic. It was concluded in section 7.2 that the nourishment in alternative 5 is far from stable and is therefore expected to cause large deposits of sediment in the Nieuwe Waterweg. The other alternatives are expected to be stable and they are therefore not expected to deposit sediments or concrete elements in the Nieuwe Waterweg.

7.3.2 Nature and recreation

Since the aim of project "De Groene Poort" is enhancing nature, it is assumed that the alternatives will not impose any limitation for the development of a nature and recreation site.

7.3.3 Flood safety

As was explained in chapter 4, the area around the Nieuwe Waterweg is very important in terms of flood defence and thus imposes conditions for the design of the nature friendly bank.

A requirement with respect to flood safety is that the surface width of the Nieuwe Waterweg is not allowed to change. Therefore, the crest height of the dam and the nourishment are designed below the mean water level. All alternatives meet this requirement. At high tide, the dam will therefore be underneath the water surface. The wetted area of the channel will obviously decrease, but it is expected that this will not have a significant effect on the discharge capacity of the channel during high water conditions [Hiddema, P., personal communication, November 12th 2015].

Thus, it is assumed that none of the alternatives will impose any limitation on the flood safety of the area. However, when nature friendly banks are constructed at a larger scale (for which plans have been made in project "The river as a tidal park"), this must be studied further.

7.4 Ecological performance

The requirements with respect to the ecological performance apply to the following abiotic requirements of the design:

- water movement;
- substrate;
- salinity.

The performance of the alternatives with respect to these abiotic requirements is explained in this section.

7.4.1 Water movement

The performance of the alternatives with respect to the maximum wave height and the current velocity was assessed in XBeach. An overview of the results is shown in Table 7.3.

	Maximum transmitted wave height [m]	**Current velocity**	
		lower part of the bank [m/s]	**upper part of the bank [m/s]**
Alternative 1 *do nothing*	1	0.28	0
Alternative 2 h_{crest}=+1.1m NAP	0.2	0.15	0.05
Alternative 3 h_{crest}=+0.70m NAP	0.25	0.25	0.05
Alternative 4 h_{crest}=+0.27m NAP	0.65	0.15	0.05
Alternative 5 *Nourishment only*	1	0.4	0

Table 7.3 Overview of the XBeach results for water movement

Wave height
As concluded in chapter 6 the maximum allowable wave height at the banks, specified from the desired ecological performance, is 0.4 m. This wave height is specified from literature, and it is unsure what kind of wave height was meant (significant/maximum/etc.). It is most likely to be a maximum value and therefore it is assumed that the value of 0.4 m is a maximum wave height. This maximum wave height can be translated into a significant wave height. An easy rule-of-thumb is that the maximum wave height is approximately equal to twice the significant wave height [Holthuijsen, 2007]:

$$H_s \approx \frac{1}{2} H_{max}$$

The maximum allowable *significant* wave height is therefore 0.2 m.

The XBeach results show that the wave heights in alternatives 1 and 5 exceed the maximum allowable wave height continuously by far. The wave heights in alternatives 3 and 4 also exceed the maximum allowable wave height, but only during small periods of time at high tide. The wave height in alternative 2 does not exceed the maximum and therefore meets the requirement.

Current velocities
The required peak current velocity ranges between 0.1 and 1.5 m/s just behind the dam and between 0 and 0.25 m/s at the shore.

The XBeach results of alternatives 1 and 5 show and increasing current velocity towards the shore with a peak of 0.3 and 0.4 m/s. The XBeach results of alternatives 2, 3 and 4 show a peak current velocity just before the dam where the waves break. Behind the dam the current velocities range between 0 and 0.05 m/s.

Tidal influence
The nourishments in alternatives 2, 3, 4 and 5 have a gentler slope than the original profile of the Nieuwe Waterweg in alternative 1. This gentle slope increases the intertidal area and,

therefore, the domain over which tidal influence is present. A larger intertidal area favours the ecological performance of the design.

7.4.2 Substrate

As was concluded in chapter 6, with respect to substrate the ecological rule of thumb applies: "the higher the diversity in parameters, the higher the diversity in species" [Bak, A., personal communication, November 13th 2014]. Therefore, the alternatives are qualitatively assessed based on their variety in substrate.

Alternative 1, the current situation in the Nieuwe Waterweg, has no variety in substrate. The banks consist of hard substrate only.

Alternatives 2, 3 and 4 have high varieties in substrate. The dam is made of hard substrate, consisting of large elements. The nourishment consists of soft substrate; a mixture of sand, clay and silt. These alternatives are with respect to the substrate suitable for a high diversity in species.

Alternative 5 has a low variety in substrate; especially lacking hard substrate in the lower parts of the bank desired for level II of the indicator species.

7.4.3 Salinity

As was concluded in chapter 6 the ecological requirement with respect to the salinity is a salinity concentration that ranges between 18 ‰– 30 ‰.

In Figure 7.7 the salinity of the Nieuwe Waterweg is plotted for a random week (in March 2015), together with the required upper and lower limits.

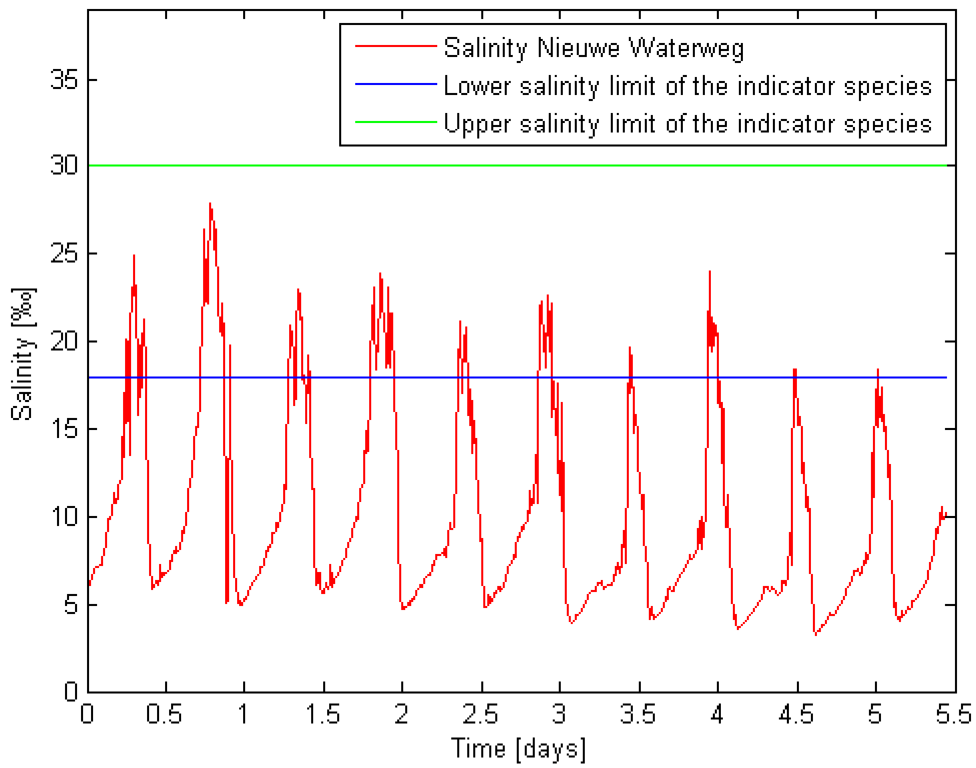


Figure 7.7 Salinity in the Nieuwe Waterweg plotted together with the lower and upper salinity limits of the indicator species (data obtained from the website of Rijkswaterstaat)

As explained before, the variation in salinity in time can be explained by the influence of the tide. As can be seen in the figure, the salinity in the Nieuwe Waterweg drops below the lower limit quite a few times. However, it is expected that this does not mean that the indicator species are not able to thrive in the Nieuwe Waterweg. The lower limit of the salinity is mainly induced by the Level II group of indicator species, the crustaceans, molluscs and polychaetes. All the indicator species in this group have been chosen based on their appearance in the Nieuwe Waterweg, and (except for the razor shell) they are all explicitly known for their occurrence in estuaries. Species that are known for their occurrence in estuaries are generally highly tolerant of dynamic salinity levels [Ross, S., personal communication, February 22nd 2015]. Furthermore, these species tend to tolerate fresh water conditions quite well for certain periods of time. Since only the lower salinity limits are exceeded it is therefore assumed that the salinity in the Nieuwe Waterweg suits the habitat requirements of the indicator organisms. No difference in salinity is expected between the different alternatives.

7.5 Circular economy

As discussed in chapter 5, the availability of coarse residual material is highly uncertain. Therefore, it is checked if alternatives that require less coarse residual material are acceptable with respect to other design requirements.

Furthermore, it was concluded in chapter 5 that it would benefit the circular economy and the business case if more dredged material could be used as a construction material in the project. An overview of the required material per alternative is shown in Table 7.4. The alternatives with a lower crest than the original design logically require less coarse residual material. Furthermore, it was expected that these alternatives have more space left behind the dam for the nourishment, so more dredged material can be stored in these alternatives.

	Coarse residual material [m^3/m]	**Dredged material [m^3/m]**
Alternative 1 *do nothing*	0	0
Alternative 2 h_{crest}=+1.1m NAP	29.5	11.2
Alternative 3 h_{crest}=+0.70m NAP	25.1	16.2
Alternative 4 h_{crest}=+0.27m NAP	17.9	17.2
Alternative 5 *Nourishment only*	0	18.5

Table 7.4 Required amounts of material per linear meter of nature friendly bank

As can be concluded from Table 7.4 there is some difference in the amount of required coarse residual material and the amount of required dredged material between the several alternatives. However, the differences are not substantial.

7.6 Evaluation

7.6.1 Method

As was briefly explained in chapter 2, a lot of standard evaluation methods exist often ranking alternatives based on weighting factors and scores of the alternative's performance. In this case the objective of simulating the performance of the alternatives is not to identify the most preferable alternative. The objective is rather to get insight in the degree of flexibility of the design.

Therefore, a method is obtained that allows an evaluation based on several perspectives: a 'balanced score card method'. The idea behind this method was explained in chapter 2. The key to this method is a multi-perspectives framework where in this case the performance is measured based on the four critical design aspects:

1. Stability;
2. Functioning of the port and surroundings;

3. Circular economy;
4. Ecological performance.

The alternatives are thus evaluated based on the performance regarding every specific critical design aspect. Three qualification categories have thereby been distinguished based on colours:

1. Red: if the design requirement is not met;
2. Orange: if the design requirement is partly met;
3. Green: if the design requirement is met.

Working with colours is a very subjective method of evaluation. However, it gives a clear, straightforward and visible insight in the trade-off between the different requirements.

7.6.2 Results

For each alternative the critical design aspects are evaluated based on the design requirements. Table 7.5 gives an elaborate overview of the design requirement per critical design aspect and the evaluation results per alternative. Each column represents a design requirement. Each row represents an alternative. The performance of the alternatives with respect to every design requirement is indicated with colours, as explained in the previous section.

	Stability			Surrounding functions	Residual material		Ecology			
	Nourishment	**Dam**	**Subsoil**	**General**	**Coarse residual material**	**Dredged material**	**Wave height**	**Current velocity**	**Tidal influence**	**Variety of substrate**
Requirement	no erosion/ sedimentation	no movement of elements	minimize settlements and scour	no limitations to surrounding functions	flexible design	high storage capacity	Hs,max = 0.2 m	v = 0 - 1.5 m/s	Variety of tidal influence over the domain	high
Alternative 1 ***zero state***	**n.a.**	**n.a.**	**n.a.**	no limitations	**n.a.**	**n.a.**	1 m	0.1 - 0.25 m/s	steep slope	low
Alternative 2 ***h_dam = +1,1m NAP***	no erosion	stable	minor settlement	no limitations	uncertainties in availability	low storage capacity	0.2 m	0.05 - 0.15 m/s	gentle slope	high
Alternative 3 ***h_dam = +0,7m NAP***	limited erosion	stable	minor settlement	no limitations	uncertainties in availability	low storage capacity	0.4 m	0.05 - 0.25 m/s	gentle slope	high
Alternative 4 ***h_dam = +0,27m NAP***	limited erosion	stable	minor settlement	no limitations	uncertainties in availability	low storage capacity	0.7 m	0.05 - 0.15 m/s	gentle slope	high
Alternative 5 ***nourishment***	a lot of erosion	**n.a.**	**n.a.**	large deposits of sediment	**n.a.**	low storage capacity	1 m	0.1 - 0.4 m/s	gentle slope	medium

Table 7.5 Results of the evaluation

7.7 Discussion

This section discusses the evaluation of the methods.

7.7.1 Results

As can be concluded from the evaluation, a dam is required for a stable nourishment. The highest dam ensures the most stable nourishment. Minor settlements of the dam are expected for every alternative.

The instability of the nourishment without the dam also means that the design has a limiting effect on the functioning of the port and surroundings, as can be seen in the evaluation of alternative 5 in Table 7.5. The other alternatives are expected to have no negative effect on the functioning of the port and its surroundings.

None of the alternatives are expected to have a substantial impact on the circular economy because of the high uncertainties in the availability of coarse residual material. Furthermore, the size of the nourishment and the scale of the project are too small to enhance the circular economy with respect to dredged material.

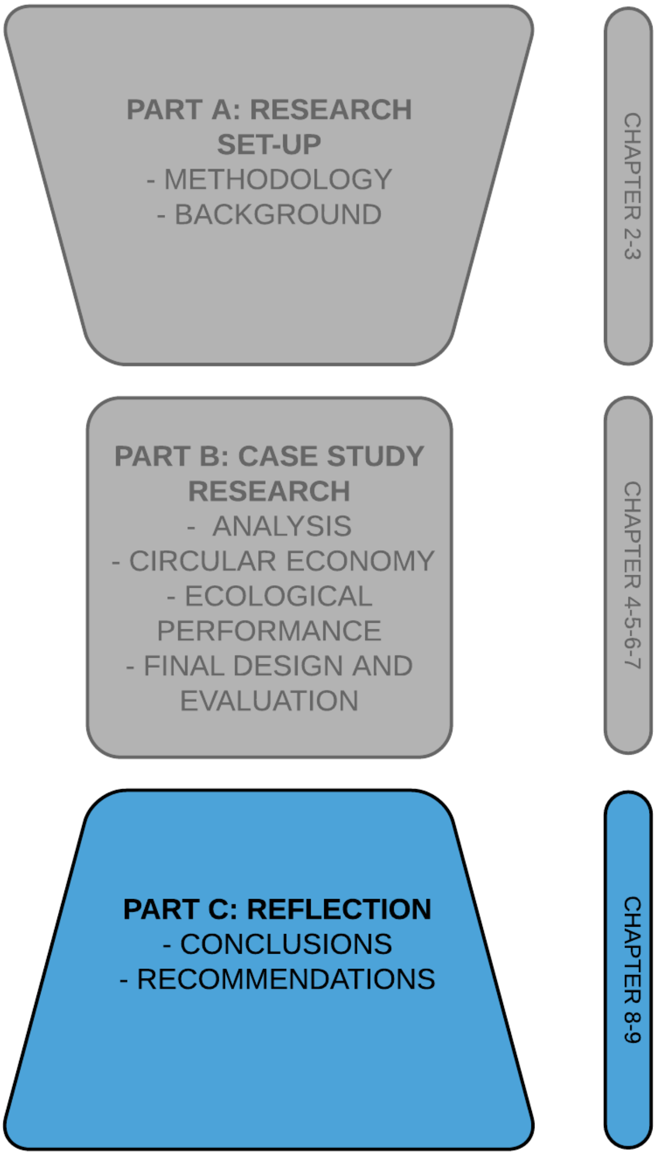
As can also be concluded from Table 7.5 the alternatives with a dam perform well in terms of ecology. In theory, alternative 2 enable the perfect conditions for the desired ecological state. Alternative 3 also performs well, only the maximum transmitted wave is slightly too high. The alternatives without a dam especially lack variety in substrate and sheltered conditions in terms of waves at the shore.

7.7.2 Preferred alternative

The optimum design seems to be a trade-off between the objectives of enhancing the circular economy and ecology. The alternative with the highest dam enhances the most suitable ecological conditions, however it requires a lot of coarse residual material of which it is unsure whether it is available or not. The higher the dam, the better the ecological performance but at the same time the higher the uncertainty of the availability of material.

Overall, alternatives 2 and 3 have the best performance. Because of the uncertainties in the availability of coarse residual material it is important that the design is flexible and can adapt to the fluctuating supply of coarse residual material. When a lot of material is available a high dam (alternative 2) is the preferred alternative. When less material is available a lower dam (alternative 3) is the preferred alternative.

Technical drawings of the final design are presented in Appendix G. The dimensions in the drawings are based on alternative 3; including a dam with a crest level of +0,70 m NAP.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CHAPTER 8-9

8. Conclusions

This chapter presents the conclusions of this study.

Nature friendly banks made of residual material were identified in chapter 1 as a promising opportunity to enhance the sustainability of a port's infrastructure. The main objective of this study was to broaden the knowledge base of constructing nature friendly banks made of residual material in a port. In order to do so, a design study was made based on an actual case in the Port of Rotterdam: project "De Groene Poort".

Section 8.1 presents the conclusions of the design study based on project "De Groene Poort". This section aims to answer the sub research questions.

Section 8.2 presents the conclusions that can be made for nature friendly banks made of residual material in a port in general. This section aims to answer the main research question.

Section 8.3 presents conclusions that can be drawn from this study for sustainable port infrastructure in general.

8.1 Project "De Groene Poort

This section presents the conclusions of the design study of project "De Groene Poort" and thereby aims to answer the sub research questions:

1. Is the envisaged construction, as proposed in the case study, stable?
2. Does the envisaged design fit with ongoing activities and functions of the port and its surroundings?
3. Will the envisaged design enable opportunities to enhance the circular economy within the port by using residual material?
4. Will the envisaged design of a nature friendly bank enable conditions suited for the desired ecological state?

Each sub question relates to a specific critical design aspect. The critical design aspects with respect to the design of project "De Groene Poort" are discussed in the following sections.

8.1.1 Stability

The first sub question relates to the stability of the design. The stability of the alternatives of project "De Groene Poort" has been assessed for the following elements of the design:

- the dam;
- the nourishment;
- the subsoil.

Based on calculations and expert consultation, the dam in alternatives 2, 3 and 4 is assumed to be stable in the proposed design (made of blocks of 300 – 1000 kg, a slope no steeper than 1:3 and a crest of 1.5 m).

As can be concluded from the XBeach results, the nourishment in alternatives 2, 3 and 4 is not 100% stable: some erosion takes place. However, the dam in these alternatives can function by trapping the sand. Therefore it is not necessary that the nourishment is 100% stable because the dam will prevent the sediment to be deposited in the Nieuwe Waterweg. Furthermore, it is expected that when riparian vegetation starts to grow, the roots of the vegetation will provide extra stability of the nourishment. The nourishment in alternative 4 is not stable at all according to the XBeach results. It can thus be concluded that the dam is providing sheltered conditions that are necessary for the nourishment to be stable.

The stability of the subsoil is assessed in terms of settlement of the dam and scour in front of the dam. According to calculations, minor settlements (order of magnitude: 20 cm) of the dam in alternatives 2, 3 and 4 will occur. This can be taken into account in the construction phase by constructing the crest of the dam slightly higher than as described in the design. Besides settlement of the subsoil, scour was assessed. The XBeach results show no development of scour. A scour hole is however expected on the long term in front of the dam in alternatives 2, 3 and 4. This can be prevented by applying scour protection, for example a geotextile.

The construction is thus not 100% stable. The instabilities can however be prevented by standard solutions. Furthermore, in this case the risks of failure of nature friendly bank remain low. Usually, hydraulic structures with an infrastructural purpose allow for small instabilities. The design in this case only has the function to retain soil and to dissipate ship waves. Therefore, keeping in mind the objective of the design, ensuring 100% stability is not necessary. Therefore it is assumed that the proposed construction is stable *enough*.

8.1.2 Functioning of the port and surroundings

The second sub question relates to the functioning of the port and surroundings with respect to the design of project "De Groene Poort".

The following surrounding functions in the vicinity of the project site were therefore assessed:

- shipping;
- flood safety;
- nature and recreation.

The requirement for shipping is to minimize wave reflection and minimize the deposits of blocks from the dam and sediment from the nourishment. As was already mentioned, it is expected that neither sediment nor blocks from the dam and the nourishment will be deposited in the Nieuwe Waterweg, except for alternative 5. The dam will impose increased reflection of waves, but it is expected that this is not substantial.

Because the project aims at enhancing ecological conditions in the area it is assumed that the project will improve the development of the nature and recreation area along the project site rather than having a negative effect on it.

As was concluded in chapter 7, the design of project "De Groene Poort" will not impose limitations on the flood safety of the area. The project is too small to have a substantial impact on the flood safety. However, when nature friendly banks are constructed at a larger scale (for which there are plans in project "The river as a tidal park") this must be investigated further.

Thus to answer the sub question with respect to the design aspect of the functioning of the port and its surroundings: yes, the envisaged design fits with ongoing activities and functions of the port and its surroundings.

8.1.3 Circular economy

The third sub question relates to the circular economy of the design. Project "De Groene Poort" has a strategic goal to enhance the circular economy within the port and its surroundings. In chapter 5 it was concluded that the project can contribute to the circular economy by:

1. acting as a valuable destination for dredged material and coarse residual material and thereby reducing waste in the port;
2. reducing the purchase of raw materials (of which the production can be expensive and a burden to the environment).

Dredged material
In chapter 5 it was concluded that a mixture of sand, clay and silt, which is normally deposited at sea, is a suitable material for the nourishment in project "De Groene Poort". Furthermore, it was concluded that the project requires a small amount of dredged material. Therefore, alternatives evaluated in chapter 7 that require store more dredged material. However, there is very little space alongside the banks of the Nieuwe Waterweg because of the intense shipping. Therefore, it can be concluded that using dredged material as a construction material in project "De Groene Poort" has a very limited impact on the circular economy of the port and its surroundings, especially when keeping in mind that a very large dredging project is being planned this year.

Coarse residual material
As was concluded in chapter 5, the availability of coarse residual material is highly uncertain because of:

- the dependency on few suppliers;
- the uncertainty if the available material meets the legislation;
- the relatively large demand of coarse material on an underdeveloped market.

Thus, with respect to the use of coarse residual material as a construction material, the design has to be flexible and adaptive to the changes in the supply of coarse residual material. This means that the project should have the opportunity to change the design according to the availability of coarse residual material. Therefore, alternatives with a lower crest than the original design have been evaluated. In chapter 7 it was shown that alternatives that require less coarse residual material enable conditions that also enhance local ecology. Furthermore, the nature friendly banks can be constructed in phases, per groynefield. The height of the crest can easily vary per groyne field. Therefore it is concluded that the design is flexible and therefore adaptive to the fluctuating supply of coarse residual material.

Summarizing, with respect to dredged material the project imposes a low demand compared to the supply. Thus, the use of dredged material in the project will not enhance the circular economy within the port because of its small impact. With respect to coarse residual material it is the other way around: the project imposes a high demand compared to the supply. Using coarse residual material in the project will thus enable opportunities to enhance the circular economy within the port. It is however unsure if it the project definitely will enhance the circular economy because the supply of coarse residual material is highly uncertain.

8.1.4 Ecological performance

The fourth sub question relates to the ecological performance of the design. Project "De Groene Poort" has a strategic goal to enhance the biodiversity within the port and its surroundings. The project specifically focusses on enhancing the diversity of migratory fish, in particular sturgeon. In chapter 6 it was concluded that the area of project "De Groene Poort" alone is too small to have a substantial impact on the biodiversity of migratory fish in the port. However, it was also concluded in chapter 6 that the project can enhance biodiversity on a local scale. Enhancing local ecology can also contribute to the habitat of migratory fish by improving their living conditions in and around the port by providing food sources (crustaceans, molluscs and polychaetes) and shelter (riparian vegetation).

The evaluation in chapter 7 shows promising results for alternatives 2 and 3 with respect to the abiotic conditions the design enables for the living conditions of the chosen indicator organisms.

However, as was also mentioned in chapter 6, the results are not 100% reliable since the requirements set by ecology are incomplete because of two main reasons:

- the habitat suitability indices do not cover all the information and should therefore only be used as a rough indication;

- ecology depends on a lot more parameters than we know of.

It can therefore not be concluded that the indicator organisms will be attracted by the design. However, it *does* indicate that the conditions created are suitable for local ecology in general.

Although it is unsure whether the conditions enabled by the design will actually attract the indicator organisms used for this study, it is certain that the design will improve the overall ecological state of the local environment. Many ecologists have agreed that every ecological development in this area is highly valuable [Bak, A., Hermans, A., De Jong, B, Klinge, M., Ross, S., personal communication, December 2014 – March 2015]. Therefore it is expected that the sheltered conditions that are created by the design impose conditions that add value to the overall ecological environment of the port.

8.2 Nature friendly banks in port area

This section presents the conclusions for nature friendly banks in a port in general and aims to answer the main research question:

Will nature friendly banks made of residual material enhance the functioning of a port and its surroundings by enhancing the biodiversity and the circular economy?

This question can be divided into two questions, concerning the circular economy and biodiversity. Both are individually assessed in the following sections.

8.2.1 Circular economy

Making use of residual material as a construction material can enhance the circular economy of a port by acting as a valuable destination for residual material, otherwise seen as "waste". Furthermore, it reduces the use of conventional construction materials of which the production can have a negative impact on the environment.

However, the nature friendly banks must have enough capacity to store residual material to have a substantial impact on the circular economy. The impact of using residual material as a construction material in a nature friendly bank on the circular economy depends on the dimensions and on the scale at which a nature friendly bank is constructed. This is also related to the space that is available along the river or channel at which the nature friendly bank is constructed.

Summarizing, the answer to the research question with respect to the circular economy is: Depending on its size and scale, a nature friendly bank made of residual material can enhance the circular economy of a port and its surroundings by making use of residual material.

8.2.2 Biodiversity

Besides being economically important port locations are also often valuable from a biodiversity point of view, often housing vulnerable ecological sites. Many ecologists have agreed that every ecological development in these areas is highly valuable [Bak, A., Hermans, A., De Jong, B, Klinge, M., Ross, S., personal communication, December 2014 – March 2015].

As can be concluded from the design study of project "De Groene Poort", the design concept of a nature friendly bank is promising for enhancing biodiversity in a port. The results presented in chapter 7 have proved that the (hydraulic) loads on the bank can be dissipated in favor of local ecological conditions.

Besides enhancing local ecological conditions and depending on the size and scale, nature friendly banks in a port area can also add value on a larger ecological infrastructure. As was concluded in chapter 6 migratory fish need space and food in the estuary, in which ports are often located. However, if a project has the objective to enhance biodiversity in terms of migratory fish, a systems approach is required. A nature friendly bank in a port on itself cannot increase the diversity of migratory fish along their migratory route that generally comprises an entire river system.

Summarizing, the answer to the main research question with respect to the biodiversity is: yes, a nature friendly bank made of residual material can enhance the functioning of a port and its surroundings by enhancing the biodiversity.

8.3 Sustainable port development in general

As was concluded from the previous section, nature friendly banks can enhance sustainable port development by enhancing the circular economy and biodiversity in and around a port.

Nature friendly banks made of residual material in a port offer opportunities for the circular economy. This is mainly because the design of nature friendly banks is flexible and can thus be adapted according to the changing circumstances on the market for residual material in a port. Nature friendly banks in a port also offer opportunities for biodiversity mainly because the ecologically important location of many ports and the ecologically important interface between land and water.

However, a nature friendly bank can in both cases (circular economy and biodiversity) only serve as a part of larger system. This means that when a port authority has the ambition to enhance the circular economy and the biodiversity, this cannot be achieved by only constructing nature friendly banks made of residual material. There must be an integral approach in which often other businesses, organizations and governments must be involved.

As was concluded every ecological development in these areas is highly valuable. Thus, many local benefits can be gained. It is thought however that if several projects are integrated a lot of benefits can be gained on a larger scale; on the system level. An integral approach is thereby necessary.

With respect to the circular economy, an integral approach would mean that more businesses and projects are involved within the circular economy of the port and its surroundings. If this is done, it is expected that the supply and demand of residual material will increase and the feasibility of such projects increase. With respect to the ecological performance, an integral approach would mean that the objectives of projects such as "De Groene Poort" are integrated with the objectives of other projects alike in the river Rhine. This means that benefits can be gained on a larger scale; in this case along the migratory route of fish in along the river Rhine.

9. Recommendations

This chapter presents the recommendations of this study.

Section 9.1 presents the recommendations for project "De Groene Poort". These recommendations may be valuable for the stakeholders of project "De Groene Poort" or for stakeholders of similar projects.

Section 9.2 presents the recommendations that can be made for nature friendly banks made of residual material in a port in general. These recommendations apply to port authorities that are looking for opportunities to enhance sustainable port development.

9.1 Project "De Groene Poort"

9.1.1 Further research

In order to get a realistic view on the physical processes, it is recommended to make a 2DH XBeach model. Making a 2DH model is obviously more complex than a 1DH model but it gives insight in processes that cannot be obtained through a 1DH model. For example:

- ship-induced water movement can be included more accurately by making use of a functionality in XBeach that simulates the passing of a ship;
- the effect of the openings in the dam on the hydraulic and geotechnical performance can be included in the model.

9.1.2 Stability

As was concluded, the nourishment in alternatives 2, 3 and 4 is not 100% stable in the XBeach model. However, it is expected that the nourishment will get increasingly stable when riparian vegetation starts to develop. To ensure stability from the start it is recommended to stimulate the growth of riparian vegetation by planting seeds. This can be combined with a protection of the nourishment by applying a biodegradable geotextile. In time, when enough stability is ensured by the roots of the riparian vegetation the geotextile will be degraded [CUR, 1999a].

Furthermore it is recommended to closely monitor the stability of the nourishment. Because project "De Groene Poort" is constructed in phases (per groyne field), the design for the next phase can be adjusted based on previous experiences.

9.1.3 Ecological performance

The design study in this report focusses on the 'wet' part of the design, in order to enhance aquatic life in the Nieuwe Waterweg. However, nature friendly banks do not only have the ability to enhance aquatic life, the interaction between the land and the water is also very interesting for terrestrial life [CUR, 1999b]. Therefore, it is recommended that more focus is put on the 'dry' part of the design in future research.

9.1.4 Circular economy

Within the participating organizations that have an interest in the circular economy (Port of Rotterdam, Rijkswaterstaat and the Municipality of Rotterdam) there is little awareness about the opportunities of the circular economy and the use of residual material as a construction material [Hof, D., personal communication, May 1st 2015]. It would benefit the development of a circular economy in the Port of Rotterdam and its surroundings if more awareness is created within these organizations. It is expected that by raising more awareness among the possibilities of a circular economy and the use of residual material more projects and businesses in the port and its surroundings will get involved and the supply and demand of several sources of residual material will increase. Consequently, the feasibility of projects that aim to use residual material as a construction material will increase.

9.2 Nature friendly banks in port area

The execution of approaches and methods from this study are only applied to one case; therefore, the body of evidence is limited. It is therefore recommended to further investigate the impact of nature friendly banks for example in other ports, but also on locations other than along a channel. For example, the old city harbours in Rotterdam are potentially the ideal shelter area for migratory fish. These harbours are not exposed to the extreme conditions induced by shipping (as is the case in the Nieuwe Waterweg) and therefore offer promising opportunities for ecology. Furthermore, these harbours are very deep (up to 20 meters). Therefore, they offer promising opportunities for the circular economy: a lot of dredged material could be stored in these old city harbours.

As was concluded in chapter 8, nature friendly banks offer opportunities for ports on a local scale. However, it is expected that they can contribute to a larger system both in terms of biodiversity (e.g. migratory route of fish) and circular economy (on a larger scale than only the port). Therefore, it is recommended to integrate such projects with other projects that share the same objectives. In case of project "De Groene Poort" this means that the project should be integrated with other projects alike in the river Rhine. It can thereby add value on a system level by improving the migratory route of migratory fish along the river Rhine. Therefore, it is recommended to integrate project "De Groene Poort" with other projects along the river Rhine that share the same objective to enhance the living conditions of migratory fish. In order to do so, international borders have to be crossed. The European Union can act as an initiator of such international project collaborations.

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Appendices

A. Interview results

This appendix presents the results of the interviews that were conducted throughout the research. Stakeholder interviews were conducted for two projects. The stakeholder interview results concerning project "De Groene Poort" are presented in section A.1. The stakeholder interview results concerning project "Shoaling of old city harbours" are presented in section A.2.

The interview results are presented in a table that contains five columns. Each row contains the information of one specific quote. The first column represents the number of the quote, the second column represents the stakeholder that made the quote, the third column represents the label of the subject in which the quote is categorized, the fourth column contains the actual quote, the fifth column contains an interpretation of a (group of) quotes.

A.1 Results stakeholder interviews project “De Groene Poort”

The results of the stakeholder interviews of project “De Groene Poort” can be found in Table Appendix A-1 below.

Number	Stakeholder	Label	Quote	Interpretation
2	Port of Rotterdam	T1	Het havenbedrijf is afhankelijk van wat er gebeurt in de Delta, het havensysteem staat namelijk in connectie met het hele deltagebied.	The ultimate goal of the Port of Rotterdam is to achieve the goals that were set in the "Port Vision 2030", in which the Port of Rotterdam states that it want to become the most sustainable port of the world in 2030.
33	Gemeente Rotterdam	T1	De stad Rotterdam heeft als doel: een aantrekkelijke woon- en werkstad te zijn. Groen in de stad speelt daarin een grote rol, dat maakt de stad aantrekkelijker voor expats, bedrijven en bewoners. De ecologie vraagt om luwe plekken, en in combinatie met het inzetten van reststromen past de Groene Poort als project goed bij de Gemeente Rotterdam.	The municipality's ultimate goal is to improve the city's working and living environment, in which ecology and a green environment plays a significant role.
38	Rijkswaterstaat	T1	Kader Richtlijn Water is een Europese richtlijn. Achtergrond: water wordt steeds schoner, onder meer sinds de Wet verontreiniging oppervlaktewater (lozingen van vervuild materiaal in de rivier zijn niet meer toegestaan). Nu is de doelstelling om ook meer leven in het water te krijgen. Dit soort gebieden staan in damwand en in steen (de kades), voor waterleven is er niet veel plek. Dus is er een programma (geldt voor heel Europa) om ecologisch leven in rivieren en polders te krijgen. Dit wordt voornamelijk gerealiseerd door milieuvriendelijke oevers te creëren op verschillende projecten.	Rijkswaterstaat's aim is based on European guidelines (KRW), to enhance aquatic life in rivers and coastal waters.
65	WNF	T1	De doelstelling van het WNF is op metaniveau de delta weer gezond maken. De deltawerken hebben natuurlijk erg veel bijgedragen aan de veiligheid bij hoog water. Maar daarmee is het systeem ook in onbalans geraakt: - Volkerak: blauwalg; - Oosterschelde: zandhonger; - Grevelingen: zuurstofloosheid in de diepe delen; - Haringvliet: slibproblematiek; - trekvissen die niet meer van zee naar rivier en vice versa kunnen zwemmen.	According to WNF, the Dutch Delta system has been harmed by the deltaworks. It is WNF's aim to reconstruct the natural processes within the Delta to bring back its biodiversity.
66	WNF	T1	Naast voordelen hebben de Deltawerken ook erg veel nadelen met zich mee gebracht. De doelstelling van het WNF is door het herstellen van de natuurlijke processen, zoveel mogelijk de problemen in de delta op te lossen.	
1	Port of Rotterdam	T2	Het project "De Groene Poort" komt voort uit het project "Landtong Rozenburg" wat onderdeel is van het BRG-project. Het BRG project bestaat uit een serie projecten om het bestaande havengebied beter te benutten (intensiveren) en de kwaliteit van de leefomgeving te verbeteren. Rijkswaterstaat, WNF en de Gemeente waren ook betrokken bij Landtong Rozenburg.	All four parties were involved with the redevelopment of 'Landtong Rozenburg', an area that neighbours the location of project "De Groene Poort". Rijkswaterstaat, Port of Rotterdam and Municipality of Rotterdam initiated the project from a collaboration to reuse material within the city and the port.
20	Gemeente Rotterdam	T2	Vanuit de Grond- en Reststoffenbank van de gemeente Rotterdam komen veel materialen vrij, waarvoor een goede bestemming binnen de gemeente wordt gezocht. Het liefst natuurlijk zo dichtbij mogelijk, zodat vervoersafstanden en dus kosten en C02 uitstoot minimaal blijven.	

Number	Stakeholder	Label	Quote	Interpretation
22	Gemeente Rotterdam	T2	Vanuit de 'Werkgroep Grondstromen' was er al een samenwerking met Rijkswaterstaat, het Havenbedrijf en WNF om te kijken hoe reststromen het best kunnen worden ingezet. Dit liep tegelijk met de samenwerking tussen Havenbedrijf en WNF, daar is het project de Groene Poort uit voort gekomen.	
39	Rijkswaterstaat	T2	Bij Landtong Rozenburg waren er over een lengte van 1km milieuvriendelijke oevers gepland. Die zijn op een gegeven moment weg bezuinigd (er was geen geld voor). Toen met Gemeente en Havenbedrijf, via grondstromenclub, gekeken of daar niet iets mogelijk was. Om met grond dat over was iets te creëren aan de oever. Dat kon. Toen moest er nog een vooroeververdediging bedacht worden. Als je dat op de klassieke manier doet, met zinkstukken e.d., dan kost dat erg veel geld. Toen is het idee opgekomen om een vooroever te maken met puin.	
41	Rijkswaterstaat	T2	WNF is belangenpartij, hebben de steur uitgezet. Hier is veel media aandacht voor geweest. Toen ik dat doorkreeg, kreeg ik door dat veel van onze belangen overlappen. Bij Groene Poort moet veel gebeuren, zonder dat er geld beschikbaar is. De enige manier om dat te doen is met een coalitie die niet per se voor de hand ligt. Met gemeente en Havenbedrijf al Groene Poort verzonnen, met steur-verhaal erbij is het nog interessanter, ook met alle media aandacht erbij.	
10	Port of Rotterdam	T3	De doelstellingen van het project zijn: - Circulaire economie (minder uitstoot en minder geld om het te laten slopen) - Terugbrengen van natuurlijke processen in het deltagebied - Dubbele doelstelling Maasvlakte 2: natuurcompensatie	The specific goals in project "De Groene Poort" for the Port of Rotterdam are: 1. Contribute in restoring natural processes within the Delta; 2. Enhance the circular economy within the port which reduces both emmissions and expenses; 3. Contribute to the dual objectives of Maasvlakte 2 by creating environmental compensation.
11	Port of Rotterdam	T3	Een belangrijk criterium voor de beschikbaarheid van materialen zijn de vervoersafstanden. Als de materialen van te ver moeten komen, dan loont het niet om het te gebruiken in de Groene Poort.	
14	Port of Rotterdam	T3	Toegevoegde waarde voor het havenbedrijf: - Minder vervoerskilometers: scheelt geld - Doelstellingen afspraken met WNF: nieuwe deltavorm. Hoe kunnen we ecologische waarde toevoegen aan dit interessante brakwater gebied. en uitstoot;	
21	Gemeente Rotterdam	T3	De Groene Poort was een goede bestemming voor de materialen uit de Grondbank.	The specific goals in project "De Groene Poort" for the Municipality of Rotterdam are: 1. Enhance the circular economy within the city which reduces both emmissions and expenses; 2. Contribute to a pleasant working and living environment by creating nature.
27	Gemeente Rotterdam	T3	De specifieke doelen voor de gemeente in dit project zijn: 1. De bijdrage aan een circulaire economie: een bestemming vinden voor restmaterialen binnen de gemeente; 2. Puin minder fijn breken om energie te sparen en natuurwaarde te creëren; 3. Fijne leefomgeving, meer groen in/om de stad.	

Number	Stakeholder	Label	Quote	Interpretation
31	Gemeente Rotterdam	T3	De Groene Poort is wat dat betreft wel een pilot project te noemen, met het hergebruiken van partijen puin hebben we niet veel ervaring. We zijn hier wel erg in geïnteresseerd, en vooral of het iets oplevert. De winst zou dus kunnen zitten in: - Vervoersafstanden (kleinere afstand naar project dan naar puinbreker); - Minder energie nodig voor puinbreken (niet meer zo fijn mogelijk); - Minder nieuwe grondstoffen nodig bij projecten.	
34	Gemeente Rotterdam	T3	Afweging: transportkosten en wat het kost om van je grond/puin af te komen.	
36	Rijkswaterstaat	T3	We hebben vaak bij projecten grond over. Als je projecten aan elkaar koppelt, valt er geld te besparen	The specific goals in project "De Groene Poort" for Rijkswaterstaat are: 1. Achieve the objectives of the European Guidelines KRW by creating 6km of nature-friendly banks alongside the Nieuwe Waterweg; 2. Pilot project: find new means to construct nature-friendly banks.
40	Rijkswaterstaat	T3	Voor Rijkswaterstaat als overheidspartij is het terugbrengen van de steur in NL te hoog gegrepen.	
43	Rijkswaterstaat	T3	Iedere partij kijkt natuurlijk wel naar eigen belangen (haven: scheepvaart, gemeente: grondstromen, WNF: steur, Rijkswaterstaat: KWR).	
54	Rijkswaterstaat	T3	Rijkswaterstaat heeft op veel plekken vooroeververdedigingen liggen. Dat kan zijn om de afslag van de oever te voorkomen (bijvoorbeeld in de Lek) maar ook om dit soort situaties te maken waardoor de ecologische kwaliteit van het water toeneemt. In dat soort gevallen kan je kleine concessies doen aan de regelgeving.	
55	Rijkswaterstaat	T3	Wel ervaring met milieuvriendelijke oevers, op de klassieke manier: met zinkstuk (van wilgentenen) of doek. Zand met zinkstuk met stortsteen erop, dat werkt goed. We hebben geen ervaring met milieuvriendelijke oevers van puin.	
60	Rijkswaterstaat	T3	Het doel van het project is in eerste instantie het halen van de doelstellingen van Kader Richtlijn Water. Daarnaast komt er ook geld vrij uit het innovatiepotje, dus in die zin is het ook een pilot project en is innovatie ook een doel.	
68	WNF	T3	Het is in belangrijke mate een pilot project/voorbeeldproject, wij willen 20 ha intergetijdengebied in dit bijzondere zoet-zout gebied. Dat is het hoofddoel, dat is ook wel weer onder te verdelen in subdoelen. We willen namelijk ook wel weten of dit de populatie trekvissen en -vogels doet stijgen.	The specific goals in project "De Groene Poort" for WWF are: 1. Contributing to the aim of creating 20ha intertidal areas in mixed fresh-salt water; 2. Pilot project: find out whether or not creating intertidal areas increases the population of migratory birds and fish and biodiversity in total.
69	WNF	T3	Steur is een 'flagship', een voorbeeldsoort. Het duurt nog wel 20 jaar voordat die terug is. We hebben 50 steuren uitgezet, in Nijmegen en Rotterdam. Je ziet wel dat al die steuren hun weg naar het havengebied vinden, maar het gaat te ver om dat als doel aan een project als de Groene Poort te koppelen. Daar zit niet zo'n causaal verband in.	
78	Bureau Waardenburg	T3	Natuurvriendelijk oevers zijn een belangrijke maatregel voor het KRW. De absolute deadline voor het KRW is 2027. Tot die tijd zijn er veel maatregels gepland, waaronder Natuurvriendelijke oevers.	Creating nature-friendly banks is one of the measures to achieve the objectives of the European Guidelines KRW. The location of project "De Groene Poort" is good, since migratory fish and birds need resting and foraging space at the mouth of a river. Therefore, all ecological development in this area is a profit for the environment.
79	Bureau Waardenburg	T3	Bij zo'n riviermonding veel trekvissen, dus dat is wel heel goed dat daar plek voor wordt gecreëerd voor die vissen om te fourageren en te rusten etc.	

Number	Stakeholder	Label	Quote	Interpretation
85	Bureau Waardenburg	T3	Alle ecologische ontwikkeling in dit gebied is een grote winst. Als alle maatregelen o.b.v. KRW worden uitgevoerd, is de terugkeer van de steur wel een realistisch doel. Er moet alleen wel genoeg leefgebied en passagemogelijkheden (t.h.v. sluizen bijvoorbeeld) worden gecreëerd voor die trekvissen.	
3	Port of Rotterdam	T4	De taakverdeling is als volgt: - WNF levert de randvoorwaarden aan voor de perfecte ecologische omstandigheden - Rijkswaterstaat doet beheer en toezicht - Havenbedrijf Rotterdam zorgt voor de uitvoering en de aanvoer van materiaal - De Gemeente Rotterdam zorgt voor aanvoer van materiaal	The design was made by the four parties together, based on their experiences. There is no detailed design and thus the design is very flexible. During the execution of ten years, the design will be altered based on new experiences. Therefore, the design is based on a learning-by-doing process.
7	Port of Rotterdam	T4	Het ontwerp is heel flexibel en dynamisch op de volgende aspecten: - materiaal - condities (scheepsgolven) - ervaring (10 jaar bouwtijd)	
8	Port of Rotterdam	T4	De vooroever die beschermt tegen scheepsgolven bestaat uit dwarsdammen met openingen t.b.v. vismigratie	
9	Port of Rotterdam	T4	Op basis van stromingspaterionen en golfconditites zijn eisen gesteld aan de steengroottes. Er zijn geen modellen gemaakt die laten zien hoe het ontwerp zich gedraagt in de ruimte en tijd.	An outer bank made out of coarse debris is created between the groynes. This outer bank should protect the foreshore against waves and currents caused by shipping, such that a protected environment for migratory fish and birds is created. The following design aspects have been taken into account: - Maximum wave height +/- 1m; - Stone sizes based on material used on groynes; - Location of the outer bank at the tips of the groynes; The slopes of the outer bank (1:2 and 1:3) are a rough estimate and based on the slopes of the existing groynes in the area. If erosion will occur, the design will be altered accordingly. The core of the outer bank consists of a sorting of fine to coarse debris. This is topped of with coarse debris. The concept of a granular filter is used for the design of the outer bank.
23	Gemeente Rotterdam	T4	. Er worden geen hoge civieltechnische eisen gesteld aan het ontwerp, het ontwerp blijft dus globaal. Het moet natuurlijk ook een flexibel ontwerp zijn omdat elke keer een andere partij materiaal zal worden gebruikt.	
24	Gemeente Rotterdam	T4	De stenen/blokken puin moeten echter wel groot genoeg zijn om stroming en golven te kunnen weerstaan. Daarom wordt er per partij materiaal gekeken of het wel voldoet aan de eisen.	
32	Gemeente Rotterdam	T4	Slib is heel gevoelig voor erosie. Slib als materiaal voor de Groene Poort is dus niet een heel goed idee om de volgende redenen: 1. Milieuvriendelijke oever erodeert weg waardoor het zijn functie verliest; 2. Slib erodeert en komt dus in de vaarweg terecht waardoor meer onderhoud baggerwerk nodig is. Als je slib inpakt zou het wel kunnen functioneren als opvulmateriaal. Slib is alleen erg nat en slap, je zou het dus eerst moeten ontwateren wat kostbaar is als het slib is vervuild.	
45	Rijkswaterstaat	T4	Stortsteen: 300-1000kg gebasseerd op materiaal dat is toegepast op de kribben	
46	Rijkswaterstaat	T4	Golven: +/- 1m, in overleg met HbR	
47	Rijkswaterstaat	T4	Technisch gezien is het een klassieke ontwerpmethode. Van klein naar grof opbouwen. Granulair filter is wel een mooi woord, is het niet echt. Het stortsteen is een sortering van fijn-grof, daarover heen gaan de betonblokken van 300-1000 kg. De kribben (die blijven liggen) zijn van hetzelfde gewicht dus het zou moeten voldoen.	

Number	Stakeholder	Label	Quote	Interpretation
48	Rijkswaterstaat	T4	Buitentalud: aangenomen, monitoren of het blijft liggen. Je zou de taluds iets flauwer kunnen maken. Als het te flauw moet zijn, dan kan je iets met zinkstukken doen.	
49	Rijkswaterstaat	T4	De taluds van de buitenoever (1:2 en 1:3) zijn geschat, moet uitwijzen of dit werkt of niet. De verwachting is dat het aan de teen van de vooroever een beetje gaat eroderen, dan wordt dit ontwerp aangepast voor de volgende kribvakken. Of fijner materiaal gebruiken, of een zinkstuk neerleggen.	
51	Rijkswaterstaat	T4	Vooroevers ter hoogte van waar de kribben zijn.	
52	Rijkswaterstaat	T4	Hoogte vooroever: ter hoogte van kribben, die liggen ongeveer 0,5m boven GHW. Er is een regel dat bij HW de vooroever onder water moet staan. Dit is vanwege de berging van de rivier, in het kader van waterveiligheid. Bovenstrooms in een rivier is de afvoer belangrijk voor waterveiligheid, maar benedenstrooms is de berging belangrijk. Benedenstrooms komt het gevaar namelijk vanuit de zee, daar komen de maatgevende hoogwater condities vandaan. Bij hoogwater op zee gaat de stormvloedkering dicht en stroomt de rivier niet meer vrij af. Dan moet de afvoer van de rivier dus tijdelijk (gedurende de duur van de storm) worden gebergd, daar is zoveel mogelijk plek voor nodig. Dus is een regel van Rijkswaterstaat dat je niet boven GHW mag bouwen (+/- 1,20m). De vooroever wordt dus eigenlijk te hoog aangelegd (+/- 1,70m). Op het volume van de berging van het gebied, is dit een heel miezerig klein beetje (maar klein vooroever dammetje). Bij maatgevende omstandigheden (grote storm), staat het sowieso onder water. Dus het is maar een beetje bedacht.	The project has a duration of ten years. This long period gives the project the oppurtunity to wait for parties residual material that are suitable. Such a long period also gives time for gaining experience and alter the design where necessary.
57	Rijkswaterstaat	T4	Kribben in dit gebied staan ter discussie. In dit gebied eb en vloed: stroming loopt dus heen en weer. Functie van kribben in dit gebied is niet echt duidelijk. Is waarschijnlijk zo aangelegd omdat dat altijd zo gedaan werd, 'geleiden' zogenaamd de stroom.	
58	Rijkswaterstaat	T4	Bij het ontwerp van de Groene Poort is het niet de bedoeling dat het gaat aanzanden, want het wordt al verondiept. Het echte doel van de vooroever is om de scheepsgolven tegen te houden om luwe condities voor ecologie te creëren.	
67	WNF	T4	Het WNF levert kennis en dus ook randvoorwaarden in.	The WWF provided the requirements for the design, which are based on the demands of migratory fish and birds. The following requirements have to be met: - During low water conditions, a large part of the foreshore
70	WNF	T4	Voor het ontwerp is er gekeken naar doelsoorten (dit geval steur): wat hebben die nodig. We willen zoveel mogelijk habitat hebben voor de soorten die we willen aantrekken, en dat zijn trekvissen en trekvogels.	

Number	Stakeholder	Label	Quote	Interpretation
71	WNF	T4	De volgende randvoorwaarden zijn daar bijvoorbeeld voor opgesteld: - We willen zoveel mogelijk intergetijdegebied, een zo groot mogelijk droogvallend gebied voor trekvogels. Het talud van de vooroever moet dus flauw zijn, zodat een groot oppervlak droogvalt bij eb; - Er moet een stuk achter de vooroever zijn dat altijd 1,5m water bevat, zodat de trekvissen bij eb ook kunnen rusten en fourageren; - Langsdam moet niet helemaal dicht zijn, want dan ben je je natuurlijke processen kwijt en dan kunnen de vissen niet in en uit zwemmen. Die opening moet gebasseerd zijn op een stabiele situatie achter de vooroever, geen sedimentatie en geen erosie; - Gebruik maken van restmateriaal: geen nieuw materiaal nodig en minder CO2 uitstoot door transport en breken.	should be dry for migratory birds; - During low water conditions, a part of the foreshore still has to contain 1,5m water for the migratory fish; - The outer bank should contain openings dimensioned such, that migratory fish can swim in and out the protected environment.
72	WNF	T4	Met de vier partijen zitten kleuren en tekenen, en toen kwam dit er ongeveer uit. We hebben geen moeilijke berekeningen gedaan maar met onze parate kennis een ontwerp gemaakt. Tijdens de uitvoeringsperiode wordt het ontwerp getest en kan het eventueel aangepast worden voor volgende kribvakken.	
80	Bureau Waardenburg	T4	Het ontwerp van de Groene Poort is inderdaad een vorm van natuurvriendelijke oevers, met een vooroever en een verondieping daarachter. Dit wordt veel in grote rivieren gedaan omdat je daar die grote scheepsgolven hebt en het leegzuigen van de oevers. Als er een schip langskomt, zuigt het de hele oever leeg. Dat is heel slecht voor kleine waterbeestjes en jonge vis, die kunnen daardoor niet overleven langs die oevers.	Every ecological development in this area is a profit. However, it is very important that a large variety in substrates will be applied in the design. A general, ecological principle says: the higher the variety in substrates (from rocks to sand), the higher the diversity in plant and animal species. The higher the biodiversity, the more robust the entire ecological system is.
81	Bureau Waardenburg	T4	Als je ontwikkeling van waterplanten hebt, dan heb je altijd waterorganismen daarop, en daar komen weer vissen op af. In de rivier kunnen ook hardere substraten (grind zorgen voor aantrek van waterorganismen (insecten, vissen). Je hebt ook organismen die hardere substraten nodig hebben om te overleven.	
82	Bureau Waardenburg	T4	Algemeen ecologisch principe: hoe meer variatie in substraten (planten, keien, hout), hoe meer verschillende substraten in een oever, hoe gunstiger voor je ecologie, dus hoe meer een diversiteit in planten- en diersoorten. Hoe meer diversiteit in flora en fauna, hoe robuuster het systeem ook is.	
83	Port of Rotterdam	T5	Financieel gezien zijn er geen concrete afspraken gemaakt, het is een samenwerking met gesloten beurzen	The application of residual ground has been done before on a large scale. However, the application of coarse debris has not been done on such a large scale before. Normally, debris is crushed and made into very fine material that is used as a basis for new roads. Breaking debris in larger chunks, usable in projects like 'De Groene Poort' is something new.
6	Port of Rotterdam	T5	Het project zit zowel in de uitvoeringsfase als in de ontwerpfase, gezien het dynamische karakter van het ontwerp. Volgende week wordt begonnen met de constructie van de langsdam in kribvak 3.	
12	Port of Rotterdam	T5	Er zijn momenteel twee partijen restmateriaal beschikbaar voor het opbouwen van de 1e buitendam: 1. Stortsteen van de oude Nerefco werf 2. Betonnen funderingsblokken van de oude parkeermeters in Rotterdam	
13	Port of Rotterdam	T5	Het vullen van de kribvakken wordt gedaan met materiaal uit de grondbank van de gemeente. De grondbank zorgt voor certificering en sturing van grondstromen.	
15	Port of Rotterdam	T5	Voor het eerste deel van de uitvoering is aannemer van Argos gekozen (firma Blom), omdat vanuit dat project de partij stenen komt.	

Number	Stakeholder	Label	Quote	Interpretation
17	Port of Rotterdam	T5	Het project heeft een uitvoeringsduur van 10 jaar. Er is geen haast mee, als het eenmaal loopt gaan partijen meedenken en gaat het project vanzelf lopen.	
28	Gemeente Rotterdam	T5	Het idee is dus om luwe condities te creëren, waarna de natuur haar werk moet gaan doen. Of dit gaat werken moeten we natuurlijk controleren.	The design has not been evaluated by making use of a model. A model of the scale of project 'De Groene Poort' will not provide the information that is necessary: the groyne fields are too small for setting up a reliable model.
29	Gemeente Rotterdam	T5	Restpartijen grond komen uit de gemeente, bijvoorbeeld van projecten met graafwerkzaamheden (bijvoorbeeld: bouw van een ondergrondse garage). De toepassing van deze restpartijen grond is veel bekend, en wordt al breed toegepast.	
30	Gemeente Rotterdam	T5	Van de toepassing van partijen puin is minder bekend. De conventionele manier om met puin om te gaan is om het naar een puinbreker te brengen en die het zo fijn mogelijk te laten maken. Dat fijngemaakte puin wordt vervolgens weer verkocht t.b.v. de wegenbouw. Het kan interessant zijn om niet meer puinmateriaal zo fijn mogelijk te maken (scheelt breekenergie) maar om gericht te gaan slopen, met in gedachte het hergebruik van sloopmateriaal. Je zou dus bijvoorbeeld aan aannemers kunnen vragen of ze bij het slopen brokken puin van een bepaalde dimensie kunnen maken, zodat deze brokken gebruikt kunnen worden bij de aanleg van milieuvriendelijke overs.	
42	Rijkswaterstaat	T5	Er is wel een verantwoordelijkheidsverdeling, maar de taakverdeling is een beetje ad-hoc ontstaan.	
44	Rijkswaterstaat	T5	Bestuursovereenkomst: het havenbedrijf, de gemeente en Rijkswaterstaat kunnen materialen uit projecten aanleveren. Als er zich een mogelijkheid voordoet, leg je het voor aan de andere partijen.	
50	Rijkswaterstaat	T5	De bodem wordt ook gemonitord, die diepte dan voornamelijk, kijken naar: - Blijft de verondieping liggen; - Zakt de vooroever weg?	The project is now in its execution phase. The first two parties of residual materials have been identified. However, the project is also still in its design phase. Throughout the execution period of 10 years the design will be monitored to see if the required conditions for migratory birds and fish will be created. If this is not the case, the design will be altered during the execution. There is no permanent division of responsibilities between the four parties. However, the roles are more or less as follows: - WWF provides the requirements that the design has to meet; - The Port of Rotterdam provides coarse material from the harbour; - The Municipality of Rotterdam provides ground for the shoaling behind the outer bank; - Rijkswaterstaat takes care of the management and supervision.
59	Rijkswaterstaat	T5	Het is niet gemodelleerd. De schaal van dit project geeft over het algemeen niet zoveel informatie bij dit soort modellen. Met kleinere projecten had het vroeger geen nut, er werd met vakken van 100 – 200 m gerekend. Het is een beetje een improvisatorisch project, het is learning by doing.	
62	Rijkswaterstaat	T5	Dit voorjaar: bijeenkomst met aannemers, slopers en wat mensen van overheden om te brainstormen over nieuwe methodes.	
63	Rijkswaterstaat	T5	Het loopt nu ineens wel snel qua beschikbare materialen. We hadden eigenlijk verwacht dat er een aantal hele grote projecten zouden vrijkomen, en dat we daarmee aan de slag zouden kunnen. Een voorbeeld is het project Breeddijk, waar een splitsingsdam wordt afgebroken, en er zoveel materiaal vrijkomt dat de helft van de vooroevers kunnen worden aangelegd.	

Number	Stakeholder	Label	Quote	Interpretation
73	WNF	T5	Aan de aannemer is meegegeven: - Een hoogte van de vooroever zodat de scheepsgolven worden tegengehouden; - een talud van de vooroever en de verondieping.	
74	WNF	T5	Fase: nu materiaal aan het verzamelen. Dat is best lastig, ook omdat we met gesloten beurzen werken dus er is geen zak geld waar we puin mee kunnen kopen. Het havenbedrijf levert in principe puin en de gemeente grond. De eerste partijen zijn nu gestort op de kade en worden binnenkort aangelegd door de aannemer.	
75	WNF	T5	We zijn begonnen met de nulmeting t.b.v. de monitoring. Rijkswaterstaat heeft een opdracht gegeven om de T0 vast te stellen. Als de eerste kribvakken zijn aangelegd gaan we weer kijken om vast te stellen of er iets veranderd is. De monitoring is een soort telling van vissen, trekvogels en het nemen van een aantal watermonsters e.d.	
76	WNF	T5	De periode van 10 jaar is zo gekozen omdat we afhankelijk zijn van het aanbod van geschikt materiaal. Met een lange uitvoeringsperiode hebben we de grootste kans op succes.	
5	Port of Rotterdam	T6	De communicatie naar de buitenwereld is lastig, elke partij wil graag iets anders onderstrepen.	The following risks can affect the succes of the project: 1. The availability of coarse material within the surroundings is the limiting factor: there may not be enough material available to succesfully complete the project; 2. A shift in priorities may be caused by the long stretch of the project and the turnover in staff; 3. Communication between four parties can get problematic; 4. The design may not be able to create the imposed, sheltered conditions. The following risks may oppose a threat for the stakeholders and their surroundings: 1. The reduction in water storage capacity may reduce the flood protecting capacity of the system; 2. The nature that is created may cause (legal) limitations for shipping.
16	Port of Rotterdam	T6	De limiterende factor van de uitvoering van het project is de beschikbaarheid van partijen steenachtig, grof materiaal om de langsdammen mee te construeren.	
18	Port of Rotterdam	T6	Rijkswaterstaat is heel benauwd als het gaat om 'Ruimte voor de Rivier' en zoutindringing.	
19	Port of Rotterdam	T6	Het grootste risico voor het Havenbedrijf is dat er door de gecreëerde natuur een beperking wordt opgelegd in de kernactiviteiten van het havenbedrijf.	
25	Gemeente Rotterdam	T6	Dit project is natuurlijk in zekere zin wel in strijd met het project 'Ruimte voor de Rivier. Maar het aanleggen van 5km milieuvriendelijke oevers is een eis van KRW waaraan Rijkswaterstaat moet voldoen.	
26	Gemeente Rotterdam	T6	Het stroomvoerend oppervlak zal natuurlijk wel afnemen, maar we verwachten dat dat niet significant zal zijn voor de afvoer bij hoogwater. Er is wel veel gesproken en gediscussieerd over deze kwestie. Een ontwerp mag natuurlijk niet het overstromingsgevaar vergroten tijdens hoogwater.	
35	Gemeente Rotterdam	T6	Geen exacte deadline: op den duur prioriteiten ergens anders; Nieuwe projecten dichter bij de stad, waar meer materiaal heen gaat omdat de vervoersafstanden daar korter zijn	
37	Rijkswaterstaat	T6	Het blijkt lastig om twee projecten zo afhankelijk van elkaar te maken, je introduceert risico's. In de praktijk lukt dat moeilijk.	
53	Rijkswaterstaat	T6	Project eigenlijk ook in strijd met Ruimte voor de Rivier, maar dat is bovenstrooms voornamelijk belangrijk i.v.m. de afvoer van de rivier.	
56	Rijkswaterstaat	T6	Het verschil is dat je bij puin de exacte sortering niet weet. Dit kan een risico zijn omdat je niet zeker weet of die sortering de golfhoogtes (van schepen) aankan, het zou kunnen eroderen.	

Number	Stakeholder	Label	Quote	Interpretation
61	Rijkswaterstaat	T6	Het grote puin is wel de limiting factor, grond is wel genoeg beschikbaar. Groot puin bestaat niet in de sloopindustrie, het wordt altijd met zo fijn mogelijk gesloopt. Aannemers zijn niet gewend om het in grotere stukken te breken, omdat er geen afzet voor is. Dat is wel een probleem. Als niemand het zo doet, is er ook geen aanbod (van grof puin). Nu heeft Boskalis aangeboden (Dries Hof) om te laten zien dat het kan. Het is een andere manier van slopen, je moet het anders vervoeren en anders slopen. Het ontwerp moet er ook op aangepast worden. Dat is het knelpunt. Bij Rijkswaterstaat zijn ze huiverig, ze komen dan ook bij aanbestedingsregels. Als Boskalis dit mag doen, dan hebben ze een voordeel. Ik wil het gooien over het eigen initiatief, dan mag je Boskalis wel deze opdracht geven. Wel moeilijk om dit van de grond te krijgen. Het is een andere aanpak, maar de regelgeving is lastig en marktpartijen gaan niet zo snel op eigen initiatief iets doen want er is geen vraag naar.	
64	Rijkswaterstaat	T6	Door verloop van personeel zou het wel van de agenda af kunnen lopen.	
77	WNF	T6	Het is natuurlijk wel een risico dat het na 10 jaar van de agenda's verdwijnt en dat het project niet is afgerond. Maar dit is niet iets wat je juridisch dicht gaat timmeren, hierin moet je elkaar ook een beetje vertrouwen.	
83	Bureau Waardenburg	T6	Zou een vooroever die "leegzuiging" bij een scheepspassage kunnen tegenhouden? In principe is het een "open" constructie, dus houdt dat die stroming wel tegen?	
84	Bureau Waardenburg	T6	Dit is een heel intensief en druk gebied, een soort snelweg voor de scheepvaart. Als de golfwerking en de zuigende werking in de oevers kan worden gereduceerd, dan heeft de ecologie daar wel baat bij.	

Table Appendix A-1 Results of the stakeholder interviews of project "De Groene Poort"

A.2 Results stakeholder interviews project "Shoaling old city harbours"

The results of the stakeholder interviews of project "Shoaling of old city harbours" can be found in Table Appendix A-2 below.

Nummer	Stakeholder	Label	Quote	Interpretation
5	Gemeente Rotterdam	T1	Dat is ook het doel van de Gemeente Rotterdam: om integraal naar de ontwikkeling van stadshavens te kijken, naar wat er in de omgeving gebeurt en wat er nodig is.	The aim of the Municipality of Rotterdam is the redevelopment of old city harbors that have lost their old function as a port
15	Rijkswaterstaat	T1	Met stadshavens heeft Rijkswaterstaat op zich niet veel te maken, maar in het kader van de KRW doelstellingen doet Rijkswaterstaat samen met de gemeente mee aan projecten waarbij de ecologie in oude stadshavens wordt verbeterd.	Rijkswaterstaat's aim is based on European guidelines (KRW), to enhance aquatic life in rivers and coastal waters.
1	Port of Rotterdam	T2	Een paar havens in de buurt van de hefbrug zijn zo'n 40 jaar geleden de havenfunctie verloren. Wanneer een haven zijn functie verlies, draagt het havenbedrijf het beheer van de haven over naar de stad, die dan een nieuwe bestemming zoekt en aan gebiedsontwikkeling doen.	Old city harbours become available for (urban) redevelopment because the Port of Rotterdam is increasingly moving its activities westward (towards the North Sea) over the years, and thus the old city harbours lose their shipping function.
3	Port of Rotterdam	T2	"Rivier als getijdepark": vanuit de stadsregio liep er een initiatief om waarin gekeken werd naar mogelijkheden om de Groene Poort verder toe te passen.	
6	Gemeente Rotterdam	T2	Er is een studie gedaan naar de potentie van het verondiepen van oude stadshavens.	The shoaling of old city harbours is part of a new project: "The river as tidal park"
7	Gemeente Rotterdam	T2	In principe komen uiteindelijk alle stadshavens vrij voor stadsontwikkeling, omdat het Havenbedrijf haar activiteiten de komende jaren steeds meer zal verplaatsen richting de Noordzee.	
10	Gemeente Rotterdam	T2	Het project 'De Rivier als Getijdenpark' is een initiatief van Stadsregio Rotterdam, een samenwerkingsverband tussen verschillende gemeenten in de Rijnmond Regio. Deze samenwerking wordt stopgezet (waarschijnlijk 1 januari 2015), maar het project zal dan waarschijnlijk onder de Gemeente Rotterdam verder gaan.	
2	Port of Rotterdam	T3	Afspraken MV2: we breiden de haven uit in zee, en zullen de komende tijd ook kijken waar er havens worden afgestoten t.b.v. projectontwikkeling (project stadshavens).	The specific goals in project "De Groene Poort" for the Port of Rotterdam are: 1. Contribute in restoring natural processes within the Delta; 2. Enhance the circular economy within the port which reduces both emmissions and expenses; 3. Contribute to the dual objectives of Maasvlakte 2 by creating environmental compensation.
4	Port of Rotterdam	T3	Herontwikkeling van oude havens is voornamelijk een aangelegenheid van de gemeente.In het kader van BRG (dubbele doelstelling MV2: verbeteren leefbaarheid stadsregio) wordt er vanuit het havenbedrijf wel geld beschikbaar gemaakt voor dit soort projecten.	

Nummer	Stakeholder	Label	Quote	Interpretation
8	Gemeente Rotterdam	T3	Het grote nadeel van die oude stadshavens die hun functie zijn verloren is dat ze erg diep zijn en dat er dus niks groeit. Verder zorgt de steile kademuur niet voor een goede overgang tussen de kade en het water, wat ook niet bevorderlijk is voor de ecologie.	The specific goals in project "De Groene Poort" for the Municipality of Rotterdam are: 1. Enhance the circular economy within the city which reduces both emmissions and expenses; 2. Contribute to a pleasant working and living environment by creating nature.
9	Gemeente Rotterdam	T3	Voor de Grondbank is verondiepen van stadshavens natuurlijk interessant, voor de grondbank is verondiepen een doel. Als je op een integraal niveau kijkt, op stedenbouwkundig niveau, is verondiepen een middel, namelijk om ecologische ontwikkeling te bewerkstelligen.	
16	Rijkswaterstaat	T3	Voor de KRW moet in de Nieuwe Maas 5km aan milieuvriendelijke oevers worden aangelegd. Tot aan bovenstrooms van Brienenoord brug is er hier en daar wel wat ruimte, maar daarna is er geen ruimte voor door de scheepvaart. Daarom wordt er nu gekeken of er in de stadshavens plek is.	The specific goal of Rijkswaterstaat in the shoaling of old city harbours is to achieve the objectives of the European Guidelines KRW within the city. In principle Rijkswaterstaat has nothing to do with the management of the city harbours, this is a concern of the Municipality. However, in order to achieve the objectives of the European Guidelines KRW, Rijkswaterstaat is funding projects that enhance aquatic life in and around rivers and coastal waters.
21	WNF	T3	Diepe basins: veel voedselrijk materiaal “zinkt” in die diepe putten, daar gaat het zuurstof verbruiken om dat materiaal af te breken, op een gegeven moment is het zuurstof op en krijg je dus stikstof omzettende bacteriën die al het organisch materiaal om gaan zetten. Naast die stikstof omzetten bacteriën kunnen er geen andere soorten zich vestigen, nul biodiversiteit dus.	The specific goals in project "De Groene Poort" for WWF are: 1. Contributing to the aim of creating 20ha intertidal areas in mixed fresh-salt water; 2. Pilot project: find out whether or not creating intertidal areas increases the population of migratory birds and fish and biodiversity in total.
22	WNF	T3	Zelfde perspectief in de doelstellingen (natuurvriendelijke oevers, getij zichtbaar maken, alternatieve manier van inrichting) en randvoorwaarden ls de Groene Poort.	
26	Bureau Waardenburg	T3	Die stadshavens kunnen dienen als “stapstenen” voor die trekvissen. Stapstenen zijn plekjes waar voedsel is en plek voor rust. De Nieuwe Waterweg is heel ongunstig voor vissen door de turbulentie en drukte van scheepsverkeer. Als er dan een mogelijkheid is om ergens te rusten en voedsel te vinden zullen ze dat gelijk benutten. Alles wat je langs zo’n scheepvaartroute aanlegt aan natuurontwikkeling is winst.	Old city harbours may function as ecological "stepstones" for migratory fish. Ecological "stepstones" are sport where there is enough food and space for resting. For fish in a busy shipping route such as the "Nieuwe Waterweg" such stepstones may be very advantageous.
11	Gemeente Rotterdam	T4	Rijnhaven is als aanbesteding uitgezet. Of er wel/niet verondiept wordt is aan het consortium.	There are some large city harbours that are/will be availabe for shoaling: - Rijnhaven - Maashaven; - Vierhaven; - Merwehaven; Heijplaat. Shoaling and 'floating green' would be a good combination. The optimum design would be if the foreshore would also be brought in slope. Currently, the Nassauhaven is being redeveloped. A terrace-shaped foreshore is created, combined
12	Gemeente Rotterdam	T4	Maashaven is nog veel in gebruik, er zou wel verondiept kunnen worden tot op dusdanige hoogte dat de binnenvaart er geen last van heeft. Van de verondieping op zich heeft de binnenvaart er dan geen last van, maar wellicht van de werkzaamheden wel. Vandaar dat men hier terughoudend mee is.	
13	Gemeente Rotterdam	T4	Vierhaven en Merwehaven zullen ook beschikbaar worden in de komende jaren.	
17	Rijkswaterstaat	T4	Met drijvend groen, verondiepen en het afbreken van oude kades en het weer in talud brengen daarvan willen we de doelstelling van de KRW in de Nieuwe Maas toch behalen.	

Nummer	Stakeholder	Label	Quote	Interpretation
19	Rijkswaterstaat	T4	Nassauhaven is nu in ontwikkeling, die terrassen dus. Ontwerp: paar damwanden met grond ertussen. Daar is nu een ontwerp voor in ontwikkeling bij de gemeente, dit wordt eind dit jaar of begin volgende jaar aanbesteed bij aannemers. Rijkswaterstaat betaalt er aan mee om de doelstelling van de KRW te halen.	with shoaling. Terraces are not gentle transitions and thus are not very natural. Therefore, WWF is not very happy with this design. However, every ecological development is a profit in this area.
20	Rijkswaterstaat	T4	Het mooiste zou zijn: verondiepen in combinatie met drijvend groen. Nog mooier zou zijn als stukken van de oever ook in talud kunnen worden gebracht. Dit is wel lastig in de stad, vaak niet esthetisch genoeg. In de Nassauhaven hebben ze ontwerp waarbij de oever in talud wordt gebracht, maar dan wordt het vrij strak aangelegd in de vorm van een soort van terrassen.	The optimum depth for aquatic life is 1-2m, a greater depth results in not sufficient transparency. If the bottom consists of silt, there is the risk of resuspension which reduces transperceny. Therefore, using silt is not advised for shoaling, except if the silt is packed in some way.
23	WNF	T4	We zijn op zoek gegaan naar nieuwe plekken binnen de stadsregio waar we natuurvriendelijke oevers kunnen aanleggen in dat interessante zoet-zoute gebied. Daarvoor zijn allerlei workshops georganiseerd om te kijken op welke locaties dat kan. Daar is uitgekomen dat oude havenbekkens een geschikte plek zijn daarvoor, bijvoorbeeld: - Rijnhaven (waar nu de aanbesteding loopt); - Maashaven; - Heijplaat.	
24	WNF	T4	In de Nassauhaven worden terrassen gemaakt, WNF is hier niet heel erg blij. terrassen zijn schoksgewijze stappen dat zie je nergens in de natuur. WNF had liever een glooiende rivieroever gezien. Dit is echter een klein haventje, en het belang is om te laten zien dat je ook andere dingen met zo'n havenbekken kan zien.	
25	WNF	T4	In het project 'De Rivier als Getijdenpark' werken veel meer organisaties samen en het loopt van de Maeslantkering tot aan Krimpen.	
27	Bureau Waardenburg	T4	Voor de juiste ecologische omstandigheden, aangroei van ondergedoken waterplanten (belangrijk voor allerlei andere beestjes) is 1-2 meter diepte nodig. Op grotere dieptes niet genoeg doorzicht.	
28	Bureau Waardenburg	T4	Bij een bodem van slib heb je al snel opwerveling van al dat fijne materiaal, en is het zicht nog slechter. Een bodem van slibachtig materiaal is dus niet gunstig. Je zou het slib kunnen inpakken, met een toplaag van zand bijvoorbeeld.	
18	Rijkswaterstaat	T4	Proef drijvend groen. Het prototype zou in december klaar moeten zijn (op schaal dus), dat wordt in het voorjaar verder ontwikkeld en in april/mei komt het in het Buizengat te liggen, waar het nog groter moeten worden. Drijvende groen is een samenwerking tussen Gemeente en Rijkswaterstaat. De Gemeente wil vooral boven water groen (voor het zicht) en Rijkswaterstaat is vooral geïnteresseerd in de situatie onder water. Met die proef proberen ze dit te combineren.	

Nummer	Stakeholder	Label	Quote	Interpretation
14	Gemeente Rotterdam	T6	Wat te doen met de steile kademuur? Dit zijn over het algemeen zware, robuuste constructies. Slopen is moeilijk en dus kostbaar.	In the redevelopment of old city harbours the following challenges have to be faced: - Demolish and recycle old, and often heavy, rugged and steep quay wall; - Find a suitable filling material;
29	Bureau Waardenburg	T6	Bij het gebruik van materiaal moet je ook kijken naar de hoeveelheid nutriënten in het materiaal. Slib is vaak erg rijk aan nutriënten, en dat kan algengroei veroorzaken. Dominantie van algen is slecht voor het doorzicht en dus slecht voor de aangroei van waterplanten. In het ergste geval krijg je blauwalg groei (combinatie van algen en bacterien), daar zitten gifstoffen in. Als die blauwalg groei in een drijflaag komt, spreidt het zich uit en kunnen er vissen en watervogels ziek van worden en dood van gaan. Algen groeien over het algemeen in stilstaande wateren, in rivieren zie je niet veel algengroei omdat er te veel dynamiek is in een rivier. In een stadshaven is er wel een groter risico op algengroei.	

Table Appendix A-2 Results of the stakeholder interviews of project "Shoaling of old city harbours"

B. Ship-induced water movement

This appendix presents a detailed explanation about the ship-induced water movement in the Nieuwe Waterweg. Section B.1 gives an introduction on ship-induced water movement in general. Sections B.3, B.4, and B.5 present methods that can be used to calculate the governing conditions. Section B.6 presents the results of the different methods and draws conclusions about the governing conditions in the Nieuwe Waterweg.

B.1 General

B.1.1 Components

The water movement generated by a moving vessel can be divided into three main components:

1. a primary wave;
2. a secondary wave;
3. a propeller jet.

The primary wave consists of:

- a front wave Δh_f;
- a water level depression Δh;
- a return current u_r;
- a stern wave z_{max}.

The front wave is the first border of the water level depression area above the bank slope. The water level depression is a drop in the water level alongside the ship. The stern wave forms the backward boundary of the water level depression and is one of the most important stress factors for the bank protection. An overview of the primary wave components can be seen in Figure Appendix B-1.

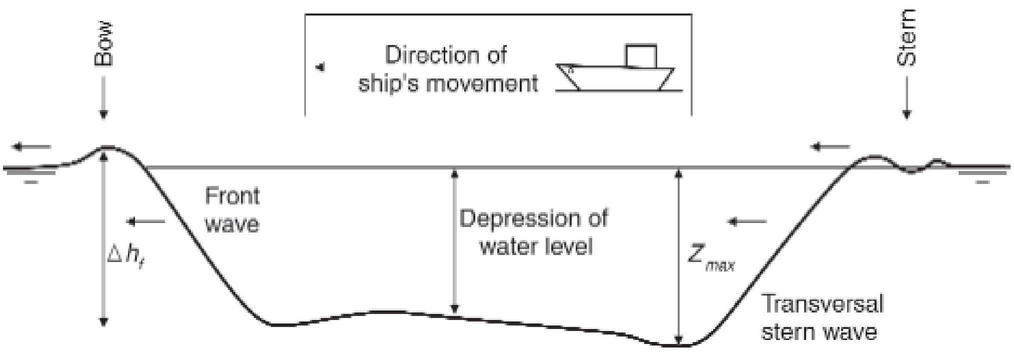

Figure Appendix B-1 Overview of the primary wave components [CIRIA et al., 2007]

Secondary ship waves consist of divergent waves and transverse waves. Interference peaks arise from interference of transverse waves and divergent waves. An overview can be seen in Figure Appendix B-2. As can be seen from the figure, the secondary waves approaches the bank as a wave train of short waves.

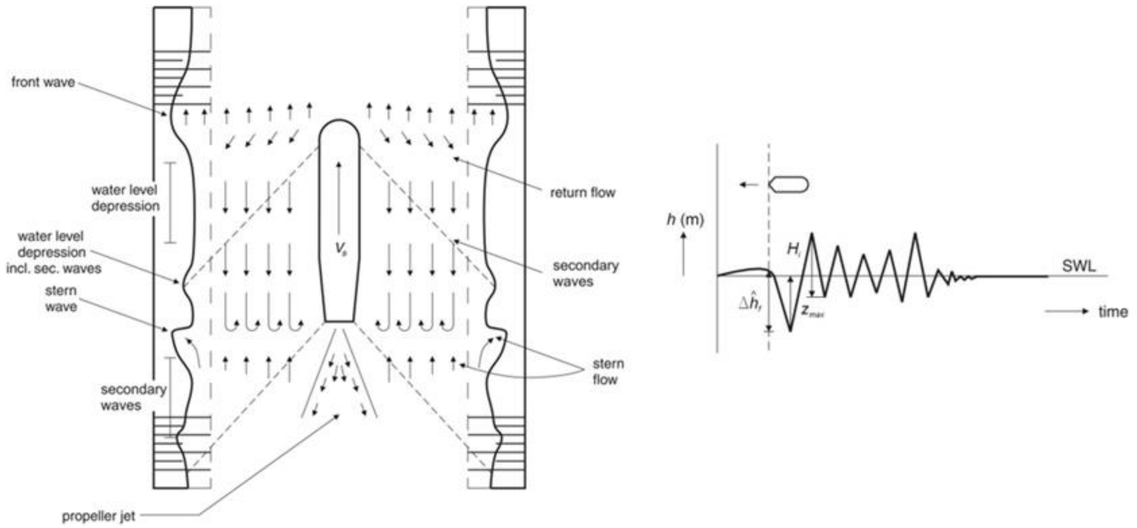

Figure Appendix B-2 Overview of secondary wave components [CIRIA et al., 2007]

B.1.2 Analysis

The available literature is divided on the governing component of the ship induced water movement on the banks and the governing conditions in the Nieuwe Waterweg. Therefore, an analysis is made based on several sources and the results are compared.

Formulas for the calculations of the ship-induced water movements are obtained from the following literature sources:

- CUR 201;
- The Rock Manual;
- Bed, bank and shoreline protection.

In sections B.3, B.4 and B.5 the methods presented by these sources are explained and presented. For every method, the ship induced waves are calculated. Section B.2 presents the important input parameters for these methods. The output of the calculations is checked with the online application cress, to see if the outcomes match and the calculations are performed well.

B.2 Input

This section describes the input used in calculating ship-induced water movements. Input for the calculations is based on both the governing ship properties and channel properties.

B.2.1 Governing ship properties

As mentioned before, the Nieuwe Waterweg, alongside which the project is situated, can be considered as a "highway for ships". In general, the ships in the Nieuwe Waterweg can be divided into three main groups:

1. inland ships;
2. seagoing ships;
3. recreational ships.

This study focusses on inland and seagoing ships: it is expected that these types of ships generate the governing loads on the banks.

In Europe, inland ships are categorized in CEMT classes. The maximum sizes of the inland vessels are established per class. The Nieuwe Waterweg has the classification 'VIb' which means ships pass with maximum dimensions as shown in Table Appendix B-1. Vessel speed information is obtained from observations of marinetraffic.com. The observed inland cargo ships sail with a speed between 8 – 9 kn. The maximum speed is assumed to be 10 kn, which corresponds with approximately 5.14 m/s.

Class [CEMT]	Length [m]	Beam [m]	Draught when laden [m]	Speed [kn]
VIb	185-195	22.8	2.5 – 4.5	8 - 10

Table Appendix B-1 Dimensions of the governing inland ship [Rijkswaterstaat, 2011a]

For sea-going ships no specific categorization exists. The available width and depth of the Nieuwe Waterweg are in this case governing for the maximum admitted sea-going ships. An overview of the dimensions of the governing sea-going ship is presented in Table Appendix B-2. The maximum speed of sea-going vessels is approximately [Port of Rotterdam harbourmaster, personal communicaton, April 28th 2015] 5 kn, which corresponds with approximately 2.57 m/s.

Length [m]	Beam [m]	Draught when laden [m]	Speed [kn]
360	60	13	4-5

Table Appendix B-2 Dimensions of the governing sea-going vessel [Port of Rotterdam harbourmaster, personal communicaton, April 28th 2015]

As can be concluded from Table Appendix B-1 and Table Appendix B-2 the governing sea-going ship is a lot larger than the governing inland ship. However as also can be concluded, large sea-going ships sail at a considerably lower speed than the inland ships. Therefore, in determining the governing ship-induced water movements, both type of ships are accounted for.

B.2.2 Channel properties

The properties of the channel have a significant effect on the ship-induced water movements. Important are:

- dimensions of the channel;
- shape of the channel's profile;
- position of the ship with respect to the banks and the channel's axis.

The profile of the Nieuwe Waterweg is plotted by making use of data obtained from Rijkswaterstaat. The original profile is simplified and reduced to a trapezoidal profile (Figure Appendix B-3).

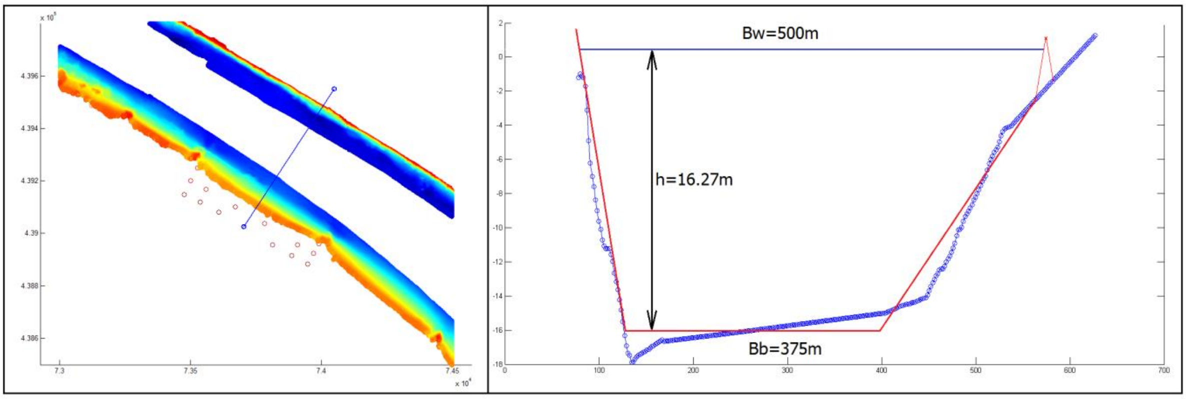

Figure Appendix B-3 Simplified profile of the Nieuwe Waterweg

It is assumed that the governing conditions are a result of ships that sail as close as possible to the bank: at the (outside) border of the traffic lane. Therefore, the location of the traffic lane must be known. This information is obtained from the navionics webapp, an online application that contains information related to ship navigation. The application contains information on nautical borders in the Nieuwe Waterweg. Within the application the distance between the projected location of the dam (at -2.5m NAP) and the nautical border is measured, which is approximately 120 metres as is illustrated in Figure Appendix B-4.

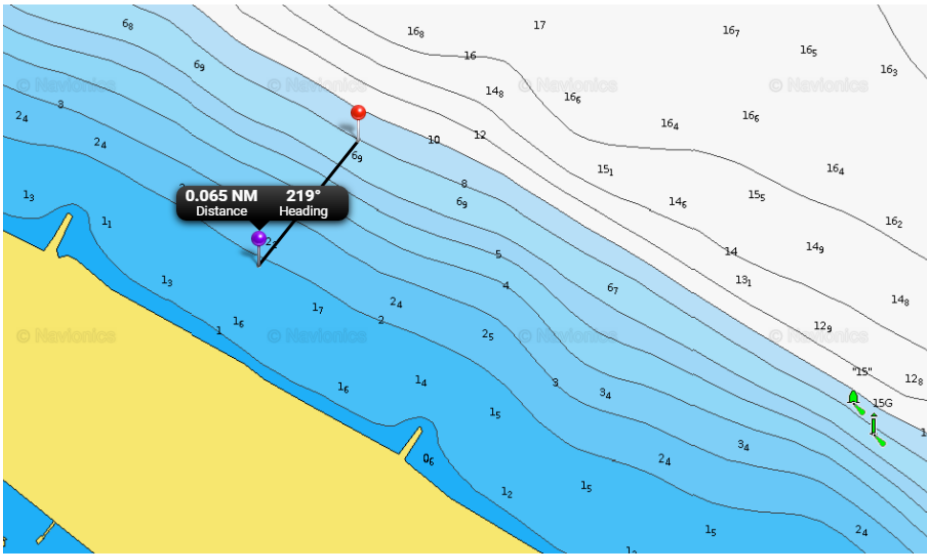

Figure Appendix B-4 Distance between the traffic lane (indicated by the green symbol on the right) and the dam = 0.065 nautical miles ≈ 120 meters

B.2.3 Important parameters

An overview of all the important parameters involved in determining the ship-induced water movements are presented in Table Appendix B-3.

Symbol		Definition	Unit
Input	V_s	Ship speed	m/s
	g	Gravitational acceleration	m/s^s
	A_c	Cross-sectional area of the channel in the undisturbed situation	m^2
	A_w and A_w^*	Cross-sectional area of the channel in the disturbed situation	m^2
	b_b	Channel width at the bed	m
	h	Local water depth	m
	m	cotan of the bank slope	-
	A_s	Cross-sectional area of the submerged part of the ship	m^2
	A_c^*	Cross-sectional area of the fairway next to the ship	m^2
	y_s	Ship position relative to the shore	m
	y	Ship position relative to the fairway axis	m
	ζ	Coefficient of proportionality (represents the ship's geometry)	-
	Fr	Froude number	-
Output	Δh	Water level depression	m
	H_i	Secondary wave height	m
	u_r	Return current	m/s
	z_{max}	Stern wave	m
	L_i	Secondary wave length	m
	T_i	Secondary wave period	s

Table Appendix B-3 Important parameters used in determining the ship-induced water movements

B.3 CUR 201

CUR 201 is a design manual that describes loads and strength on a nature friendly bank and the specific aspects of different constructions. The theory of determining ship-induced water movements as described in CUR 201 is explained in this section.

B.3.1 Primary wave

The front wave is not relevant for the dimensioning of the banks, therefore no formulas for the front wave are considered in the CUR201.

The water level depression that occurs is highly dependent on:

- the size of the passing ship;
- the size of the cross section of the waterway;
- the sailing speed and the distance of the passing ship to the shore.

In common-sized waterways (e.g. width=50m and water depth=4m), water level depressions of 0.3 to 0.5 meters are common. In extreme cases (small sized channel, large ship, high speed), values of 1 meter are possible. The maximum duration of the water level depression depends on the ship length and the sailing speed and usually ranges between 20 and 60 seconds. This temporary water level depression is generally not governing for the civil engineering part of the bank.

The depression of the water level at centric sailing is calculated using the method of Schijf. Schijf introduced a correction factor to correct irregularities in the velocity field that will increase the depression of the water level and return current velocity. The depression of the water level can be determined with the following equation:

$$\Delta h = \frac{V_s^2}{2g}(\left(\frac{A_c}{A_w}\right)^2 - 1)$$

with:

$$A_w = b_b * (h - \Delta h) + m(h - \Delta h)^2 - A_s$$

When taking into account that the ship is not sailing eccentric, the water level depression becomes:

$$\Delta h_{ecc} = 3 - 4 * \frac{A_c^*}{A_c}$$

The stern wave occurs at the rather abrupt termination of the water level depression. This is usually associated with a continuous breaking wave. The load of this breaking stern wave is usually governing for the dimensions of the shore protection. The height of the stern wave in a common-sized waterway is in the order of 0.3 to 0.5 m. The stern wave can be calculated using the following equation:

$$z_{max} = 1.5 * \Delta h_{ecc}$$

B.3.2 Secondary wave

The secondary ship waves mainly impact the shore around the still water level. In particular, these waves cause wave run-up and overtopping and are therefore of interest to determine the height of the bank protection. In practice, the secondary waves have a height of 0.4m and the wave period ranges between 2 and 3 seconds.

Properties of the secondary wave can be calculated using the following equations:

$$Wave\ height = H_i = 1.2 * h * \left(\frac{y_s}{h}\right)^{-0.33} * \left(\frac{V_s}{\sqrt{gh}}\right)^{4.0}$$

$$Wave\ length = L_i = 4.2 * \frac{V_s^2}{g}$$

$$Wave\ period = T_i = 5.1 * \frac{V_s}{g}$$

B.4 Rock manual

The Rock Manual is a design manual for rocky structures in coastal and shoreline engineering. It presents information on the use of rock in structures and on the loads in coastal areas. The theory of determining ship-induced water movements as described in the Rock Manual is explained in this section.

B.4.1 General

The ship-induced water movement depend on:

- ship types;
- sailing behaviour (ship speed and position in the waterway);
- dimensions and the geometry of the waterway .

In most cases, push-tow units or loaded conventional motor vessels are responsible for the severest primary wave, while fast-moving vessels, such as loose tugs, service vessels and recreational ships for the severest secondary waves.

B.4.2 Primary wave

The height of water level depression, front wave and stern wave varies at the bank with an average between 0.3 m and 0.5 m although occasionally heights of 1.0 m may occur. The duration of the water level depression generally varies between 20 s and 60 s depending on the type of ship and the ship speed. The period of the front and transversal stern waves is about 2–5 s. Return currents up to 1.5 m/s are possible. The water level depression and the maximum stern wave can be calculated using the following formulas:

$$\Delta h = \frac{V_s^2}{2g}\left(\left(\frac{A_c}{A_c^*}\right)^2 - 1\right)$$

$$z_{max} = (1 + 4A_w^*) * \Delta h$$

B.4.3 Secondary wave

Fast-moving ships, for example container vessels, loose tugs or freighters that are not fully loaded, generally generate the most severe secondary waves. In average situations ship wave heights vary between 0.25 m and 0.5 m, with maximum values of about 1.0 m. The wave period ranges between 2–4 s.

$$H_i = 1.2 * h * \left(\frac{y_s}{h}\right)^{-1/3} * \frac{V_s^4}{(gh)^2}$$

$$L_i = 4.2 * \frac{V_s^2}{g}$$

$$T_i = 5.1 * \frac{V_s}{g}$$

B.5 Bed, bank and shore protection

The book 'Bed, bank and shore protection' contains information about engineering the interface between land and water. The theory of determining ship-induced water movements as described in this book is explained in this section.

B.5.1 Primary wave

Banks are loaded by primary waves in two ways: by the return flow and by the stern wave. The primary wave is dominant in relatively small waterways where the blockage of the cross-section by ships is not negligible. This occurs when the ship's submerged cross-section is small compared to the channel's cross-section. Within the primary wave, the stern wave usually gives the most severe attack on the banks of the waterways.

The stern wave z can be calculated with the following equations

$$\frac{V_s^2}{gh} = \frac{2 * z/h}{\left(1 - \frac{A_s}{A_c} - \frac{z}{h}\right)^{-2} - 1}$$

Taking into account eccentricity the stern wave becomes as follows:

$$z_{ecc} = \left(1 + \frac{2y}{b}\right) z$$

B.5.2 Secondary wave

The secondary waves are dominant when the blockage factor As/Ac is small. The magnitude of the secondary ship waves depends much more on the shape of the bow than on the draught or length of the ship. Experimental data of the secondary ship wave height can be described with the following relation:

$$\frac{H}{h} = \zeta \left(\frac{y_s}{h}\right)^{-1/3} Fr^4$$

The coefficient of proportionality ζ represents the ship's geometry. The wave height greatly increases with the speed, reaching a theoretical maximum at Fr=1. Fr can be calculated with the following equation:

$$Fr = \frac{V_s}{\sqrt{gh}}$$

B.6 Results and conclusions

B.6.1 Results

The results of the calculations of the governing ship waves for both inland as well as sea-going shipping for the several methods are shown in Table Appendix B-4. All calculated values of wave components have the same order of magnitude. However, the values do vary. As can be concluded, the most severe wave attack is expected to be a result of the inland ships. This is because inland ships sail considerably faster than seagoing ships.

Relevant wave components	Cur201		Rock manual		Bed, bank and shore protection	
	Inland	Sea-going	Inland	Sea-going	Inland	Sea-going
Water level depression [m]	1.9	0.64	2.6	0.6	0.87	0.76
Stern wave [m]	2.8	0.96	3.9	0.9	1.3	1.14
Secondary wave [m]	1.04	0.14	0.28	0.04	0.18	0.01
Secondary wave period [s]	2.7	1.6	2.7	1.6	2.7	1.6

Table Appendix B-4 Results of the governing ship waves for different methods

B.6.2 Primary wave

The formulas that are available to calculate the primary wave all include the water level depression as a function of the blockage: As/Ac. The Nieuwe Waterweg is a very large channel, so it is assumed that the blockage is not significant in calculating the primary wave. Several sources say that the primary wave can be neglected because of the insignificant blockage factor in this case [Schiereck, 2012]. However, this is questionable since the ships do sail quite close to the banks. Therefore, it is assumed that the primary wave cannot be neglected.

Therefore in this case, the primary wave components are determined based on qualitative statements in literature. According to the rock manual and the CUR201, the average water level depression ranges between 0.3 m and 0.5 m although occasionally heights of 1.0 m may occur. The duration of the water level depression varies between 20 s and 60 s depending on the type of ship and the ship speed.

Given the fact that the ships sail quite a distance from the shore, in this case a maximum water level depression of 0.5 m is assumed with a duration of 40 s. The stern wave is always higher than the front wave, so the latter is considered to be insignificant. The stern wave height is around 1.5 times the water level depression, which in this case is 0.75 m relative to the water level depression. The period of the stern wave is assumed to be 3 s.

B.6.3 Secondary wave

The secondary wave height is mainly based on the ship's speed, the water depth and the distance it is sailing from the bank. The outcomes for the secondary wave height range between 0.3 m and 1.1 m with a period of 2.7 s. This corresponds with the secondary wave height used in the original design of project "De Groene Poort", in which a wave height of 1 m was used. Therefore, a secondary wave height of 1m is assumed with a period of 2.7 s.

An overview of the governing ship induced waves is shown in Table Appendix B-5.

Relevant wave component	Height [m]	Period [s]
Water level depression	0.5	40
Stern wave	0.75	3
Secondary wave	1	2.7

Table Appendix B-5 Governing ship induced waves

C. Habitat requirements of the indicator species

This appendix presents information about the indicator species that were identified in chapter 6 in order to assess the ecological performance of the design.

Section C.1 presents information on level I of the indicator species: migratory fish. Section C.2 presents information on level II of the indicator species: molluscs, crustaceans and polychaetes. Section C.3 presents information on level III of the indicator species: riparian vegetation.

The information of the indicator species is presented in a table, containing:

- Specific information of the species (e.g. name, main food source, etc.);
- important biotic and abiotic habitat requirements.

C.1 Level I: Migratory fish

Type of species	Common name	Scientific name	Main food sources	Water movement			Substrate			Salinity	Reference
				Wave attack	Tidal influence [% flooding]	Current [m/s]	Type of material	Grading	Orientation		
Migratory fish	Atlantic sturgeon	Acipenser sturio	Polychaetes Molluscs Crustacean Other, small fish	Insufficient information	Insufficient information	0,8 - 1	Sand Silt	Insufficient information	Insufficient information	< 30 ‰	[de Kok & Meijer, 2012]
	River lamprey	Lampetra fluviatilis	Detritus of all aquatic life Parasitic of aquatic life	Insufficient information	Insufficient information	Moderate conditions	Silt	Fine	Insufficient information	Insufficient information	[Rijksinstituut voor Kust en Zee, 1999]
	European smelt	Osmerus eperlanus	Crustacean Other, small fish	Insufficient information	Insufficient information	Moderate conditions	Insufficient information		Insufficient information	Insufficient information	[Deltares, 2011]
	Sea lamprey	Petromyzon marinus	Detritus of all aquatic life Parasitic of aquatic life	Insufficient information	Insufficient information	Moderate conditions	Silt	Fine	Insufficient information	Insufficient information	[Deltares, 2011]
	Twait shad	Allosa fallax	Crustacean Other, small fish	Insufficient information	Insufficient information	Moderate conditions	Insufficient information	Insufficient information	Insufficient information	< 35 ‰	[Rijksinstituut voor Kust en Zee, 1999]
	Allis shad	Allosa Allosa	Crustacean Other, small fish	Insufficient information	Insufficient information	0-2	Insufficient information	Insufficient information	Insufficient information	< 35 ‰	[Deltares, 2011]
	Atlantic salmon	Salmo salar	Crustacean Other, small fish	Insufficient information	Insufficient information	0-6	Insufficient information	Insufficient information	Insufficient information	< 35 ‰	[Deltares, 2011]

Table Appendix C-1 Habitat requirements of level I of the indicator species: migratory fish

C.2 Level II: Molluscs/crustaceans/polychaetes

Type of species	Common name	Scientific name	Food source	Water movement			Substrate			Salinity	Reference
				Wave attack	Tidal influence [% flooding]	Current [m/s]	Type of material	Grading	Orientation		
Molluscs	Common mussel	Mytilus edulis	Organic particles from water	Very Exposed Exposed Moderately exposed Sheltered Very sheltered	70 - 100	0.5 - 3	Boulders Sandy mud Muddy gravel Artificial (metal/wood/concrete) Muddy sand	coarse	Insufficient information	18 - 40 ‰ (BIOTIC)	[Deltares, 2011] [MarLIN, 2006]
	Razor shell	Ensis Ensis	Suspended organic detritus	Sheltered Very sheltered Extremely sheltered Ultra sheltered	Insufficient information to quantify	0.5 - 1.5	Clean sand	fine - coarse	Insufficient information	30 - 40 ‰	[MarLIN, 2006]
Crustaceans	Common/ brown shrimp	Crangon Crangon	A wide variety of animal and plant material	Very Exposed Moderately exposed Sheltered Ultra sheltered	Insufficient information to quantify	0.5 - 1.5	Clean sand Mud Muddy sand Sandy mud	fine	Insufficient information	18 - 40 ‰	[MarLIN, 2006]
	Common marine hermit crab	Pagurus Bernhardus	Organic particles from water	Exposed Moderately exposed Sheltered Very sheltered	Insufficient information to quantify	Insufficient information	Bedrock Large to very large boulders Rockpools Clean sand	fine - coarse	Insufficient information	30 - 40 ‰	[MarLIN, 2006]
Polychaetes	Catworm	Nephtys hombergii	Molluscs, crustaceans & other polychaetes	Moderately exposed Sheltered Very sheltered Extremely sheltered	Insufficient information to quantify	Insufficient information	clean sand muddy sand sandy mud	fine - coarse	Insufficient information	18 - 30 ‰	[MarLIN, 2006]
	Lugworm/ sandworm	Arenicola marina	Micro-organisms (bacteria), benthic diatoms, meiofauna, and detritus	Moderately Exposed Sheltered Very sheltered	Insufficient information to quantify	0.5 - 3	Salt marsh Seagrass Mixed Muddy gravel Muddy sand Sandy mud clean mud	fine	Insufficient information	18 - 40 ‰	[MarLIN, 2006]

Table Appendix C-2 Habitat requirements of level II of the indicator species: molluscs/crustaceans/polychaetes

C.3 Level III: Riparian vegetation

Type of species	Common name	Scientific name	Water movement			Substrate	Salinity	Reference
			Wave attack	Tidal influence	Current			
	Dwarf eelgrass	Zostera Noltii	Sheltered Extremely sheltered < 0.4 m	4-67% dry conditions per 14 days	0.04 - 0.25 m/s	Sandy mud Muddy sand Mud	15 - 35 ‰	[Deltares, 2011] [MarLIN, 2006]
Riparian vegetation	Common eelgrass	Zostera Marina	Sheltered Extremely sheltered < 0.4 m	0-5% dry conditions per 14 days	0.2 - 0.9 m/s	Gravel Muddy gravel Sandy mud Muddy sand	10 - 30 ‰	[Deltares, 2011] [MarLIN, 2006]

Table Appendix C-3 Habitat requirements of level II of the indicator species: riparian vegetation

D. Dimensioning of the dam

D.1 Introduction

The main requirements in dimensioning the dam are the requirements with respect to stability, ecological performance and functionality of the port and its surroundings.

The stability of the dam is in this case of randomly placed blocks mainly determined by the gradient of the slope and the sizes of the concrete elements. The element size is assessed in section D.2. The slope stability is assessed in section D.3. The width of the crest is determined in section D.4.

D.2 Element size

The sizes of the concrete elements are based on the stability requirement: no loss or movement of elements within the dam may occur.

Several methods exist to assess the element size. However, there is no method that is 100% applicable in the case of using concrete elements as a bank protection in the Nieuwe Waterweg. Usually, in situations like the Nieuwe Waterweg, quarry stone is used in the construction of the bank protections. The use of concrete blocks in The Netherlands is generally only economical in case very large elements are required, for example at the sea defences. So formulas that calculate the required size of the concrete elements usually apply to large wind and storm waves rather than ship induced waves. Therefore an assessment is done based on different methods, using formulas that apply to both ship waves and wind waves, and dimensions of quarry rock and concrete elements. Section D.2.5 discusses the results of the several methods used.

D.2.1 Input parameters

Banks are loaded by primary ship waves (by the return flow and by the stern wave) and by secondary ship waves. In general the secondary ship size is governing in dimensioning the element size [CUR, 1999b].

In some cases dams or breakwater are dynamic: blocks are allowed to move to a certain extent. In this case that is not acceptable since it is required that no obstruction of the waterway may occur because of the important shipping function of the Nieuwe Waterweg. The damage number used in the methods is therefore set very low.

Several methods apply a factor for the shape of the blocks. It is assumed that concrete elements with a cube shape are used. In terms of stability this is safe, since elements with a shape other than cubes are considered to be more stable because of the higher interlocking capacity compared to cubes.

An overview of the important parameters used in determining the element size is presented in Table Appendix D-1.

Symbol	Definition	Unit
d_n	nominal diameter of the cube	m
H_s	Significant wave height	m
Δ	Relative density	-
N_{OD}	Number of displaced cubes (measure for the damage)	-
N	Number of ship passages	-
s	Wave steepness	-
g	Gravitational acceleration	m/s^2
T	Wave period	s
S	Damage number	-
C_h	Coefficient for the type of waves (8.2 for ship waves)	-
P	Factor for the permeability (0.1 for a sand-clay underlayer)	-
ξ	Breaker parameter	-
W	Weight of the cube	N
ρ_r	Density of the material	$[kg/m^3]$
K_d	Stability coefficient (6.5 for concrete cubes and little to no damage)	-
α	Slope angle	°

Table Appendix D-1 List of important parameters used in determining the element size

D.2.2 Van der Meer for concrete cubes

Van der Meer gives the stability for various frequently used blocks. He makes a distinction between displaced blocks and moved blocks [Schiereck, 2012]:

$$d_n = \frac{H_s}{\Delta(6{,}7\frac{N_{od}^{0,4}}{N^{0,3}} + 1{,}0)s_{om}^{-0,1}}$$

$$s = \frac{2\pi H}{gT^2}$$

D.2.3 Pilarczyck

If the dam is under wave attack, the dimensioning can be done using the following formula confirm the theory of Pilarczyck. The physical meaning of S in this formula is the amount of stones that is displaced. Generally, there is "no damage" when less than 3 stones are displaced [d'Angremond & Van Roode, 2001].

$$d_n > \frac{H}{\Delta C_h P^{0,18}(\frac{S}{\sqrt{N}})^{0,2}\xi^{-0,5}}$$

D.2.4 Hudson

Since 1943, systematic investigations into the stability of rubble slopes have been performed at the Waterways Experiment Station in Vicksburg, USA. On the basis of these experiments, Hudson proposed the following expression as the best fit for the complete set of experiments [d'Angremond & Van Roode, 2001]. Different from the other formulas used in the calculation of blocks, this formula of Hudson approaches the stability of a block in terms of weight rather than the diameter.

$$W \geq \frac{\rho_r g H^3}{\Delta^3 K_d \cot\alpha}$$

D.2.5 Stern wave

As mentioned, usually secondary wave heights are governing in determining the element size. However, part of the bank below the still water level is loaded by the stern wave. Therefore the required element size in the stern wave is also checked. The stability in the stern wave can be calculated based on experimental data as follows [CUR, 1999b]:

$$d_n = \frac{z_{max}}{1.5(cot\alpha)^{0.33}\Delta}$$

D.2.6 Results and conclusion

The results of the element sizes and their associated weights are shown in Table Appendix D-2.

Method	d_n [m]	W [kg]
Van der Meer	0.58	478
Pilarczyck	0.42	182
Hudson	0.56	414
Stern wave [CUR201]	0.49	278

Table Appendix D-2 Results for the minimum element size

The results are of the same order of magnitude and vary between element sizes of 0.42 m to 0.56 m, with varying weights of 182 kg to 478 kg. In a sample of coarse residual material there will be a range of block weights. In this case, a standard grading of 300 – 1000 kg is suitable to account for the stability of the dam. This is associated with a maximum element diameter of 0.75 m. This standard grading has also been applied on the groynes in the area, which are known to be stable [Hiddema et al., 2013]. This confirms the assumption that using a 300 – 1000 kg grading ensures a stable dam.

D.3 Slope

D.3.1 Slope stability

Although the stability of individual stones on a slope under wave attack is certainly not the only criterion for the proper functioning of the dam, it deserves great attention. The stability of a slope as a whole is usually referred to as the macro-stability, in contrast to the micro-stability which deals with the grains/elements on a slope (see section D.2). Macro-stability is usually approached with a slip-circle analysis.

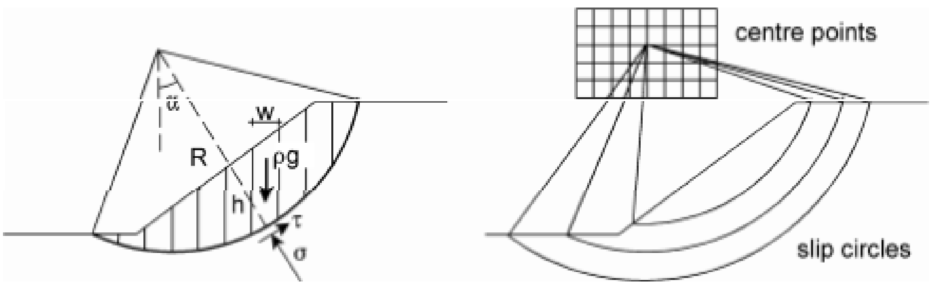

Figure Appendix D-1 Slip circle approach of macro-stability [Schiereck, 2012]

In a slip circle approach the weight of the soil represents the load and the shear stress of the soil along the circle represents the strength. This is illustrated in Figure Appendix D-1. In a thorough study many slip circles must be considered. This is typically work for a computer. When no computercode for stability is available (this case) an approach with micro-stability gives a safe slope angle [Schiereck, 2012]. The calculation methods in section D.2 applied a slope of 1:1,5 – 1:3. It is therefore expected that a gradient of 1:3 ensures sufficient stability in this case [Van den Bos, J., personal communication, December 10th 2014].

D.3.2 Wave reflection

Waves will reflect from nearly all sloping structures. Rubble slopes are often used in harbour and coastal engineering to absorb wave action. Such slopes will generally reflect significantly less wave energy than the equivalent non-porous or smooth slopes. Wave reflection is described using the reflection coefficient, that can be defined as follows [CIRIA et al., 2007]:

$$C_r = \frac{H_r}{H_i} = \sqrt{E_r/E_i}$$

In which:

H_r	=	reflected wave height;
H_i	=	incoming wave height;
E_r	=	reflected wave energy;
E_i	=	incoming wave energy.

If 100% of the incoming wave energy is reflected it can be assumed that the reflection coefficient equals 1. The reflected coefficient for sloping structures like the dam in project "De Groene Poort", a permeable structure with limited crest lever, is smaller. The reflection coefficient can be determined as follows [d'Angremond & Van Roode, 2001]:

$$C_r = 0.081P^{-0.14}cot\alpha^{-0.78}s_{op}^{-0.44}$$

In which:

P	=	notional permeability factor (=0.6 for an armour layer with no filter);
α	=	angle of the slope (=18.43 for a 1:3 slope);
s_{op}	=	fictitious wave steepness based on the peak wave period.

The fictious wave steepness is based on the local wave height H and the wave period T, and can be determined as follows [CIRIA et al., 2007]:

$$s_0 = \frac{2\pi}{g}\frac{H}{T^2}$$

With a wave height of 1m and a period of 3s, the fictious wave steepness becomes 0.07. Subsequently the reflection can be calculated: $C_r = 0.12$. Thus, 12% of the incoming wave energy is reflected.

D.4 Crest width

The crest width may be influenced by requirements for stability and the ecological performance. With respect to the stability requirement, the minimum crest width is two times the element diameter. The diameter of the elements has a maximum of 0.75 m. Therefore, the minimum crest width for stability requirements is 1.5 m.

The minimum crest width is also influenced by the ecological requirement. This is because the crest width has an influence on the transmitted wave height behind the wave. The maximum allowable wave height behind the dam, required for the ecological performance, is 0.4 m. The maximum transmitted wave can be calculated by using the following set of equations: [CUR, 1999b]:

$$K_t = a - 0{,}4h_d/H_i$$

$$a = \left(\frac{B}{H_i}\right)^{-0{,}31}\left(1 - e^{-0{,}5\xi}\right)A_{dam}$$

$$\xi = T\left(\frac{2\pi H_i}{g}\right)^{-0{,}5}\tan\alpha$$

In which:

K_t	=	transmission coefficient, the ratio between the incoming wave height and the

transmitted wave height: $K_t = \frac{H_t}{H_i}$ [-];

a	=	parameter describing all the influences like incoming wave height and crest width [-];
h_d	=	constructiehoogte t.o.v. N.A.P.
H_i	=	incoming wave height [m]
B	=	crest width [m]
ξ	=	breaker parameter
A_{dam}	=	factor for the type of dam.

E. Geotechnical stability

This appendix discusses the geotechnical stability of the design.

Section E.1 presents the geotechnical data that was obtained and interpreted. Section E.2 presents settlement calculations. In section E.3 the phenomena of scour is assessed.

E.1 Geotechnical data

Geological data and information on drilling and soundings near the project site can be obtained from the DINO database, a portal of TNO Geological Survey of the Netherlands, where all the data can be viewed and retrieved for free.

The following data is obtained:

- Vertical cross-section of the soil along the project site;
- A CPT (Cone Penetration Test);
- Samples of the upper soil layers.

The data and how they can be interpreted is presented in the following sections.

E.1.1 Overall subsoil composition in the area

The upper subsoil layer (until a depth of -24m) in the project area consists of Holocene deposits mainly comprising sand layers and clay. Below the Holocene deposits the other geological deposits are situated, consisting mainly of sand and gravel. In assessing the subsoil stability the Holocene deposits are of interest because these consist of compressible clay layers. The composition of the subsoil layers are illustrated in Figure Appendix E-1.

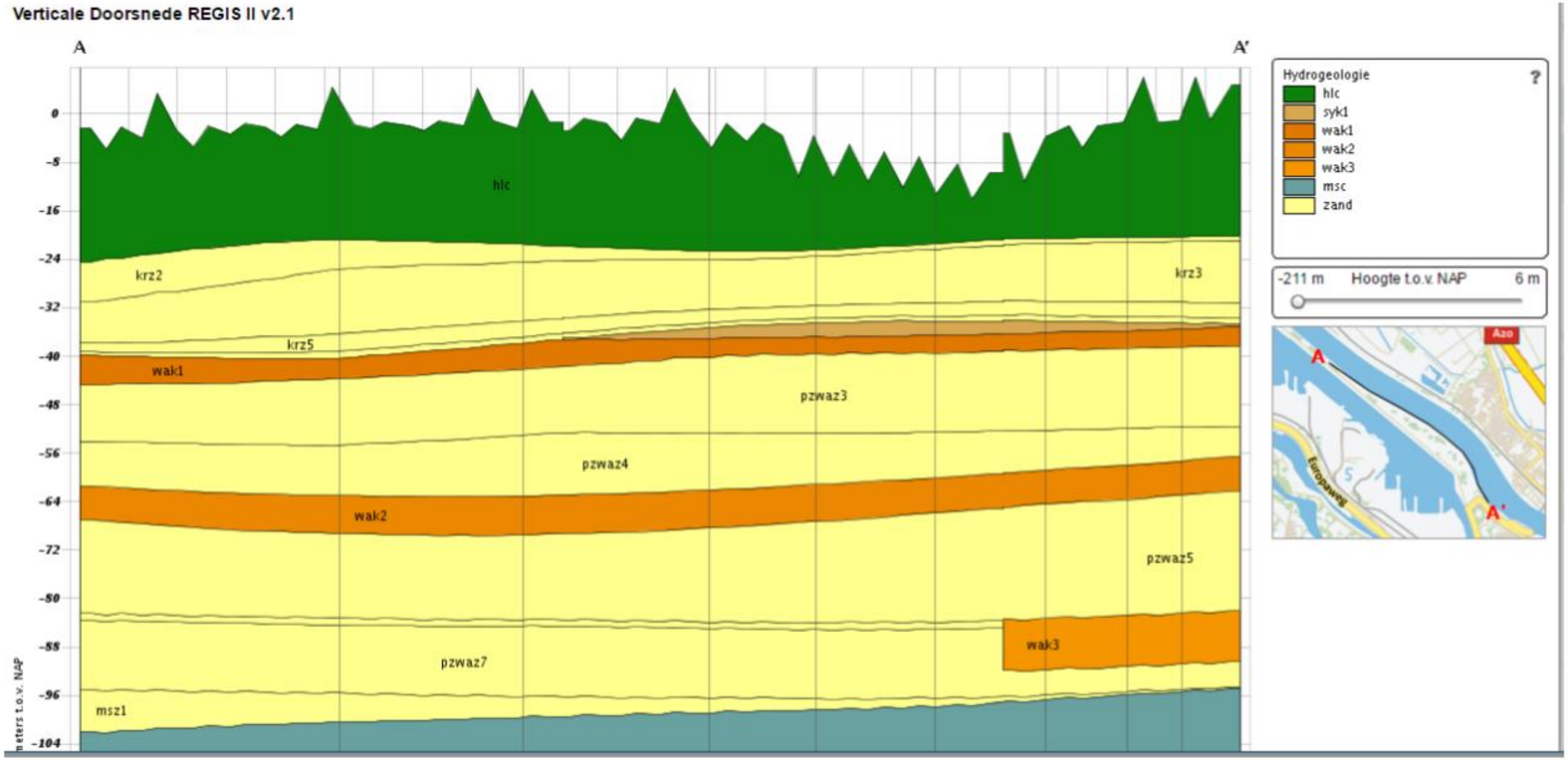

Figure Appendix E-1 Vertical cross-section of the soil along the project site (image obtained from the DINOloket: www.dinoloket.nl)

E.1.2 CPT and soil samples

In order to make an overview of the subsoil composition at the project site, data has obtained from one specific groyne field. An overview of the groyne field is presented in Figure Appendix E-2. A CPT (Cone Penetration Test) has been executed in the centre of the groyne field, indicated by the black triangle. Furthermore, soil samples have been taken on multiple locations within the groyne field, indicated by the red dots.

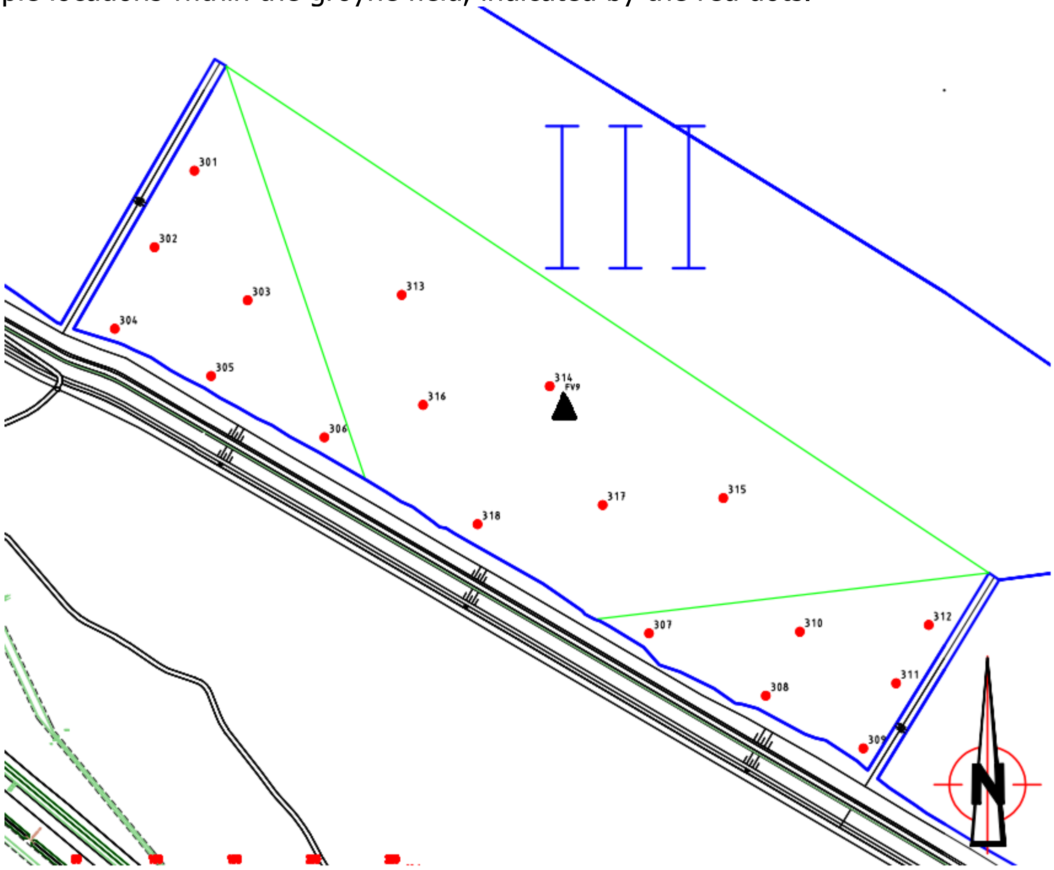

Figure Appendix E-2 Overview of CPT and soil sample locations

A CPT includes data on local friction of the soil to a certain depth. The CPT gives an idea of the composition of the soil layers and the bearing capacity of the soil. A CPT of a groyne field at the project site is shown in Figure Appendix E-3.

Soil samples give a more detailed insight in the composition of the upper layers of the subsoil, compared to a CPT. The results of the soil samples are found in Figure Appendix E-4, Figure Appendix E-5 and Figure Appendix E-6.

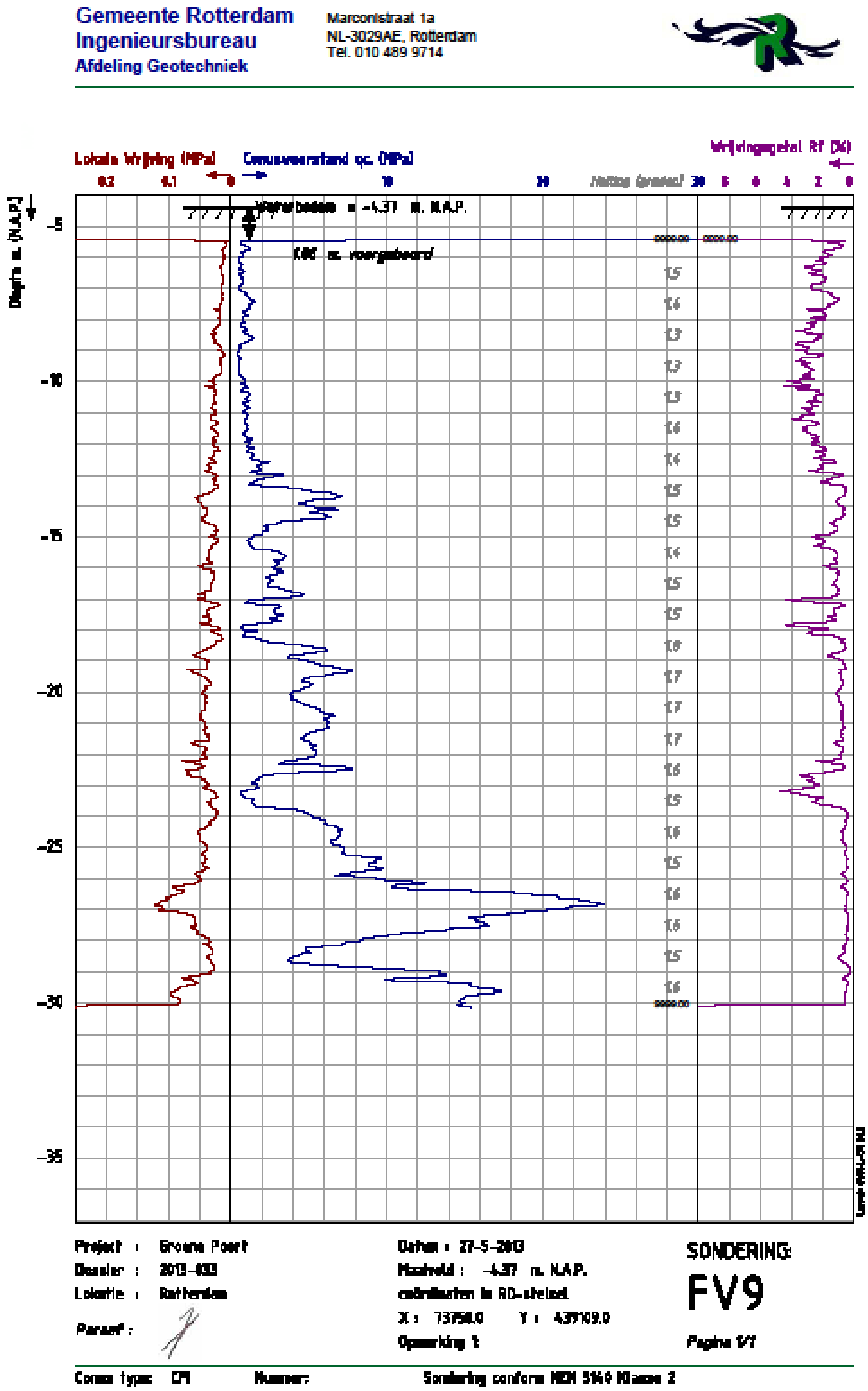

Figure Appendix E-3 CPT of a groyne field at the project site

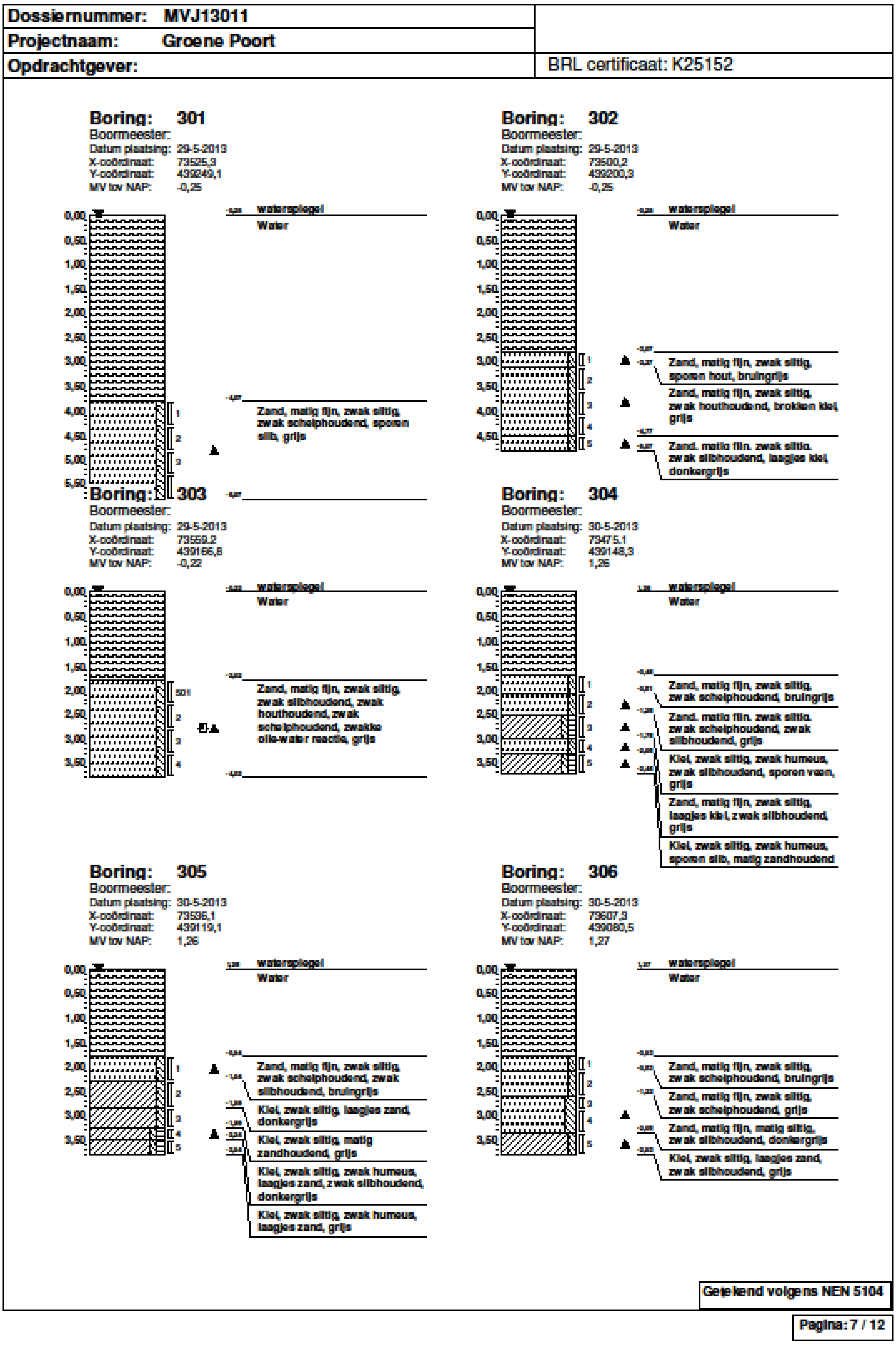

Figure Appendix E-4 Soil samples (#1 of 3)

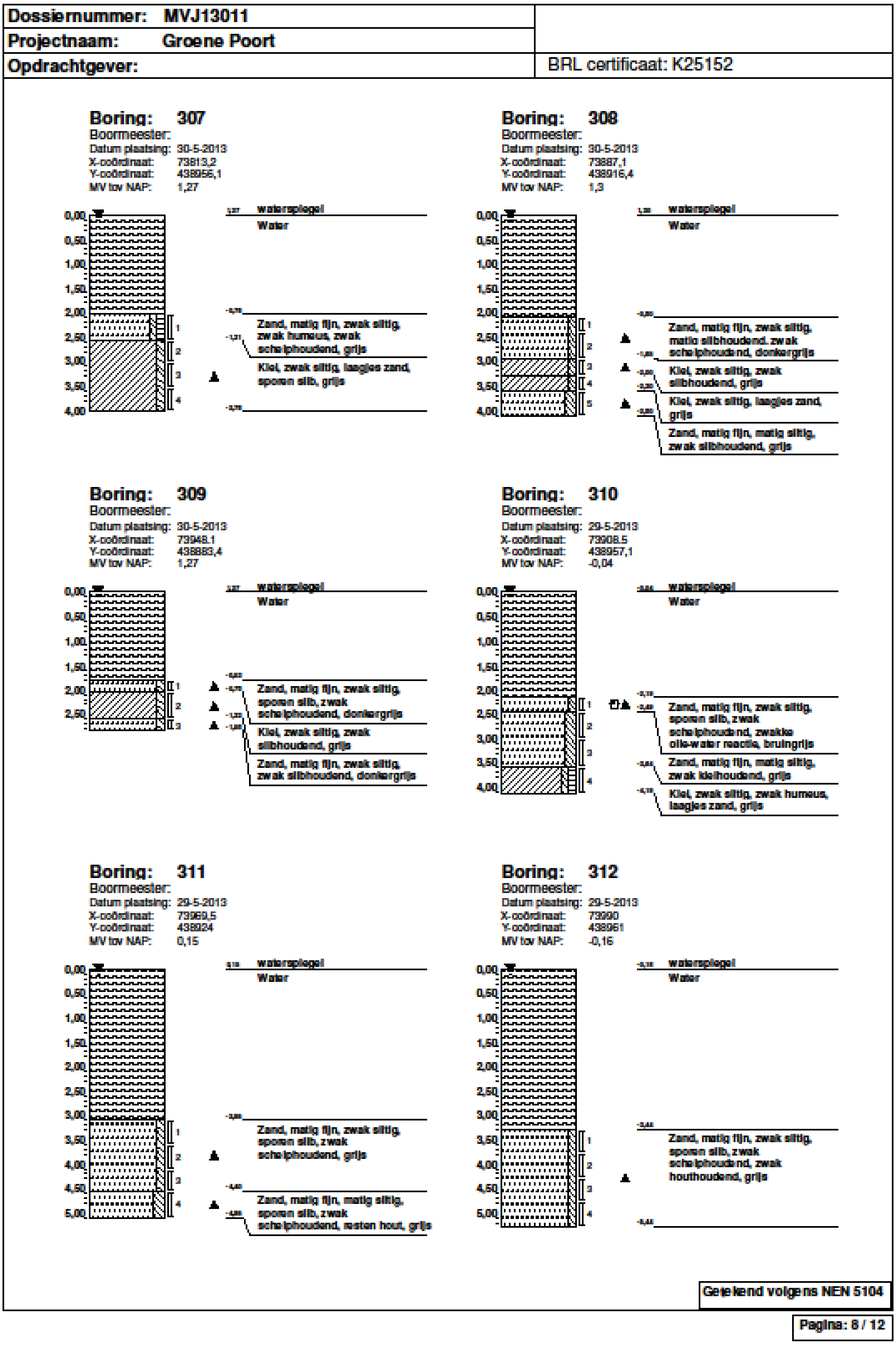

Figure Appendix E-5 Soil samples (#2 of 3)

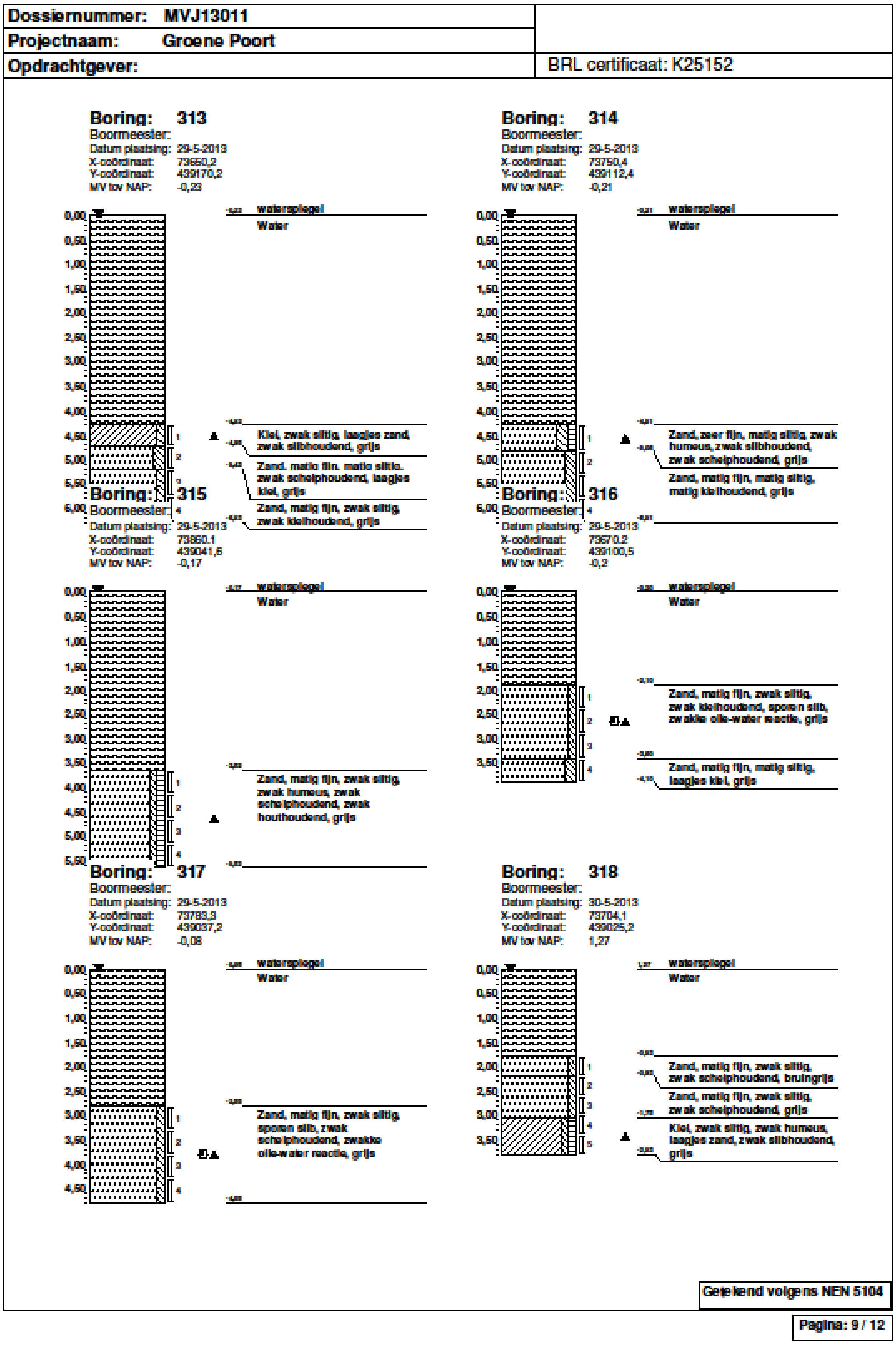

Figure Appendix E-6 Soil samples (#3 of 3)

E.1.3 Interpretation of the geotechnical data

Based on the soil samples and the CPT scan it can be concluded that the top layer mainly consists of sand: only at only at one location clay is found at the top layer (boring 313 in Figure Appendix E-6). The shallow subsurface to -13m NAP consists of clay with embedded sand layers. Under NAP -13m is a package of mainly sand layers, alternating with thin layers of clay. The groyne field contains very little silt. However, locally silt is detected in between the clay and sand layers.

The clay layers are highly compressible and thus the thickness of the clay layers is of importance in assessing the settlement of the dam. It is estimated that the thickness of all clay layers together is approximately 3 m [Rijkswaterstaat, 2012].

E.2 Settlement of the dam

E.2.1 Theory

In general hydraulic structures are founded on a geotextile in order to prevent scour and large settlements. Usually, the allowances of settlements are small. The reason for the occurrence of settlements is clear. The extra deadweight load of the dam must be borne by the grain skeleton of the subsoil, so by the normal stresses and shear stresses that develop in the contact points between the grains. When the shear stresses become too great a reorientation of the grain skeleton takes place, in such a way that the volume of the pores decreases and the number of contact points between the grains thus increases to such an extent that an equilibrium is obtained. Settlements therefore are the consequence of a decrease of the pore content in the subsoil. These settlements are called the primary settlements. Except primary settlements also secondary settlements occur in the subsoil. These secondary settlements result from creep of the grains themselves due to the extra deadweight load of the embankment. These secondary settlements are also referred to as the secular effect [Esveld, 2007].

E.2.2 The formula of Koppejan

The formula of Koppejan takes into account both the primary as well as secondary settlement effects. The formula reads as follows:

$$\frac{\Delta h}{h} = (\frac{1}{C_p} + \frac{1}{C_s} * \log\left(\frac{\Delta t}{t_d}\right) * \ln(\frac{\sigma_i + \Delta\sigma}{\sigma_i})$$

In which:

Δh	=	settlement;
h	=	thickness of the compressible layer
C_p	=	primary compression coefficient (=7 for clay) [Esveld, 2007];
C_s	=	secondary compression coefficient (=18 for clay) [Esveld, 2007];
Δt	=	time;
σ_i	=	initial effective stress;
$\Delta\sigma$	=	increase in effective stress.

The increase in effective stress can be calculated by making use of the following formula:

$$\Delta\sigma = h_{dam} * (1 - p) * \rho$$

In which:

h_{dam}	=	construction height [m];
p	=	porosity of the elements (assumed: 0.4) [-];
ρ	=	density of concrete (=23) [kg/m^3].

The initial effective stress is:

$$\sigma_i \approx (7 - 2.5) * 18 = 81$$

E.2.3 Calculations

At first the increase in effective stress as a result of the extra load imposed by the dam must be calculated for every alternative. Subsequently the expected settlement can be calculated. An overview of the results is presented in Table Appendix E-1.

	Increase in effective stress [kPa]	**Settlement Δh [m]**
Alternative 1 *do nothing*	n.a.	n.a.
Alternative 2 h_{crest}=+1.1m NAP	49.7	0.23
Alternative 3 h_{crest}=+0.70m NAP	44.2	0.21
Alternative 4 h_{crest}=+0.27m NAP	38.2	0.18
Alternative 5 *Nourishment only*	n.a.	n.a.

Table Appendix E-1 Overview of the settlement per alternative

E.3 Erosion of the subsoil

E.3.1 Scour

The dam in the design of project "De Groene Poort" is founded on sand, like many coastal structures. When the combined effects of waves and currents exceed a threshold level, bed material may be eroded from areas of high local shear stress. Close to the structure, wave and current velocities are often increased by the presence of the structure, thus leading to increased movement of bed material in this area. This commonly appears as local scour in front of or alongside the structure and this may in turn exacerbate a degradation in subsoil levels [CIRIA et al., 2007].

The principal effects of a structure are [Schiereck, 2012]:

- an increase in local peak orbital velocities in front of the structure, due to the combination of incident and reflected waves;
- concentration of wave and tidal currents along or close to the structure.

The process of scour along a structure is illustrated in Figure Appendix E-7.

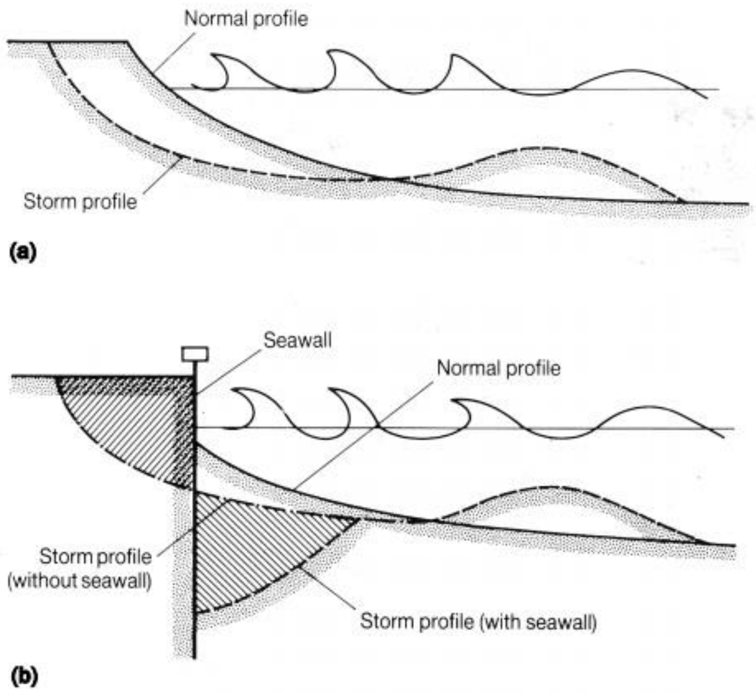

Figure Appendix E-7 The process of scour in front of a seawall as is also expected in front of the dam in project "De Groene Poort" [Dean, 1987]

Scour is thus expected to develop in front of the dam. The amount of scour is further assessed with the XBeach model to check if measures like applying a geotextile are required.

E.3.2 Underlayer

As soon as artificial structures, like the dam in project "De Groene Poort", disturb the governing flow and wave attack fixation of the bottom by taking protective measures becomes necessary. The flow velocity and the turbulence of the flow can penetrate through the large stones of the dam. This can lead to the outwash of subsoil particles which may cause extra settlements and erosion near the toe. Therefore, it must be prevented that subsoil particles pass the pores of the upper layer (the filter layer). This can be prevented by applying a granular filter or a geotextile [Schiereck, 2012].

Geotextiles can replace several filter layers, resulting in a thinner filter. However, in this case a very strong geotextile would be required because of the relatively heavy dam. Therefore, in this case it is chosen to apply a granular filter as a base layer for the dam.

Several design criteria exist for determining the dimensions of the underlayer. An easy rule of thumb is that the underlayer consists of stones with a diameter half of the upper layer. Furthermore, the thickness of the underlayer is 2 times the width of the applied stones [CIRIA et al., 2007]. The dam is made of elements with a diameter of approximately 0.75 m. So in this case, the underlayer consists of elements with a diameter of approximately 0.4 m and has a thickness of approximately 0.8. The underlayer is constructed on a geotextile in order to prevent subsoil particles from washing out.

F. XBeach model description

This appendix briefly discusses the main features of the XBeach model. A comprehensive description of the model, including all equations, can be found in the user manual of XBeach [Roelvink et al., 2010].

F.1 Background

XBeach, acronym for "eXtreme BEACH behaviour model", is an open source model and was funded and developed by a consortium of UNESCO-IHE, Deltares (formerly Delft Hydraulics), Delft University of Technology and the University of Miami. XBeach is a two-dimensional (2DH) numerical model which is originally developed to simulate hydrodynamic and morphodynamic processes and impacts on sandy coasts with a small domain size compared to other, similar models and on the time scale of storms (see Figure Appendix F-1). The small domain size is also the reason for the choice of XBeach, since this study focusses on the hydrodynamic environment of one groyne field in the Nieuwe Waterweg.

Hydrodynamic processes include short wave transformation (refraction, shoaling and breaking), long wave (infragravity wave) transformation (generation, propagation and dissipation), wave-induced setup and unsteady currents as well as overwash and inundation. Morphodynamic processes include bed load and suspended sediment transport and bed update [Roelvink et al., 2010].

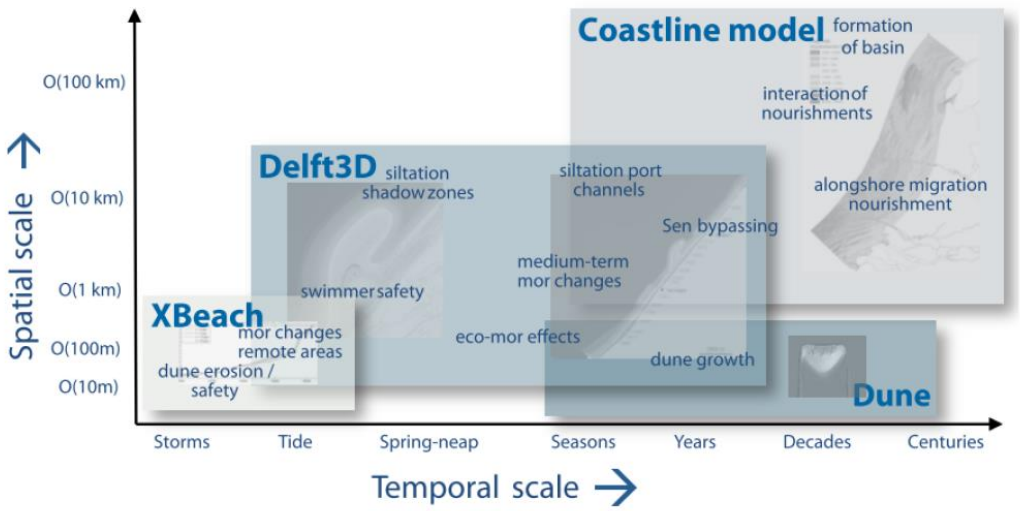

Figure Appendix F-1 Time and spatial scales for hydrodynamic processes and the position of several computational models within this framework [Baart et al., 2012]

F.2 Model properties

F.2.1 Process-based

XBeach is a process-based model where the equilibrium state follows from a balance of forces and transport contributions. The functionality of XBeach is divided among a number of modules. In one single numerical step each module is called in a specific sequence. XBeach starts with the reading the bathymetry input. Subsequently the radiation stresses are calculated in the wave module. The flow module uses the changes in radiation stress to calculate surface elevation and velocities. This will lead to sediment transport and eventually towards an update of the bed level, as is illustrated in Figure Appendix F-2.

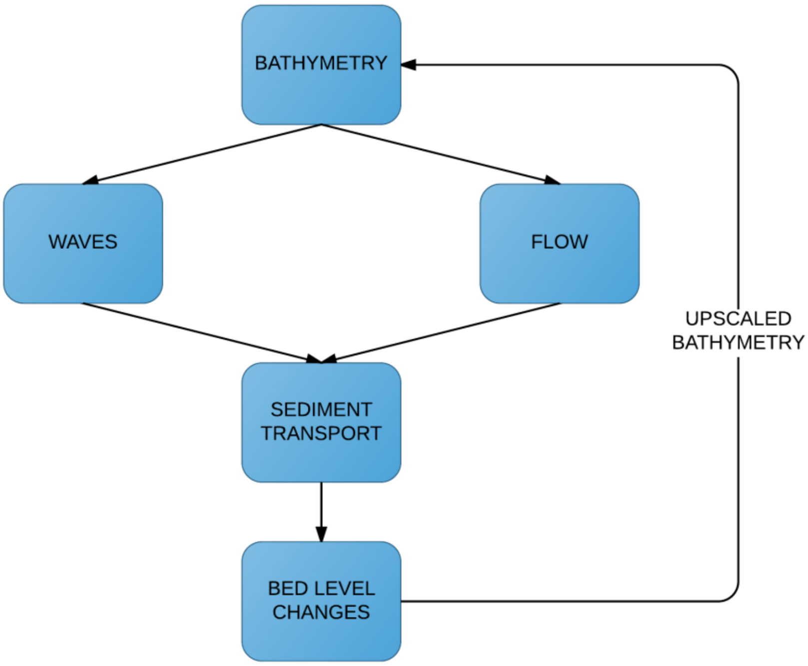

Figure Appendix F-2 XBeach processes using an upscaling approach

Wave and current output from the short wave and flow modules together form a hydronamic module. The hydronamic module is input for the morphodynamic module which encompasses the sediment transport and bed level changes. In the new time-step, the short waves module uses output from the morphology and flow modules, given that the bed levels and surface elevations change per time-step. This process is illustrated in Figure Appendix F-3.

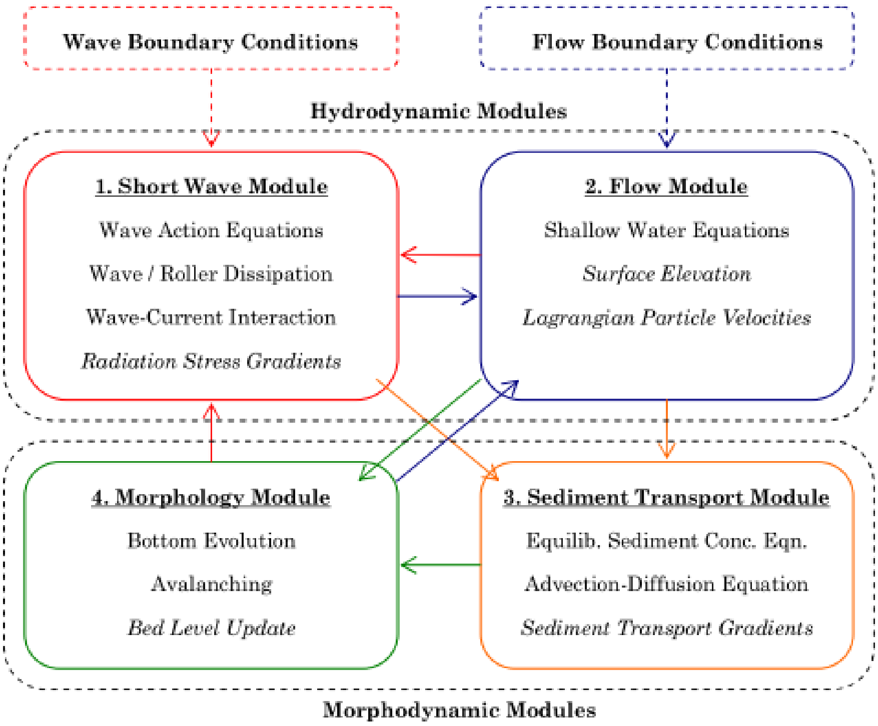

Figure Appendix F-3 Different modules in XBeach, arrows indicate connectivity [Daly, 2009]

The different processes and their simulation methods are briefly explained in the sections below.

F.2.2 Bathymetry

XBeach uses a rectilinear model grid [Den Bieman, 2013]. The used computational grid has a constant resolution in alongshore or y-direction and a gradually varying resolution in cross-shore or x-direction. The used coordinate system is oriented towards the coast in the x-axis and the y-axis describes the long shore distance as illustrated in Figure Appendix F-4.

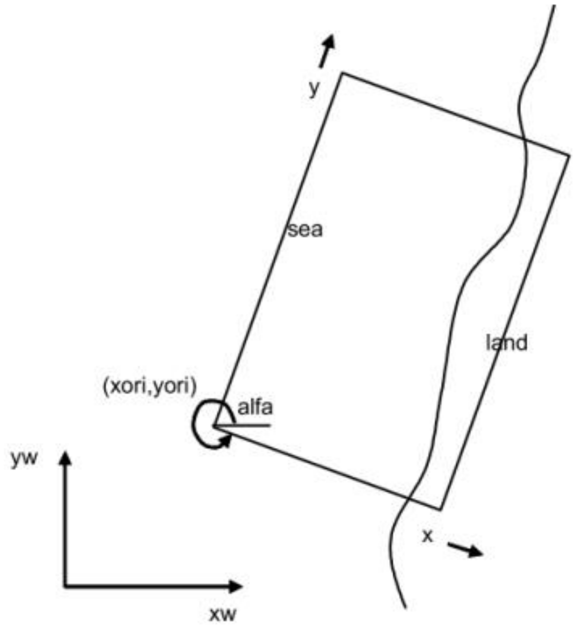

Figure Appendix F-4 XBeach coordinate system [Roelvink et al., 2010]

F.2.3 Hydrodynamic module

The most important equations in the hydrodynamic module are the wave action equation, the roller energy equation, the radiation stresses equations and the shallow water equations.

The wave action equation

Different from most other physics-based models, XBeach solves short wave equations (= order of magnitude 10s per cycle) on the time scale of the long wave groups and thus it solves long waves.

The model is forced using a time dependent version of the wave action balance equation in shallow water, similar to the HISWA model [Holthuijsen, 2007]. In this wave action balance the directional distribution of the wave action is taken into account whereas the frequency spectrum is represented by a single characteristic mean frequency.

$$\frac{\partial A}{\partial t} + \frac{\partial c_{g,x}}{\partial x} + \frac{\partial c_{g,y} * A}{\partial y} + \frac{\partial c_\theta * A}{\delta\theta} = -\frac{D_{waves}}{\sigma}$$

In which:

A = wave action defined as E/σ;
E = wave energy;
σ = intrinsic wave frequency;
c_g = wave group velocity;
c_θ = velocity in directional space;
D_{waves} = the energy dissipation due to breaking waves.

Roller energy equation

While the wave action balance adequately describes the propagation and decay of organized wave energy, is has often been found that there is a delay between the point where the waves start to break and the point where the wave set-up and the longshore current start to build. This transition zone effect is generally attributed to the temporary storage of shoreward momentum in the surface rollers. The roller energy balance is coupled with the wave action balance where dissipation of short wave energy serves as a source for the roller energy balance. The frequency spectrum is represented with a single frequency.

$$\frac{\delta E_{roller}}{\delta t} + \frac{\delta c_x E_{roller}}{\delta x} + \frac{\delta c_y E_{roller}}{\delta y} + \frac{\delta c_\theta E_{roller}}{\delta \theta} = -D_{roller} + D_{waves}$$

In which:
E_{roller} = roller energy in each directional bin;
D_{roller} = dissipation term surface roller;
D_{waves} = dissipation term wave breaking.

Radiation stresses
Both the wave action balance as well as the roller energy balance result in a spatial distribution of wave energy. According to the linear wave theory this distribution can be used to calculate the gradients in radiation stress. There are thus two contributions to the radiation stress: roller-induced and wave-induced. These terms are simply added up in XBeach.

$$F_x(x,y,t) = -(\frac{\delta S_{xx,waves}+\delta S_{xx,roller}}{\delta x} + \frac{\delta S_{xy,waves}+\delta S_{xy,roller}}{\delta y}$$
$$F_y(x,y,t) = -(\frac{\delta S_{yy,waves}+\delta S_{yy,roller}}{\delta y} + \frac{\delta S_{xy,waves}+\delta S_{xy,roller}}{\delta x}$$

In which:
F_x = wave forcing in x-direction;
F_y = wave forcing in y-direction;
S_{xx} = radiation stress of wave propagation in x-direction;
S_{yy} = radiation stress of wave propagation in y-direction;
S_{xy} = shear stress radiation stress.

The shallow water equations
The shallow water equations are used to determine the generation of long waves and other variations in water level, for example the setup in the surfzone. The model uses the non-linear shallow water equations [Roelvink et al., 2010]. The shallow water equations are given by:

$$\frac{\partial u^L}{\partial t} + u^L \frac{\partial u^L}{\partial x} + v^L \frac{\partial u^L}{\partial y} - f v^L - v_h \left(\frac{\partial^2 u^L}{\partial x^2} + \frac{\partial^2 u^L}{\partial y^2} \right) = \frac{\tau_{sx}}{\rho h} - \frac{\tau_{bx}^E}{\rho h} - g \frac{\delta \eta}{\delta x} + \frac{F_x}{\rho h}$$

$$\frac{\partial v^L}{\partial t} + u^L \frac{\partial v^L}{\partial x} + u^L \frac{\partial v^L}{\partial y} - f u^L - v_h \left(\frac{\partial^2 v^L}{\partial x^2} + \frac{\partial^2 v^L}{\partial y^2} \right) = \frac{\tau_{sy}}{\rho h} - \frac{\tau_{by}^E}{\rho h} - g \frac{\delta \eta}{\delta y} + \frac{F_y}{\rho h}$$

$$\frac{\delta \eta}{\delta t} + \frac{\delta h u^L}{\delta x} + \frac{\delta h v^L}{\delta y} = 0$$

In which:
h = water depth;
u = Lagrangian velocity in x-direction: $u^L = u^E + u^S$;
u^E, u^S = Eulerian velocity in x-direction, Stokes drift in x-direction
v = Lagrangian velocity in y-direction: $v^L = v^E + v^S$;
v^E, v^S = Eulerian velocity in y-direction, Stokes drift in y-direction;
τ_{bx}, τ_{by} = bed shear stresses;
τ_{sx}, τ_{sy} = windstresses;
g = gravitational acceleration;
η = water level;
F_x, F_y = wave-induced stresses;
v_h = horizontal viscosity;
f = Coriolis effect.

F.2.4 Morphodynamic module

As explained, the morphodynamic module consists of the sediment transport module and the morphology module. The sediment transport module calculates sediment transport gradients. These sediment transport gradients are input for the morphology module in which the bed level changes are calculated. The important formulas and theories used in the morphodynamic module are explained in this section.

Advection-diffusion

Sediment concentrations in the water column are modelled using a depth-averaged advection-diffusion equation. Advection is transport mechanism of a substance by a fluid due to the fluid's bulk motion. Diffusion is the net movement of a substance from a region of high concentration to a region of low concentration. The entrainment or deposition of sediment is determined by the mismatch between the actual sediment concentration and the equilibrium concentration. The depth-averaged-advection-diffusion equation reads as follows:

$$\frac{\delta hC}{\delta t}+\frac{\delta hC(u^E+u_A sin\theta_m)}{\delta x}+\frac{\delta hC(v^E+u_A cos\theta_m)}{\delta y}+\frac{\delta}{\delta x}\left(D_s h\frac{\delta C}{\delta x}\right)+\frac{\delta}{\delta y}\left(D_s h\frac{\delta C}{\delta y}\right)=\frac{hC_{eq}-hC}{T_s}$$

In which:

C = depth-averaged sediment concentration (varying on wave group time scale);
D_s = sediment diffusion coefficient;
T_s = adaptation time at which the sediment concentration changes;
h = local water depth;
C_{eq} = equilibrium concentration.

As explained, the entertainment or deposition of sediment is determined by the mismatch between the actual sediment concentration C and the equilibrium concentration Ceq. The equilibrium sediment concentration can be calculated with the use of various formulations, but in XBeach by default the extended transport formulation of Van Rijn (2007) is used:

$$C_{eq}=\frac{A_{sb}}{h}\left(\sqrt{(u^e)^2+0.64u_{rms,2}^2}-u_{cr}\right)^{1.5}+\frac{A_{ss}}{h}\left(\sqrt{(u^e)^2+0.64u_{rms,2}^2}-u_{cr}\right)^{2.4}$$

In which:

A_{sb} = bed load coefficient;
A_{ss} = suspended load coefficient;
u_{rms} = orbital velocity.

The effect of turbulence due to wave breaking (k_b) is included with the use of an increased orbital velocity formulation [Reniers, 2004]:

$$u_{rms,2}=\sqrt{u_{rms}^2+1.45k_b}$$

Bed level change

Bed level changes are a result of gradients in sediment transport. The bed level change in time can be calculated using the following equation:

$$\frac{\delta z_b}{\delta t}=-\frac{f_{mor}}{(1-\rho)}\left(\frac{\delta S_x}{\delta x}+\frac{\delta S_y}{\delta y}\right)$$

In which:

f_{mor} = morphological acceleration factor (morfac);
ρ = porosity;
S_x = computed sediment transport rate in x-direction;

S_y = computed sediment transport rate in y-direction.

The sediment transport rates are calculated as follows:

$$S_x = hC(u^E + u_A sin\theta) + \frac{\delta}{\delta x}\left(D_s h \frac{\delta C}{\delta x}\right)$$
$$S_y = hC(v^E + u_A cos\theta) + \frac{\delta}{\delta y}\left(D_s h \frac{\delta C}{\delta y}\right)$$

F.3 Model input and approach

F.3.1 Set-up

For the set-up of the model the latest version of XBeach is downloaded: version 1.21.3667 "Groundhog Day" released on February 7th 2014. A Matlab toolbox, developed by Deltares, is used to make the set-up of the XBeach model easier. The toolbox contains a variety of functions to setup the XBeach model and run it. It also contains functions to read model output and to analyse and visualize the results.

Upon running the XBeach executable the file params.txt is read. The params.txt file contains the following types of input:

- (non-default/advanced) settings;
- grid and bathymetry;
- waves and flow;
- morphology.

These types of input are explained in the following sections.

F.3.2 Settings and advanced options

It is generally strongly recommended to specify as few parameters explicitly as possible and rely on the XBeach defaults for the other parameters. However, for the proper functioning of the model a few advanced options are used:

- Sediment composition;
- Non-erodible layer module;
- Groundwater module;
- facua.

These advanced options are explained in this section.

Non-erodible layer module
By default XBeach specifies a uniform bed composition. However, in this case the dam is not made of the same material as the nourishment and the subsoil. For reasons of simplicity it is assumed that the dam is non-erodible. In reality this is off course not true, however the stability of the dam is not assessed in XBeach so for the model this is an acceptable assumption.

The struct and ne_layer keywords enable the user to specify non-erodible structures in the model. To switch on non-erodible structures 'struct=1' is specified in the params.txt file. The location of the structure is specified in an external file referenced by the ne_layer keyword. The file has the same format as the bathymetry file (explained in section F.3.3). The ne_layer file specifies the thickness of the sand layer above the hard layer that will not erode. A ne_layer file with only zeros therefore defines a fully non-erodible bathymetry and a file with only tens means an erodible layer of 10 meters. Only at the grid cells where the value in the ne_layer file is larger than zero erosion can occur. Non-erodible layers are infinitely deep and thus no erosion underneath these layers can occur.

In this case an assessment is made of erosion at the area behind the dam, including the nourishment, and just in front of the dam where scour might occur. So in these areas an erodible layer of 10 meters is specified. The rest of the layers are specified as non-erodible.

Groundwater
The dam in project "De Groene Poort" is porous: water can flow through. It is important to specify this in the model, in order to simulate the tidal influence behind the dam. This is done by making use of the groundwater module. By default infiltration/exfiltration of groundwater is not accounted for in XBeach: the bathymetry is specified as a non-porous layer. The groundwater module allows the user to specify horizontal and vertical permeability the subsoil or in this case a structure. In this case, high horizontal permeability is specified so the water level in front of and behind the dam communicate, simulating the tidal influence behind the dam.

The groundwater module is switched on by using the keyword 'gw = 1' in the params.txt file. Subsequently, permeability coefficients are specified that determine the level of permeability of the bathymetry. Vertical and horizontal permeability coefficients can be set differently using the keywords kz and kx respectively.

The initial bed level of the aquifer is read from an external file referred to as the 'aquiferbotfile'. This file has the same format as the bathymetry file explained in section F.3.3 below.

Facua
Onshore transport by wave asymmetry is important for the cross-shore sediment transport and morphology, and should be included in the default settings as well [Trouw, Zimmerman, Mathys, Delgado, & Roelvink, 2012]. A calibration factor time averaged flows due to wave skewness and asymmetry can be specified by the keyword 'facua'.

By increasing the facua the erosive processes will be (partly) counteracted with an asymmetric onshore sediment transport. One hypothesis is that on steep beaches wave asymmetry becomes more important. The model is calibrated by varying the facua between 0.0 and 0.3. A calibration analysis with respect to the zero-state model has shown that a facua of 0.3 results in an accurate morphological result for the case study.

F.3.3 Grid and bathymetry

In this research the design of project "De Groene Poort" is evaluated partly in XBeach in the cross-shore. Therefore a 1DH model is set-up, which evaluates the alternatives in the x-direction only. The grid thus has no points in the y-direction. The number of x points in the grid is: nx = 139. The X.grd file contains the x-coordinates of these points. The Y.grd file contains the y-coordinates of the grid but in this case (1DH) only contains zeros. The bed.dep file contains the bathymetry information of the initial profile of a groyne field in the Nieuwe Waterweg. This information was obtained from Rijkswaterstaat. The bed.dep file simply contains the heights for all grid points. One row in the bed.dep file corresponds to one cross-shore transect (and thus in the case of a 1DH model one point of x).

F.3.4 Wave and flow input

Waves
XBeach uses a directional grid to solve the wave action balance. The model allows users to apply different options for wave boundary conditions at the offshore boundary.

As explained in chapter 4 and appendix B the governing waves in the Nieuwe Waterweg are ship-induced. The ship-induced waves consist of several components, of which it was concluded that the water level depression, stern wave and secondary wave are governing. Therefore, these wave components are specified in XBeach.

The water level depression is specified in the offshore flow boundary conditions, by lowering the tidal conditions with 0.5m every fifteen minutes (= 1 ship passage) for 40 seconds.

The stern wave zmax and the secondary wave are specified in a time-series as short wave energy. The keyword 'instat = ts_2' specifies a second-order time series of waves. The wave boundary condition of this type needs a separate file containing the short wave energy the free surface elevation, gen.ezs.

The wave energy is determined by using the following equation [Holthuijsen, 2007]:

$$E = \frac{1}{2}\rho g a^2$$

In which:

ρ = density of water = 1025 kg/m^3 for marine water

g = gravitational acceleration = 9.81 m/s^2

a = the amplitude $\approx \frac{1}{2}H$

	H	**a**	**E**
Stern wave z_{max}	0.75	0.375	707
Secondary wave H_s	1	0.5	1256

Table Appendix F-1 Wave input parameters

The imposed wave signal is illustrated in Figure Appendix F-5

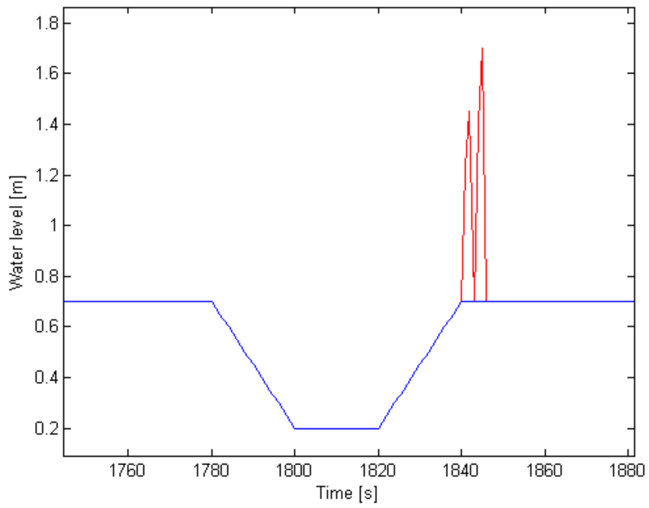

Figure Appendix F-5 Imposed wave signal in XBeach

Flow

Flow boundary conditions need to be specified on all sides of the domain. In this case, difference is made between the offshore and the landward boundary:

- Front = seaward boundary condition: time varying tide including one tidal cycle with governing spring and neap tide conditions;
- Back = landward boundary condition: 0 (= reflective wall).

The tidal information is obtained from the website of Rijkswaterstaat and specified in a .txt file. In the params.txt file a reference is made to this file using the keyword 'zs0file = tide.txt'.

F.3.5 Morphological input

The morphological input comprises a description of the sediment composition and morphological update characteristics.

Sediment composition

As described in section F.3.2 the bed is partly specified as a hard layer (the dam). The rest of the domain has a uniform composition. Subsoil in project "De Groene Poort" consists of a mixture of sand, clay and silt. The nourishment also consists of this material.

The sediment input determines the composition of the bed. In this case the simplest situation is applied: an XBeach simulation with uniform sediment. It is sufficient to specify the uniform grain size, using keyword D50 indicating the median grain size. Furthermore, porosity and sediment density are specified using the keywords por and rhos. In this case no sorting of sediment will be simulated.

In chapter 5 the soil type "sandy clay loam" was identified as suitable for project "De Groene Poort". This mixture of sand, clay and silt has a porosity between 0.4 and 0.5 and a density (without pores) between 2400 kg/m^3 and 2600 kg/m^3 [Soil Suvery Staff, 1993]. Therefore an average porosity of 0.45 and an average of 2500 kg/m^3 is specified in XBeach.

Morfac
The morfac is a well-known numerical method in reducing the computational time. The morphological acceleration factor can speed up the morphological time scale relative to the hydrodynamic time scale. It means that a hydrodynamic simulation of 10 minutes with a morfac of 6 simulates the morphological evolution of an hour. In this case a morfac of 10 is specified.

F.3.6 Example of a params.txt file

An example of a params.txt file, which contains all XBeach settings, is shown below.

```
%%% XBeach parameter settings input file                    %%%
%%%                                                 %%%
%%% date:     19-May-2015 15:58:32                          %%%
%%% function: xb_write_params                              %%%

%%% Ground parameters%%%

rhos = 2500
por = 0.45

%%% Grid parameters %%%

depfile    = bed.dep
posdwn     = 0
nx         = 139
ny         = 0
alfa       = 0
vardx      = 1
xfile      = x.grd
yfile      = y.grd
xori       = 0
yori       = 0
thetamin   = 225
thetamax   = 315
dtheta     = 90
thetanaut  = 1
facua = 0.3

%%% Groundwater parameters %%%

kx         = 0.01
kz         = 0.000010000
ky         = 0.000010000
dwetlayer = 0.01
aquiferbotfile = aquiferbot.txt
gw0 = -5
gwflow     = 1

%%% Initial conditions %%%

zs0        = 0

%%% Model time%%%

tstop      = 45000

%%% Morphology parameters %%%

morfac     = 10
morfacopt  = 0
struct     = 1
ne_layer   = nebed.dep

%%% Tide boundary conditions %%%

zs0file    = tide.txt
tideloc    = 1

%%% Wave boundary condition parameters %%%

instat     = ts_2

%%% Flow boundary conditions

back = 0

%%% Output variables %%%

tintg      = 1
tstart     = 0
nglobalvar = 5
zb
zs
H
u
v
```

F.4 Model output and results

F.4.1 Alternative 1: Zero state

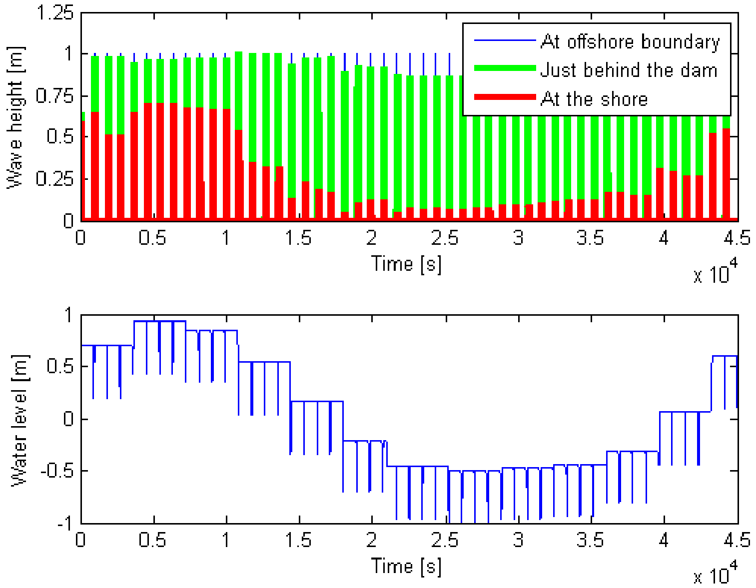

Figure Appendix F-6 Varying wave attack in time and space (upper image) and varying water levels (lower image)

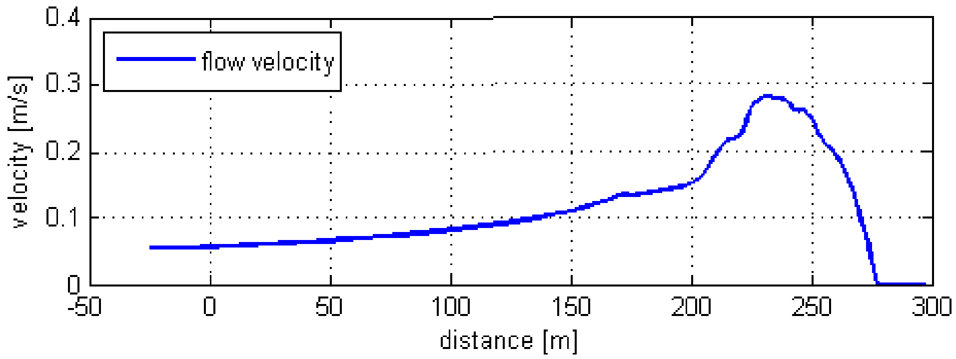

Figure Appendix F-7 Flow velocity varying in the cross-shore direction

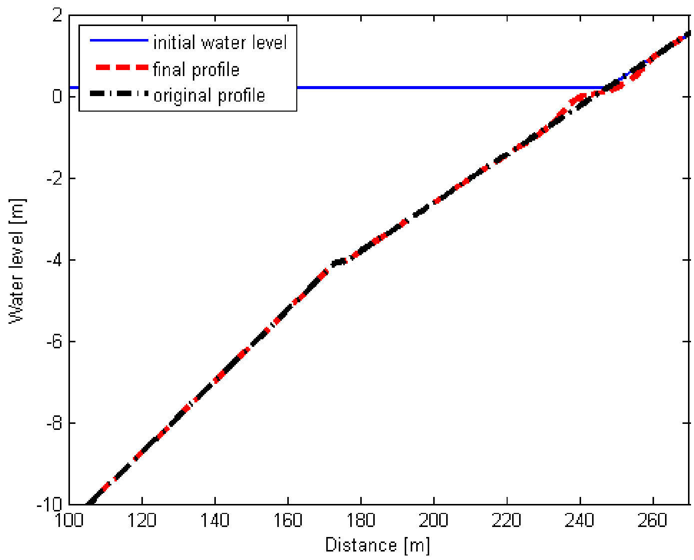

Figure Appendix F-8 Erosion patterns

F.4.2 Alternative 2: h_{crest}=+1.1m NAP

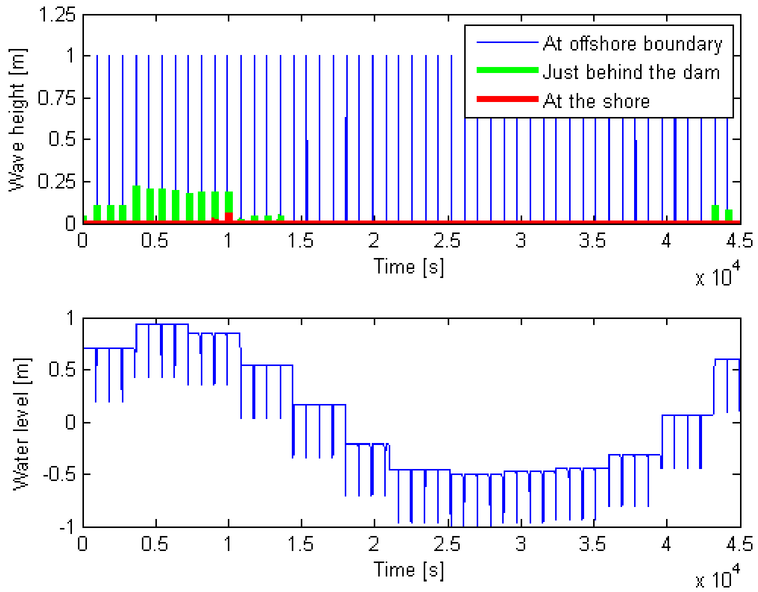

Figure Appendix F-9 Varying wave attack in time and space (upper image) and varying water levels (lower image)

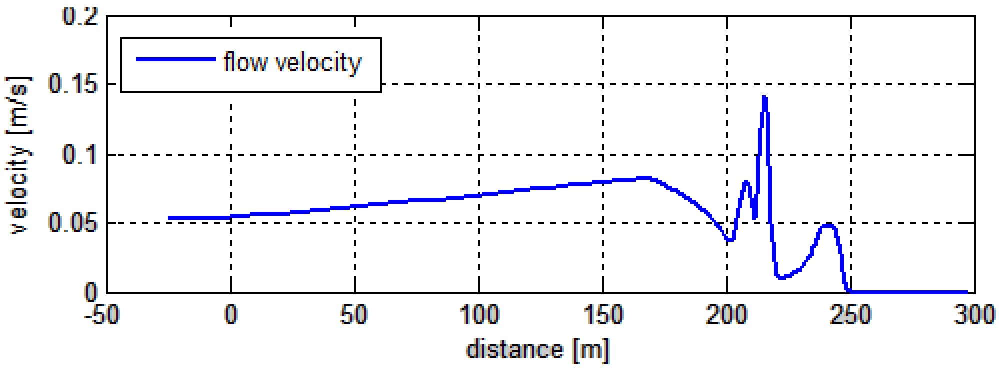

Figure Appendix F-10 Flow velocity varying in the cross-shore direction

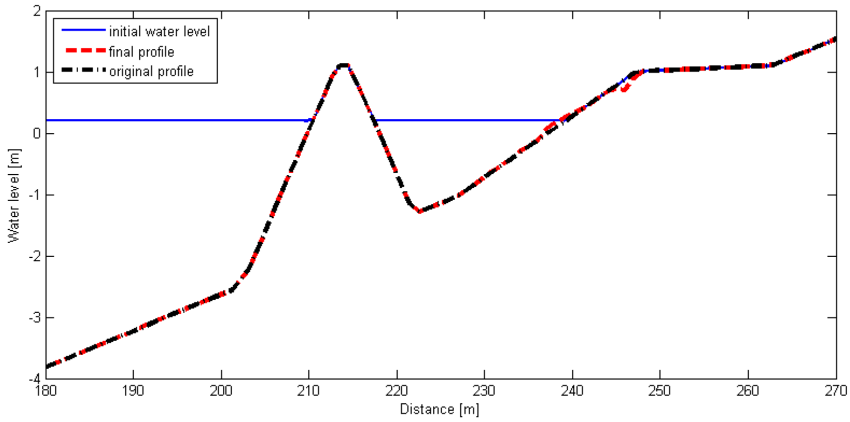

Figure Appendix F-11 Erosion patterns

F.4.3 Alternative 3: h_{crest}=+0,7m NAP

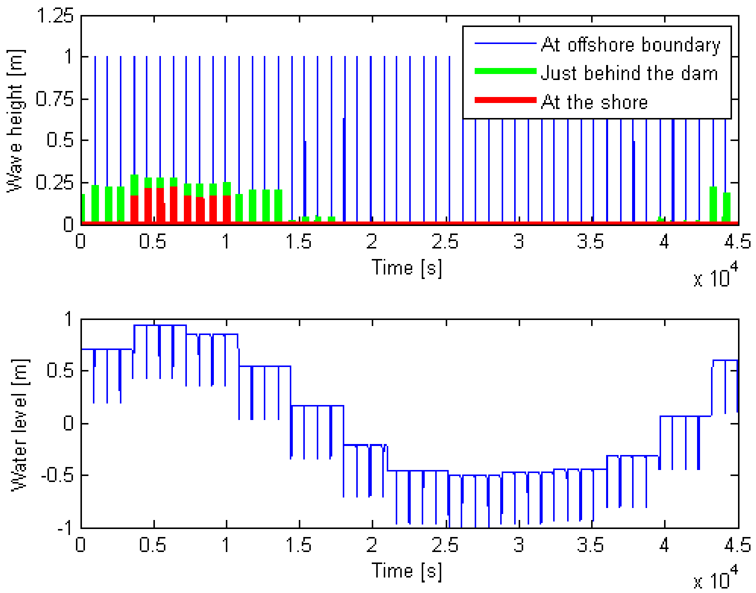

Figure Appendix F-12 Varying wave attack in time and space (upper image) and varying water levels (lower image)

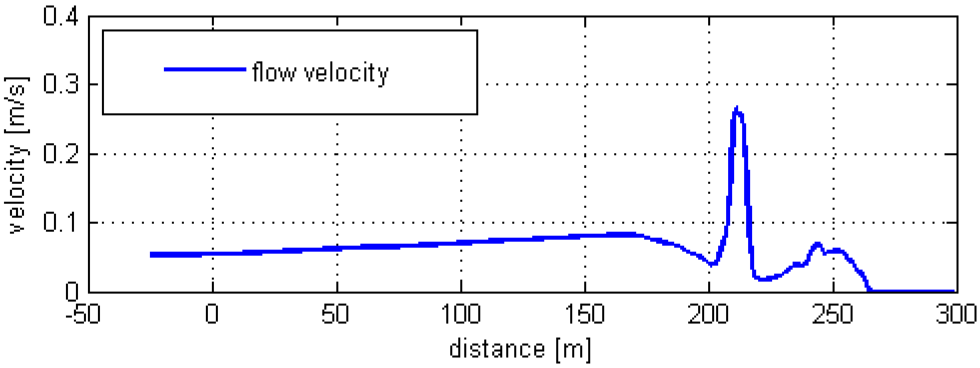

Figure Appendix F-13 Flow velocity varying in the cross-shore direction

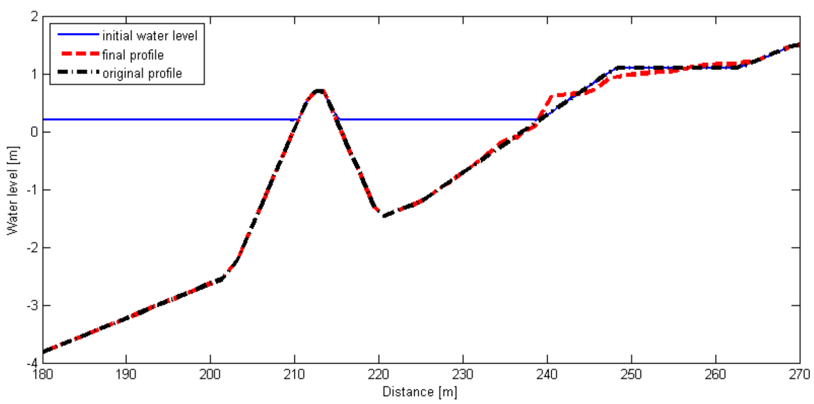

Figure Appendix F-14 Erosion patterns

F.4.4 Alternative 4 h_{crest}=+0,27m NAP

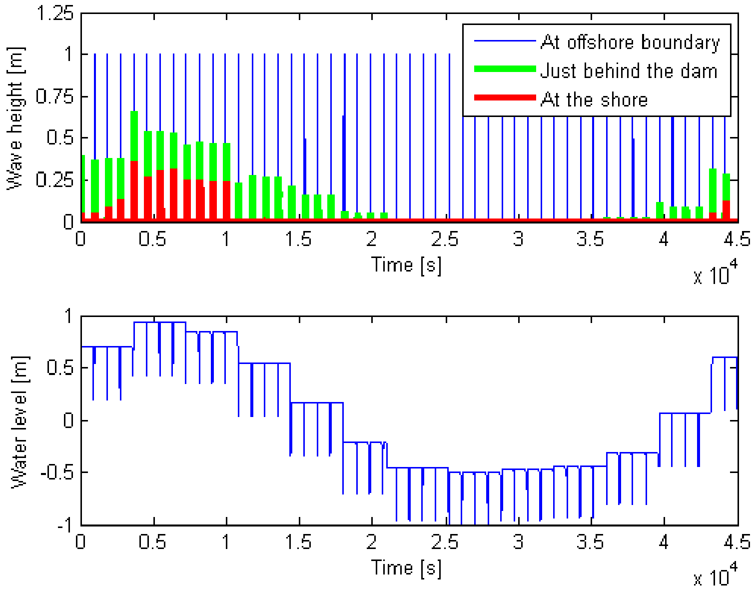

Figure Appendix F-15 Varying wave attack in time and space (upper image) and varying water levels (lower image)

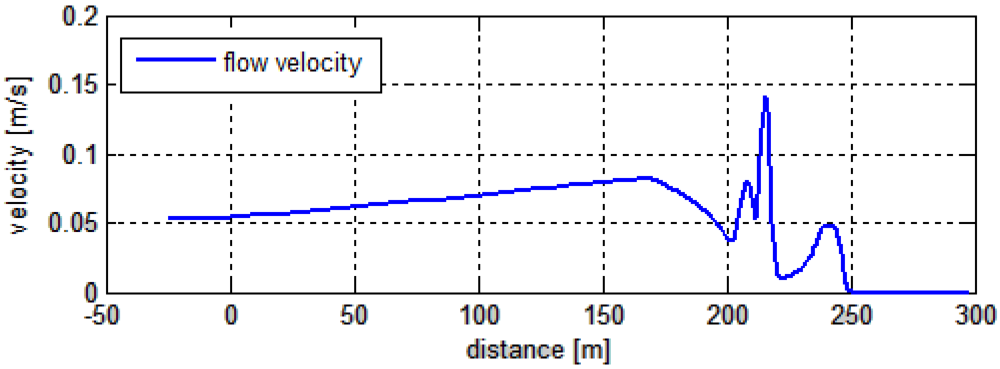

Figure Appendix F-16 Flow velocity varying in the cross-shore direction

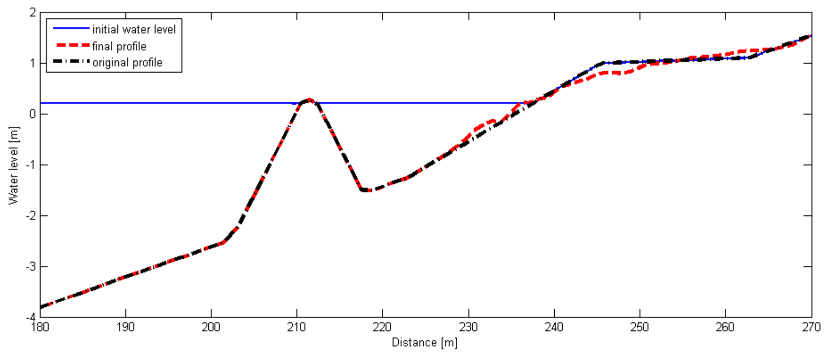

Figure Appendix F-17 Erosion patterns

F.4.5 Alternative 5: Nourishment

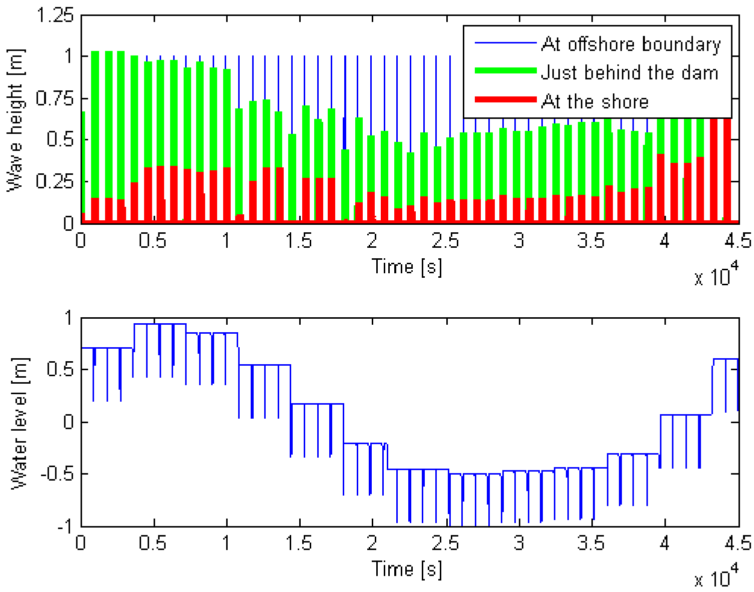

Figure Appendix F-18 Varying wave attack in time and space (upper image) and varying water levels (lower image)

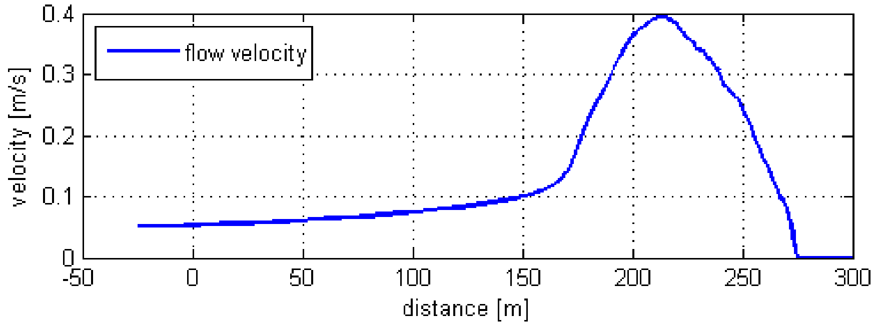

Figure Appendix F-19 Flow velocity varying in the cross-shore direction

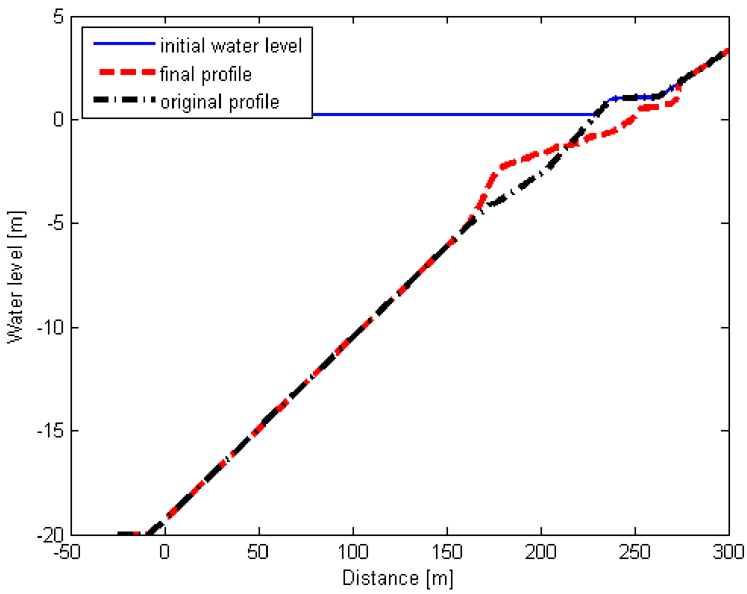

Figure Appendix F-20 Erosion patterns

G. Final design

This appendix includes the technical drawings of the final design.

The first drawing gives an overview of the design. It shows the location in the area, a top view and a cross-section of the Nieuwe Waterweg including the design.

The second drawing includes two details. Detail A presents detailed information on the technical aspects of the design. Detail B presents information on the ecological aspects of the design and gives an indication of how and where the indicator species fit in the design.