

From resistance to coexistence

Towards a more integrated coastal defence system in city of Ostend by adapting nature-based solutions

P5 Report

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P5 Report

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In the end, I would like to express my sincere gratitude to my parents. It is their unconditional support that gave me the opportunity to explore and study abroad and to pursuit my dreams.

It is my greatest fortune to have you all. :)



Fig.0-1 Another time statue

Source: Artwork of Antony Gormley, photo by the author

A big fat sky and a thousand shrieks
The tide arrives and the timber creaks
A world away from the working week
Où est la vie nautique?
That's where the sea comes in…

Dishevelled shells and shovelled sands,
Architecture all unplanned
A spade 'n' bucket wonderland
A golden space, a Frisbee and
The kids and dogs can run and run
And not run in to anyone
Way out! Real gone!
That's where the sea comes in…

Impervious to human speech, idle time and tidal reach
Some memories you can't impeach
That's where the sea comes in
A nice cuppa splosh and a round of toast
A cursory glance at the morning post
A pointless walk along the coast
That's what floats my boat the most
That's where the sea comes in…

Now, voyager - once resigned
Go forth to seek and find
The hazy days you left behind
Right there in the back of your mind
Where lucid dreams begin
With rolling dunes and rattling shale
The shoreline then a swollen sail
Picked out by a shimmering halo
That's where the sea comes in…

Could this be luck by chance?
Eternity in a second glance
A universe beyond romance
That's where the sea comes in…
Yeah, that's where the sea comes in…

---John Cooper Clarke,
Nation's Ode to the Coast

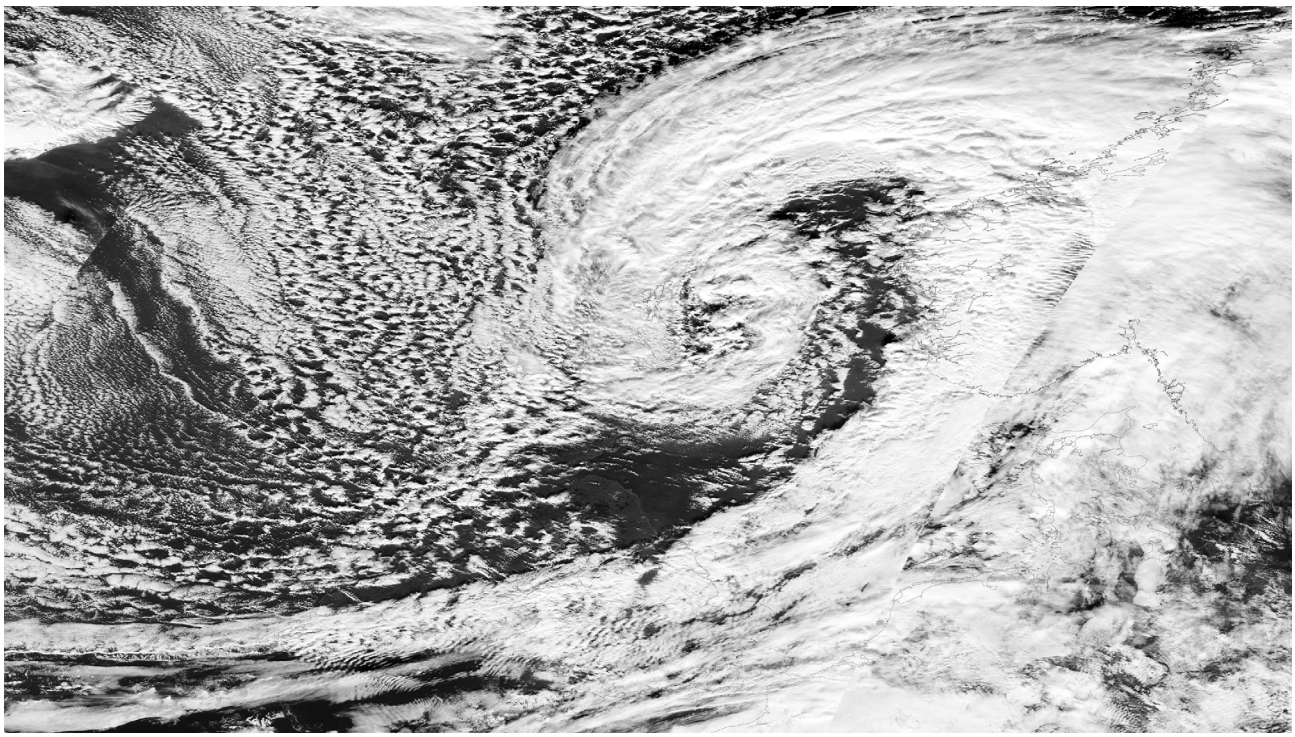

Fig.0-2 Tilo over the North Sea on 8 November 2007

Source: NASA

Summary

Coastal areas are regions where interaction of the sea and land processes occurs. The confrontation and symbiosis between people and nature in the coastal areas has also become an important part of the history of human development.

The mutual dynamics of urban and sea are the main reason why the coastal areas are so fascinating and charming, making these areas with less than 20% of the surface on the earth own more than 45% of people and 75% of mega-cities in the world. However, behind these dynamics there is also a great deal of uncertainty and vulnerability due to the climate change. As a result, people built high walls between urban and sea in order to resist the risks, namely engineer-based coastal defence.

Within the North Sea region, Belgium has the most urbanized and engineer-based coastline, and Ostend is one of the densest cities and the weakest links in the current defence line in Belgian coastal plain. The Linear defence line did protect the city from the main coastal risk, the storm surge, in the past, but it destroyed the dynamic relation between land and sea at the same time, making the future even more risky as the climate continues to change. So more nature-based defence solutions are needed. However, although Nature-based solution (NBS) is already not a new idea, it is very hard to apply it in dense urban areas such as Ostend due to the limited space and time scope.

Except for the risks from sea side, Ostend also assumes responsibility for discharging the inland water. When the sea level rises, the inland water can not be discharged. Besides, the city centre of Ostend consists of large quantities of high-rise holiday apartments, usually empty during the most risky season. While local residents lives in lower rise buildings in lower areas. The centralized drainage system and the living pattern have caused the ‘double risks’ to the city.

This project aims to create a more nature-based coastal defence system in the city of Ostend, using city centre as a design testing area. The main idea is not only focusing on reducing the probability of the risks, but also considering the impacts, which means not putting the whole defence responsibility to the coastline, the nearshore area can actually help for the mitigation and the city itself can also be more resilient. On the sea side, the oyster reef restoration helps to mitigate the wave energy. On the coast, the dune restoration and nature accumulation process are considered. On the urban side, the main idea is creating multi-level buffering system based on the current infrastructure. The interventions on three sides are linked with each other and also work together to enlarge the beneficial scope.

By doing so, the sea side, the coast and the urban can all be part of the defence system. The new system rebuilds the dynamic relation between land and sea, reducing the risks, as well as benefiting nature restoration, public life, urban social and spatial resiliency.



Fig.0-3 Dutch coast line

Source: Photo by the author

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Fig.1-1 Dutch Delta Work

Source: Photo by the author

01 Introduction

1.1 Motivation
1.2 Manifesto
1.3 Scale Definition

1.1 Motivation

Dealing with the multiple values in the coastal areas

Delta systems are always beautiful and unique intersections of communities, ecosystems and industry (Peyronnin, 2016). In a wider region, the coastal areas, their values have self-evident importance and diversity. They directly underpin or contribute to a number of economic sectors, including but not limited to tourism, energy, commercial fisheries, minerals and infrustructure construction.

However, since the the wide variety of values and interests are concentrated in these areas, the conflicts and chaos can also happen due to the limited resources. As the coastal areas are often-vulnerable regions, the multiple values should be carefully dealt with during the human interventions.

Regarding the nature as a stakeholder

"All at once nature is innocent, is unprovided, is sure, is unsure, is fruitful, is destructive, is pure force and is tainted and cursed."

--- Raymond Williams, Ideas of Nature, 1980

One of the earliest accounts directly considering the natural environment as a stakeholder was presented by Näsi (1980). In his contribution stakeholders are described as follows: 'Interest groups and interest systems consist of individuals, groups, institutions, and of the natural environment which interact with the firm. All these systems have different expectations and demands on the firm and the firm is also responsible for all these systems'. Although this description is about the business environment, we can also take it into consideration into the interventions in the coastal areas that nature plays a essential role in the decision making.

More relatively, McHarg (1969) also spelled out the need for urban planners to consider an environmentally conscious approach to land use, and provided a new method for evaluating and implementing it. The Dutch Delta Commission also put forward the concept of 'working together with water', which actually regard the water as a partner or collaborator when creating a much safer environment in the Netherlands.

But nature never takes the initiative to raise his own demands. When we creat the defence system in the coastal areas, we often take the social economy as a starting point, but often only pay attention to nature when we need nature to help us reach our goals, ignoring the needs of the natural system itself..

As decision makers, how we can discover and consider nature's appeals is a topic that worth considering.

Tackling the uncertainties caused by the dynamics in the coastal areas

The dynamics of the coastal areas lie in the interaction between water motion and bathymetry topography, which affects the natural response of coastal systems to change in external conditions and to human interventions — from the scale of seabed ripples up to the scale of entire barrier and delta systems (Dronkers, 2005). Even though people are more and more capable to grasp the trends of this dynamics, the specific future development is still uncertain.

Thus, the decision making and the spatial intervention in the dynamic areas strongly requires a certain degree of flexibility to prepare for possible future changes.

Figuring out the relation between the coastal defence system and the urban fabrics

In Dutch experiences, the characteristics of the coastal cities are closely linked to the dynamic and complex character of the delta and to the way hydraulic engineering was able to deal with this dynamism and complexity (dike town, polder town, dam town, etc.). One the other hand, the coastal related activities and the urban structure also influence each other in a compact way. For example, the development of the port will promote the urbanization of the surrounding areas, and the coastal-towards expansion of the city will also promote the construction of coastal projects.

Therefore, exploring the relationship between coastal defence system and urban fabrics to make them more integrated and mutually improving is an issue that worth exploring in the development of coastal cities.

Can we redefine the coastal defence system?

Currently, the main focus of the coastal defence system is resistance, which means fight against possible disasters caused by natural changes. But this definition is only focused on the single system itself. If we summarize the motivations mentioned above, considering the multiple values, the interests of the nature, the future uncertainties and the relation with the urban fabric, redefining the coastal defence system becomes the biggest motivation for this project.

1.2 Manifesto

Coastal areas are regions where interaction of the sea and land processes occurs. Since ancient times, the coastal areas have been attracting people with their mystery and rich resources. The confrontation and symbiosis between people and nature in the coastal areas has also become an important part of the history of human development.

The dynamics of sea and the urban are the main reason why the coastal areas are so fascinating and charming. For instance; the waves rising and falling in the sea, the accumulation and erosion along the coastlines and finally, the expansion and contraction of the cities. These long-term cumulative and ongoing dynamics make coastal areas particularly important and unique. The mutual dynamics of urban and sea result in the abundant energy resources, complex ecosystems and diverse civilizations, making these areas with less than 20% of the surface on the earth own more than 45% of people and 75% of mega-cities in the world. Be more specific, the coastline of the North Sea is a extremely diverse and rich landscape varies from fjords, river estuaries to mudflats, sandy beaches, etc. At the same time, the areas that is outlined by the coastline are also one of the most valuable and attractive coastal areas in the world.

On the other hand, behind these dynamics there is a great deal of uncertainty, with which comes the growing human beings' fear. As a result, people built a high wall between urban and sea in order to create the sense of security, just like the coastal defence line that already came into being as early as the late Middle Ages in Belgium. Till now, this wall is still stretching all along the 65-kilometer Belgian coastline, becoming higher and higher with the technical progress.

However, resistance does not create any sense of security, but only creates greater uncertainty. Facing the current risks, the importance of the coastal defence system is even more pronounced. It should be a transitional buffer zone instead of a sharp and hard barrier.

Studies have shown that there are already multiple weak links in the hard defence line in Belgium, so how do we fix them? Shall we build it higher and harder? What would happen if we let the sea, urban and coastal defence become a whole integrated dynamic system? Can we transform conventional engineering and adopt nature-based solutions? And how can we build together with nature in the extreme urbanized areas, where the temporal scale and spatial scale are both limited?

As stated in these questions, the thesis mainly studies and discusses the important medium for the intersection of sea and land in coastal urban areas - the coastal defence system. In the context of the North Sea and the specific condition of Belgian Coastal Plain and city of Ostend, the thesis aims at finding a new model of coastal defence system, which allows human society and nature to get along more harmoniously while coping with the climate risks.



Fig.1-2 Coastal Types in the North Sea region

Source: TT Studio group work based on Quante, M.; Colijn, F. (2016)

1.3 Scale Definition

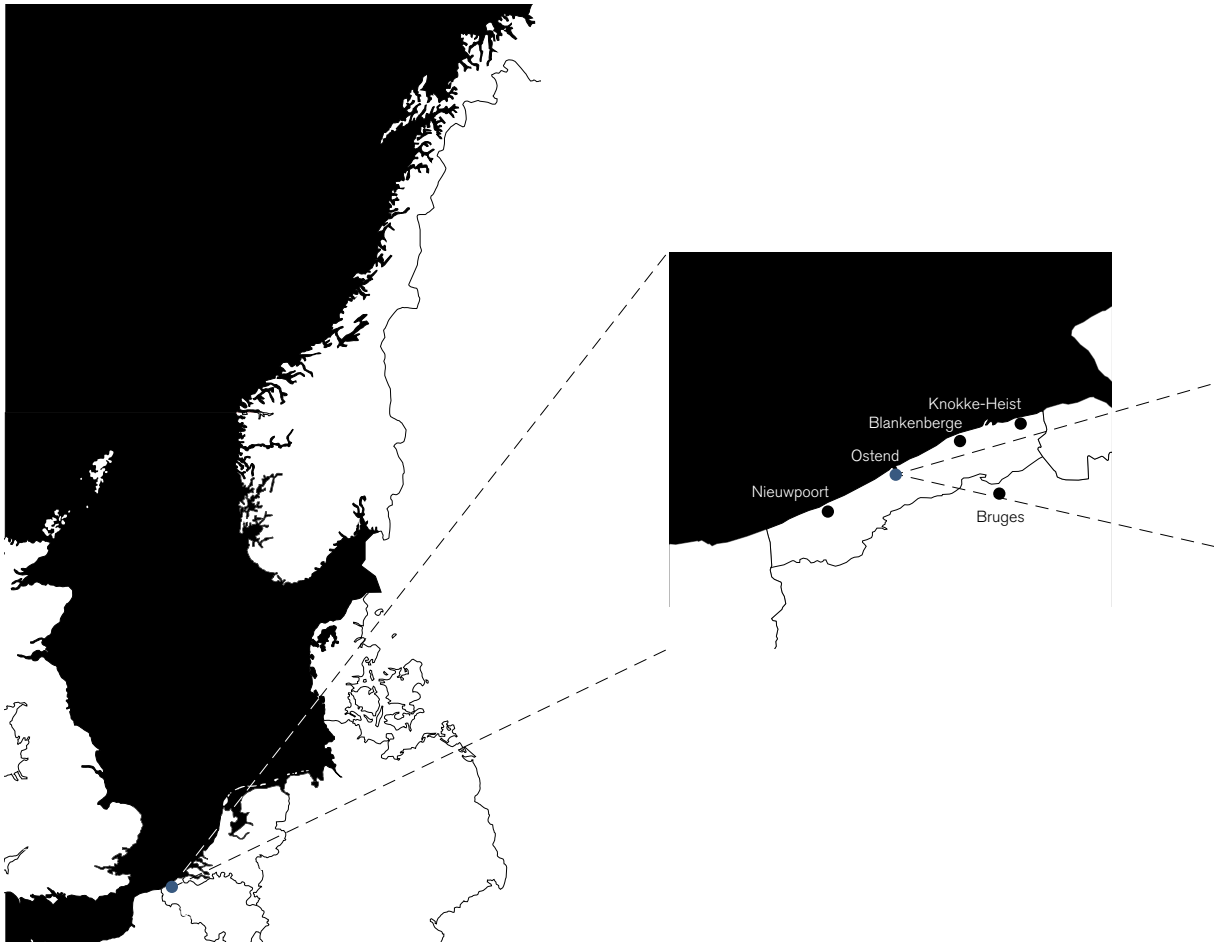
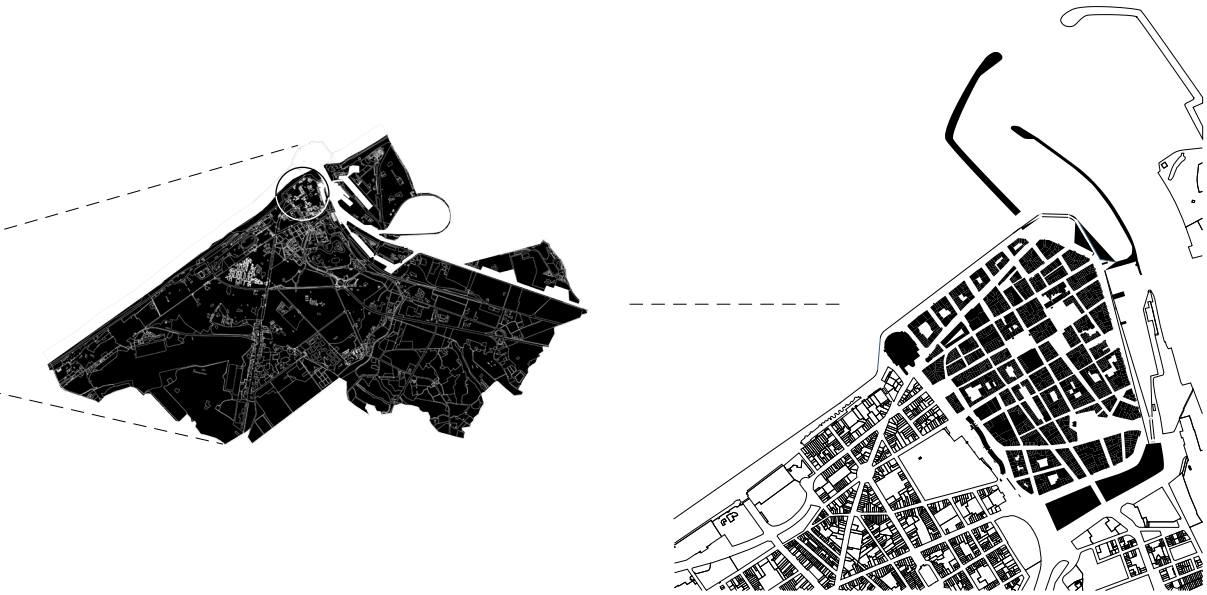


Fig.1-3 Scale definition

Source: Made by author

Territorial Scale

Macro Scale - Belgian Coastal Plain



Meso Scale - City of Ostend

Micro Scale - City Centre of Ostend



Fig.2-1 Belgian coast line

Source: https://www.belgianboutique.com/magazine/architecture/belgian-coast-very-linear-landscape

02 Problem Fields & Methodology

2.1 Phenomenon and Trends
2.2 Problem Statement
2.3 Research Question
2.4 Research Aim
2.5 Conceptual Framework
2.6 Research Methods
2.7 Methodological Framework

2.1 Phenomenon and Trends

Climate change as an accelerating fact

Based on the Representative Concentration Pathways 8.5 (RCP 8.5), originating in the Assessment Report 5 (AR5) from 2014, the downscaled climate change effects on the North Sea Region are analysed.

Under the projection of +1m relative sea level rise (SLR), the North Sea Region is facing many risks and the most direct one is the flooding. Due to the aftermath of SLR, the entire seascape is expected to fully reshape, where most vulnerable countries to those changes are Belgium, the Netherlands, Germany, Denmark, also part of England. The increasing amount of sea water will affect many aspects of the human habitat, for instance the entire primary sector of the economy, the appearance of the wide maritime areas etc.

Beside, the climate change also causes the increasing emergence of extreme weather. For example, according to Martin Beniston, the frequency of winds will increase up to 7% in North West of the North Sea Region (Martin Beniston, 2007). These conditions will create more storms along the coastal regions of Belgium, the Netherlands, Germany and Denmark, leading to storm surges, wind will push water towards the coast, it accumulate in a storm surge (Martin Beniston, 2007) and will transport moisture on northern Europe and Scandinavia. That determines the excess of precipitation over evaporation. (Hurrell, 1995; Sündermann, 1981).

Thus, through the mapping we can get the conclusion that the southern coastal areas of the North Sea Region are the most vulnerable areas regard to the climate change effects.

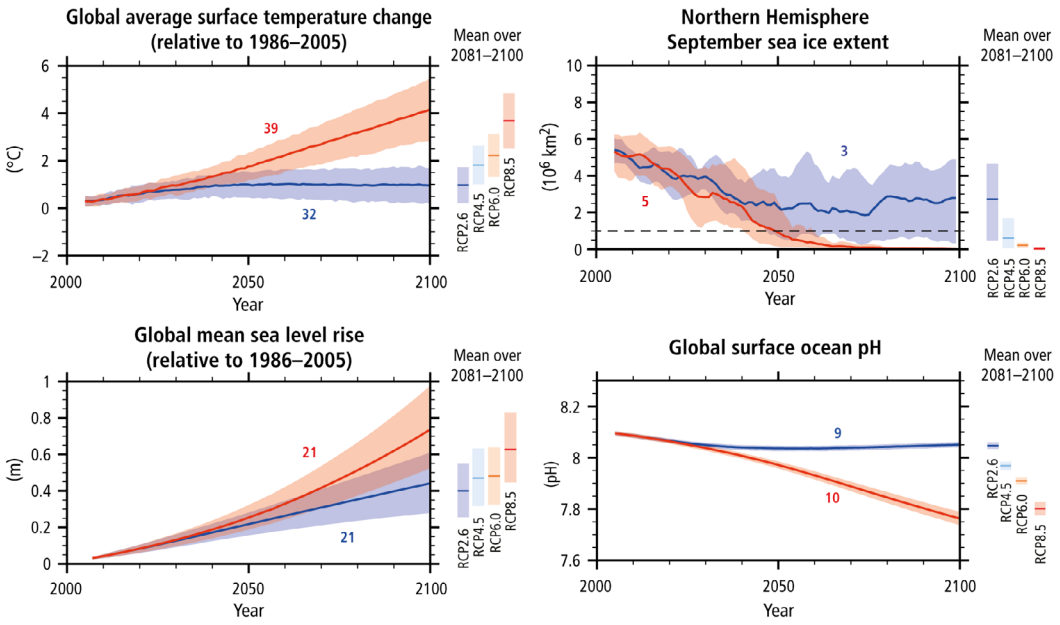


Fig.2-2 Climate change facts

Source: https://ar5-syr.ipcc.ch/topic_futurechanges.php

Urbanization in the coastal lowland as an ongoing process

Coastal zone has historically been a natural place for human settlements as they typically offer ready access to water and fertile soil (UNU-IHDP, 2015). Nowadays, the coastal areas are still and will continue to be the areas with the densest population and economic activities in the world. It contains more than 45% of the human popilation, yields 90% of the global fisheries, produces about 25% of global biological productivity with only less than 20% of the Earth's surface (Crossland et al., 2005).

Specifically, in the North Sea area, the most urbanized areas concentrate in the south coast line that includes north-western coastal area of Germany, western coasatl area of the Netherlands and Belgium and eastern coastal area of UK. Over the past 50 years, the population living in European coastal municipalities has more than doubled to reach 70 millions inhabitants in 2001 and the total value of economic assets located within 500 metres from the coastline has multiplied to an estimated 500-1000 billion euros in 2000 (Eurosion, 2004).

In the future, the trends that population growth and urbanization in coastal areas will continue. According to the EUROSTAT, The EU population is projected to increase by 3.4 % between 2015 and 2050, and the most significant growth will happen in the southern and western coastal area of Norway, western coastal area of the Netherlands, Belgium and eastern coastal area of UK. These trends bring the development potential of these regions, but also bring the increasing environmental pressure.

Therefore, the southern coastal areas of the North Sea Region are also facing the socio-economic impacts such as population growth and urban expansion.

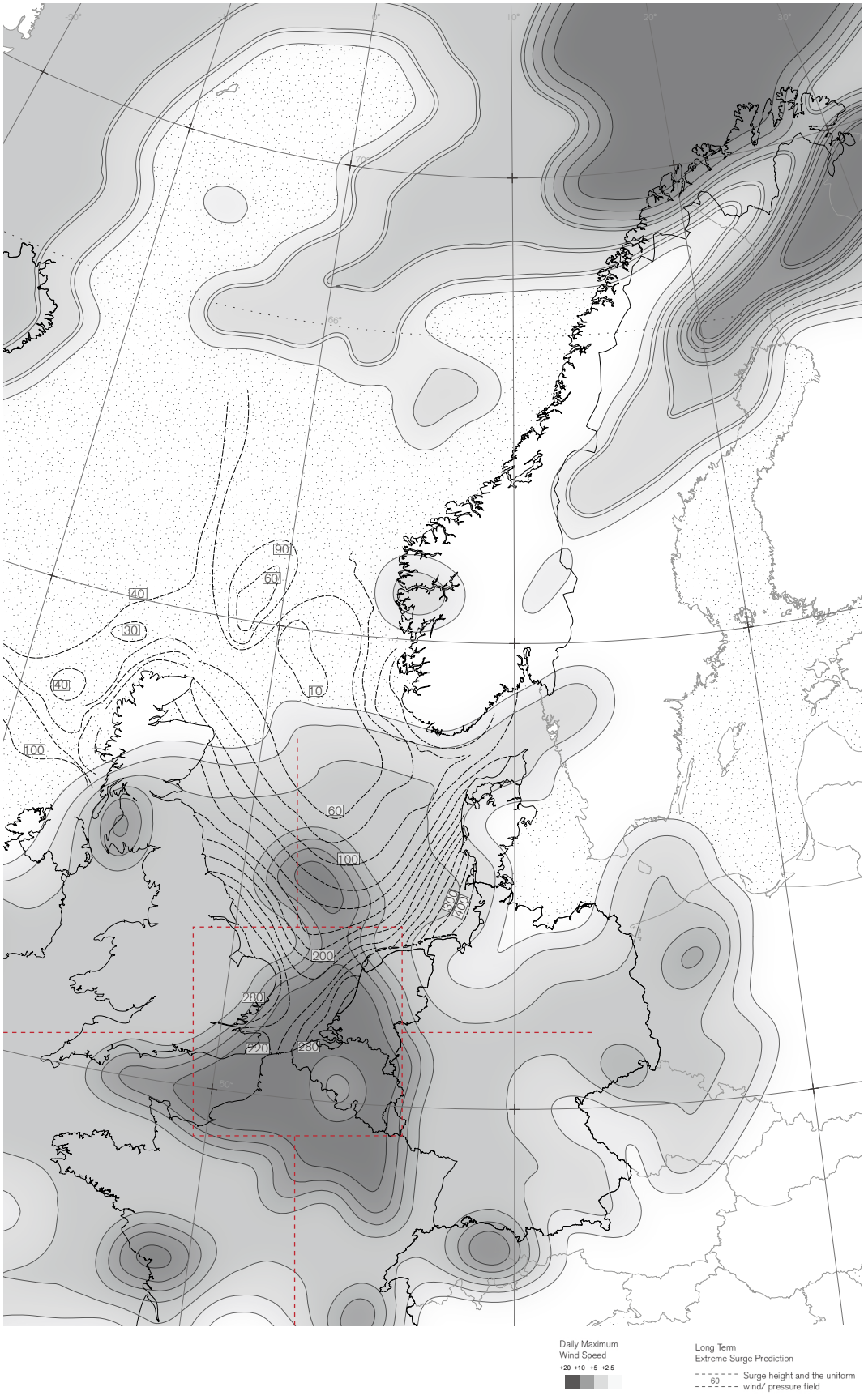


Fig.2-3 Extreme Winds and Storm Surge

Source: TT Studio group work based on Martin Beniston, D. B. (2007) and Jürgen Sündermann, W. L. (1981)

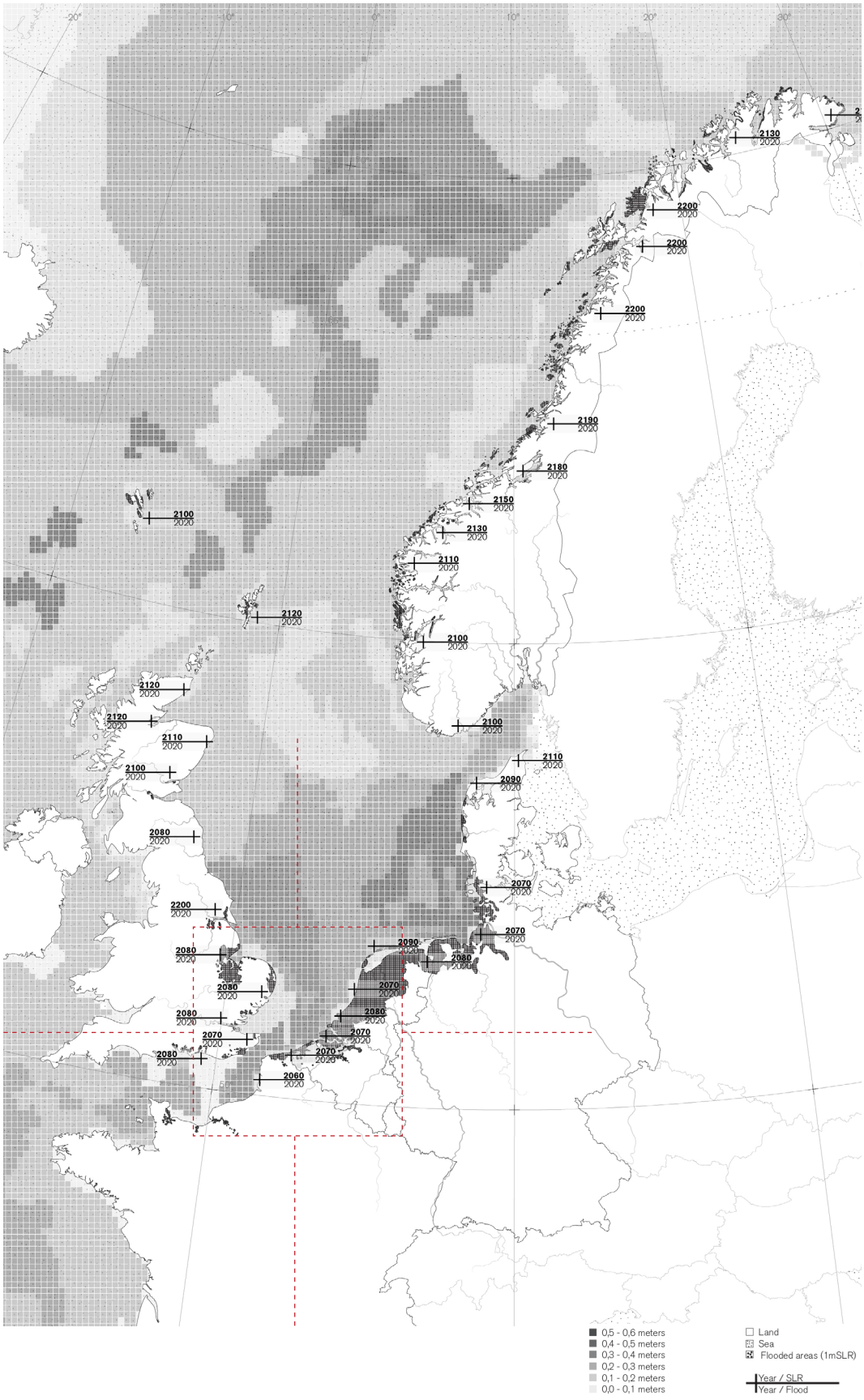


Fig.2-4 Relative Sea Level Rise

Source: TT Studio group work based on European Environment Agency (2017)

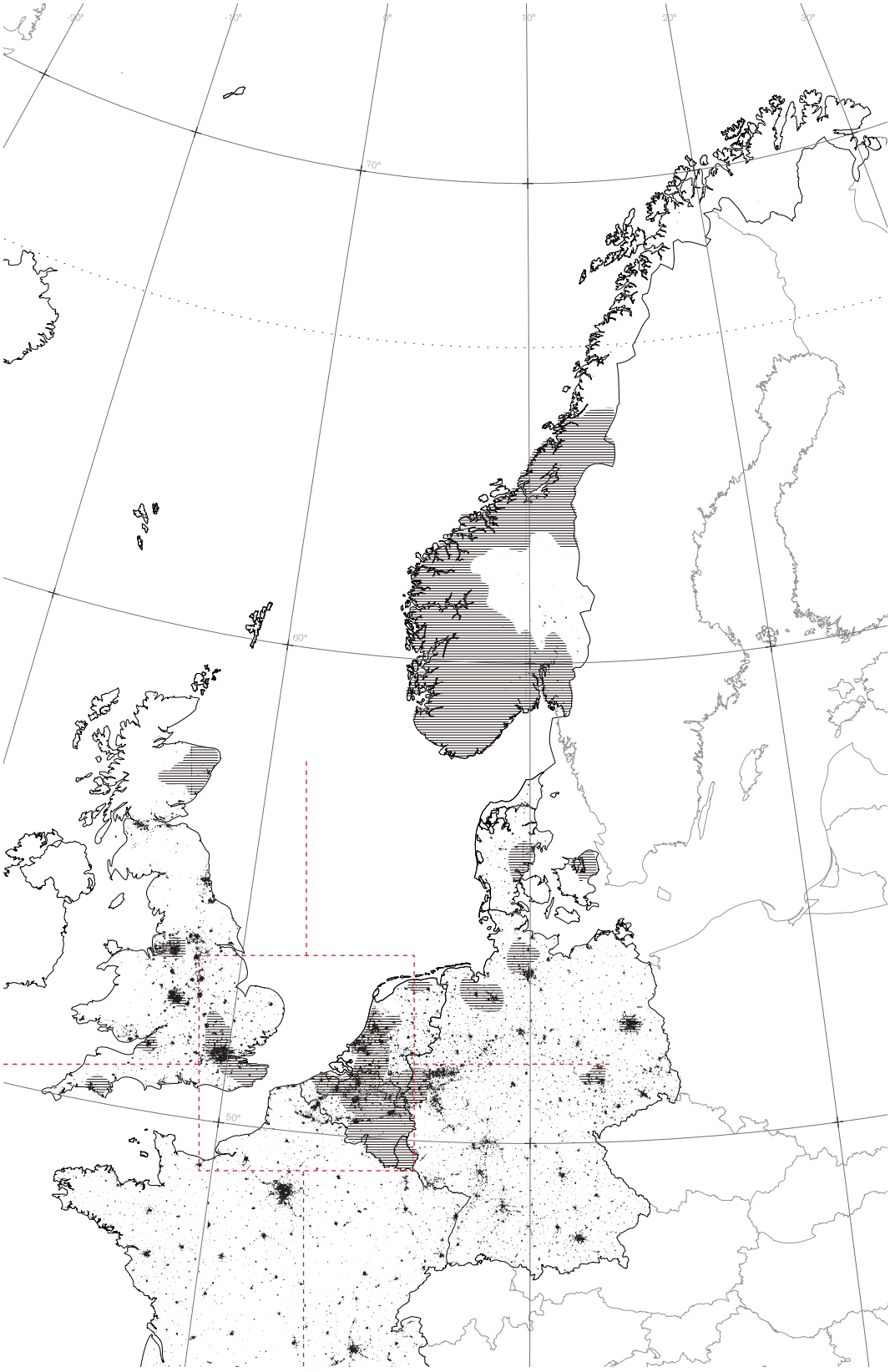


Fig.2-5 Urbanization trends in the North Sea area

Source: TT Studio group work based on Eurostat regional yearbook (2018)

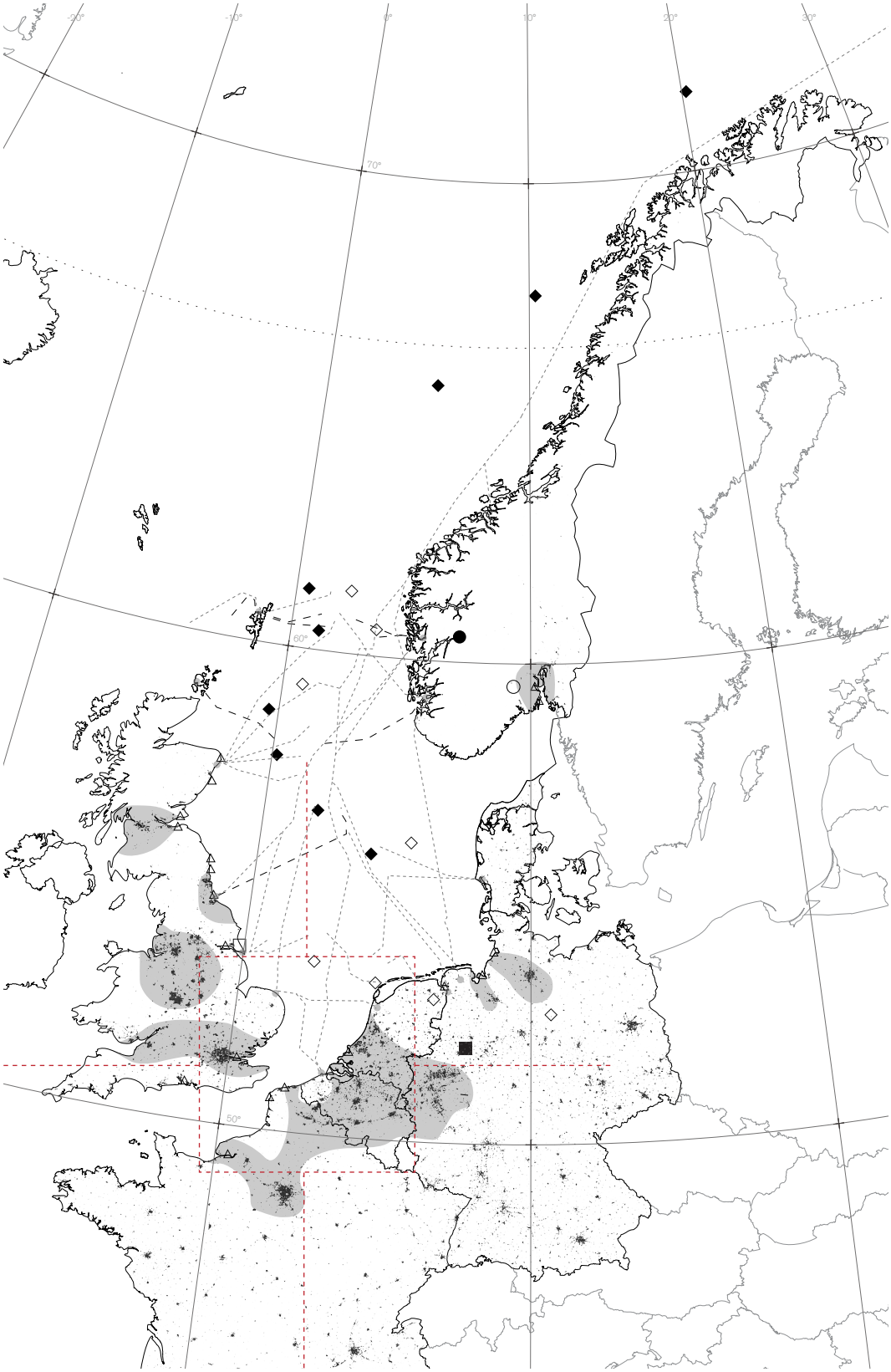


Fig.2-6 Industrial sites in the North Sea area

Source: TT Studio group work

Current coastal defence solutions

Based on the above analysis, we know that the southern coastal areas of the North Sea Region will be mostly influenced by both climate change effects and socio-economic impacts, thus, the coastal defence system in those areas plays an extremely important role, and it is necessary to review the current coastal defence system.

Normally, we can divide the defence approaches into two categories, namely 'grey' defences and 'green' defences.

'Grey' coastal defences, also called 'hard' defences, are structural measures like series of groynes, series of offshore and submerged breakwaters, revetments and seawalls (Bosboom & Stive, 2012). Basically, they protect the coastal areas by avoiding the sediments to be eroded or be transported in alongshore and cross shore directions of the coastline.

With less severe impacts on the environment, 'green' coastal defences are 'soft techniques' that are more nature-based, thus also more sustainable and flexible in terms of human interventions. Typical green coastal defences include beach nourishment, beach stabilisation, managed retreat, dune regeneration, marshland creation, revegetation and coral reef enhancement. These measures imply that 'natural' processes and movements are allowed to continue (Bosboom & Stive, 2012).

The choice for a 'grey' or a 'green' defence depends on both the characteristic of the problems concerned and on economic considerations. Actually, both of them have negative impacts on the ecosystem in the beginning (Bosboom & Stive, 2012). For example, beach nourishment in coastal zones that have a rich nearshore ecological value (e.g. seagrass meadows) is also disrupt the existing biological communities and habitats in subaerial zones of beaches and in the borrow sites where dredging occurs (Board, 1995). And it is also unsustainable to create sandy beaches in areas where the sand and sediments are inadequate. So even though the 'green' defence looks like more environmental friendly, the use of 'grey' measures for coastal protection can still not be totally disregarded.

Based on these two categories, the 'Conventional Coastal Engineering' and 'Nature-based Solutions' are the two major solutions that tackle the climate change effects. Both of these two solutions are the combinations of different approaches. The main difference is whether it is dominated by structural construction or by natural processes.

Grey Defence

Sea wall



Rock Armour



Low Crested Reef



Groyne



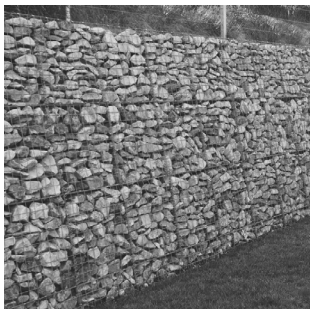
Cliff Fixing



Dune Regeneration



Gabion

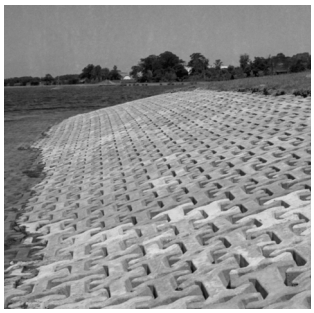


Afforestation of Coastal Dunes



Green Defence

Revetment



Beach Nourishment



Mangrove Preservation & Planting



Coastal Barrage



Managed Retreat



Coral Reef Preservation

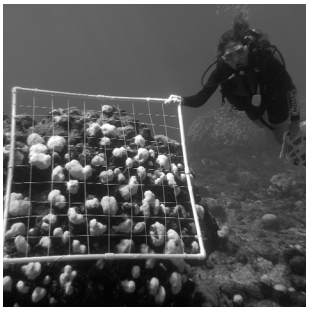


Fig.2-7 Coastal defence approaches

Source: https://www.theswimguide.org/2016/09/22/difference-soft-hard-engineering/ https://www.bbc.com/bitesize/guides/z2234j6/revision/1

Zoom in - Southern coastline of the North Sea Region

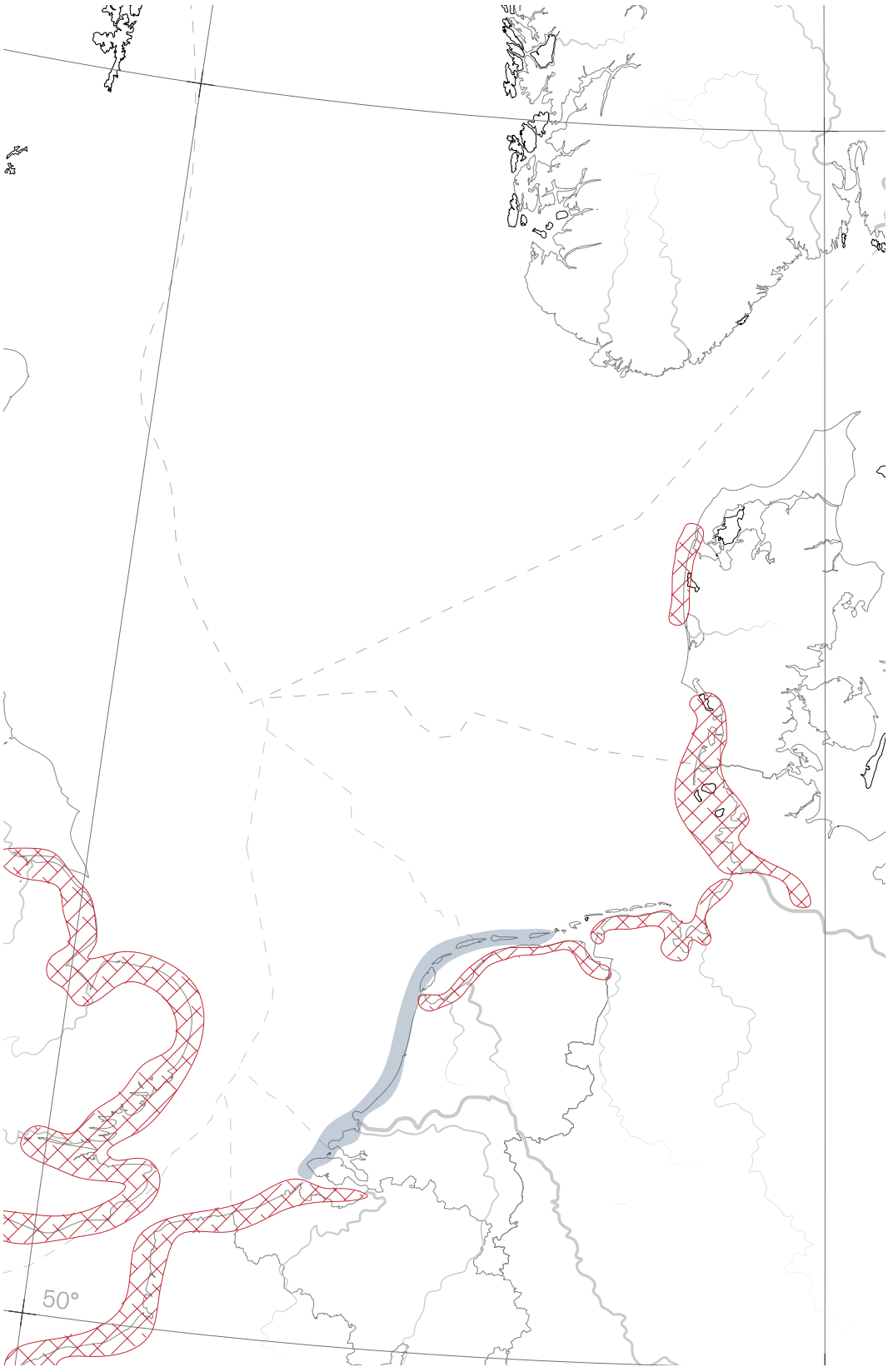


Fig.2-8 Overview of coastal defence system in southern areas of the North Sea Region.

Source: Made by the author

When zooming in to the southern North Sea coastal, we discover that except for to the Netherlands, the coastal defence of other contries are all mainly based on coastal engineering. And after overlapping the coastal urbanization situation, the Belgian Coastal Plain (BCP) can be regarded as the 'hardest' area among the southern North Sea.

The BCP is situated at the southern part of the North Sea between The Netherlands and France. The coastline is 67 km long consisting mostly of sandy beaches with sea walls in front of the cities and dunes in between.

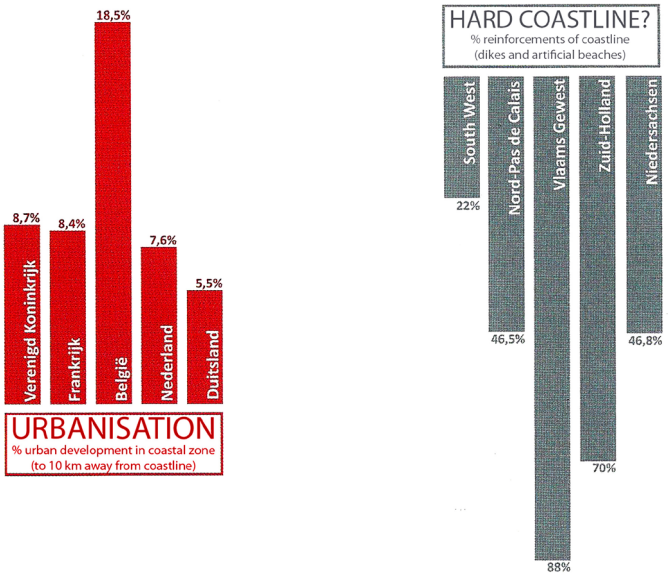


Fig.2-9 Urbanization and "hardness" of the Belgian Coast

Source: EUROSIAN (2004)

The coastline is characterized by a high building and population density, an important source of income from tourism, important harbours, a lot of fishery, a hinterland dominated by agriculture, and some valuable nature reserves.

Compared to other North Sea areas, the BCP is a very dense region and also the most artificial one, which means it is the most challenging area for transformation of the coastal defence system.

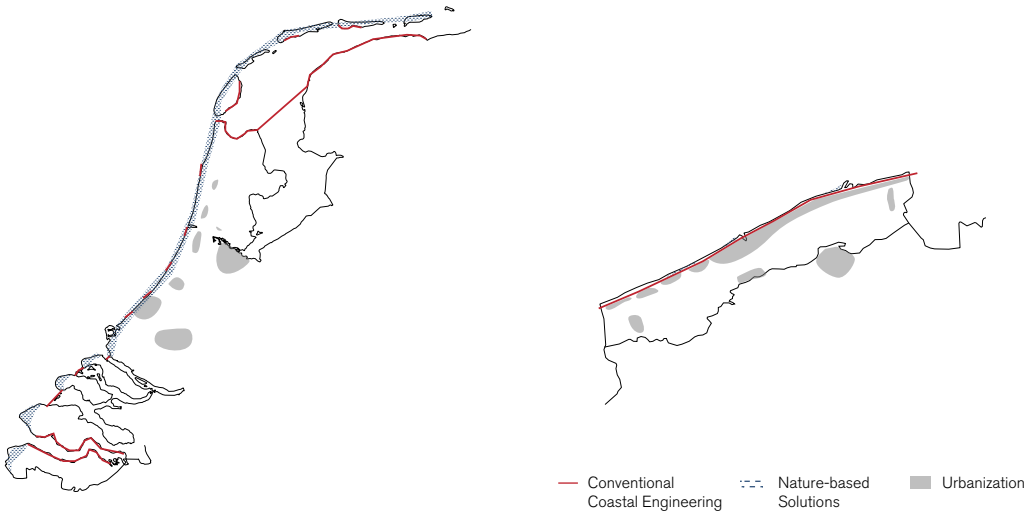


Fig.2-10 Comparison between dutch costal line and belgian coastal plain

Source: Made by the author

Zoom in - Belgian Coastal Plain (BCP)

The density map of the BCP shows that city of Ostend is the densest city in the BCP. The land use map also shows Ostend is the most urbanized city in the BCP. Combining the situation of the Belgian coastline, we can infer that city of Ostend is the 'hardest' part of Belgian coastline.

Moreover, recent studies showed that one third of the Belgian coastline is not sufficiently protected against severe storm events. All weak links have been determined based on stability and breaching calculations of the sea defences. The map illustrates that the current defence system in the city of Ostend and its surrounding areas is also very vulnerable and facing the increasing chanllenges due to the climate change effects.

Based on the above analysis, the most challenging part of BCP - city of Ostend is selected as the key research area.

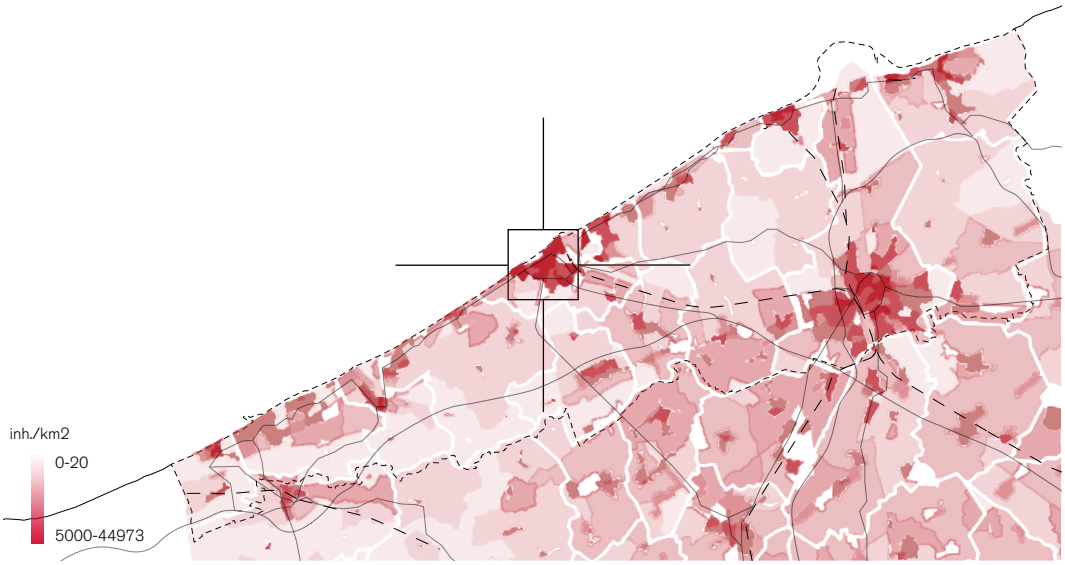


Fig.2-11 Population density

Source: Made by the author based on Statistics Belgium, 2010

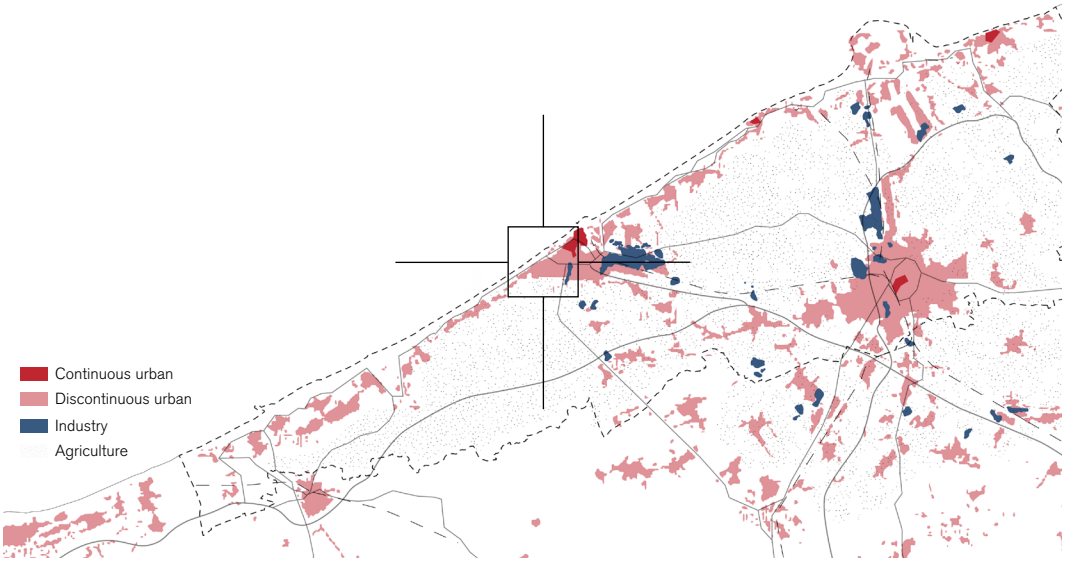


Fig.2-12 Land uses according to CORINE 2006, level 2 categorisation

Source: Made by the author based on Belgian Coastal Urban Environments (2012)

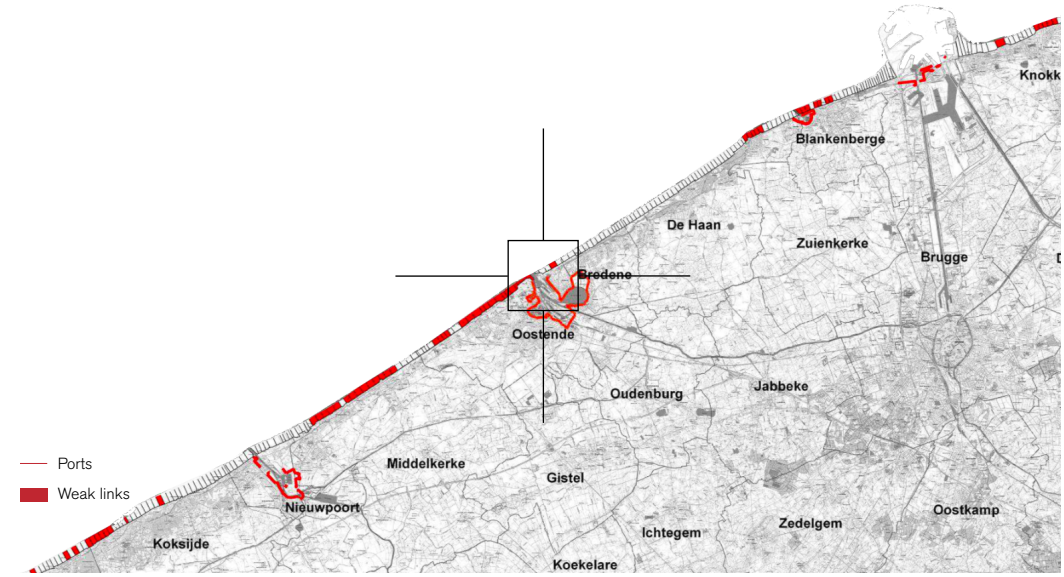


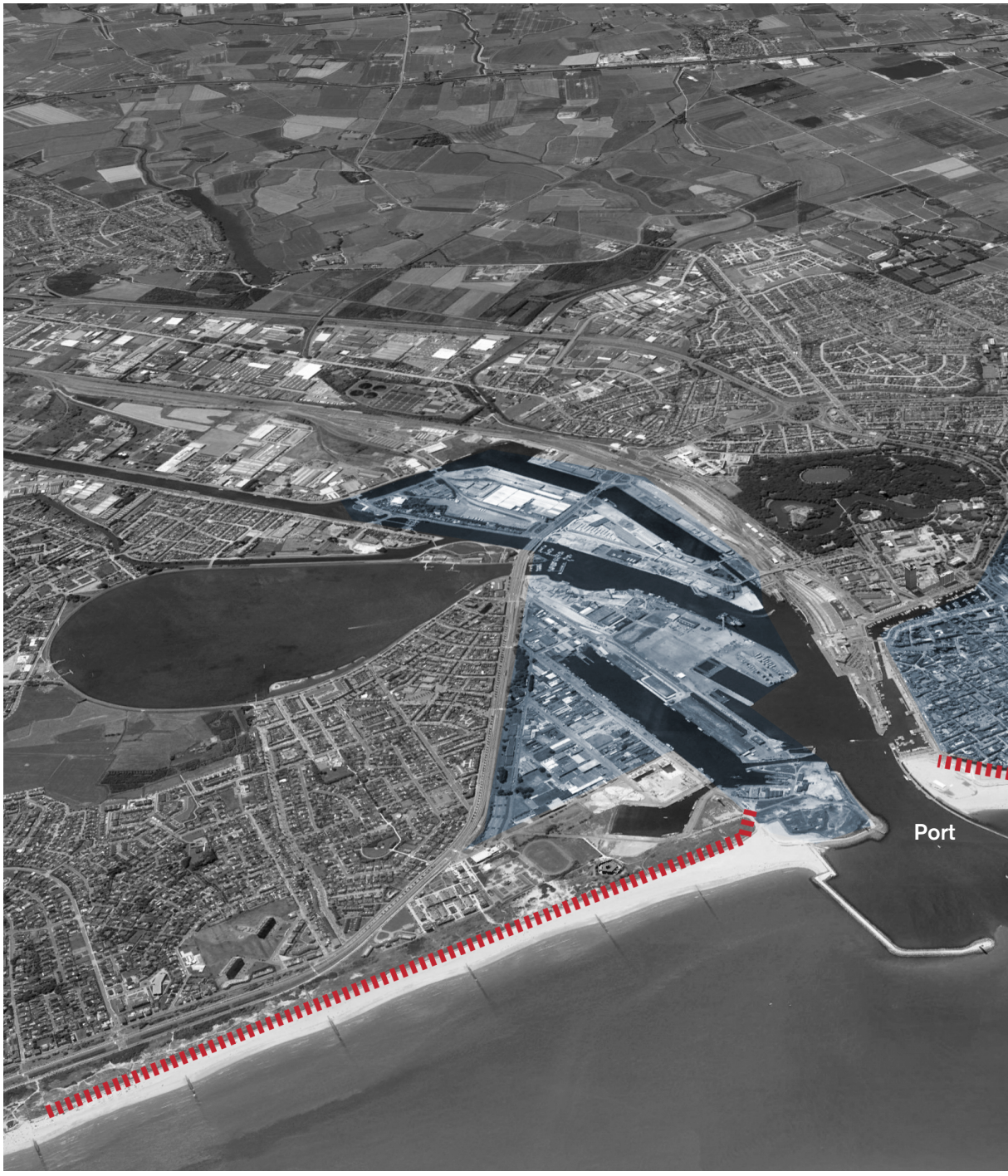
Fig.2-13 Weak links at the Belgian coastal zone

Source: An integrated master plan for Flanders future coastal safety (2015)

Zoom in - City of Ostend

First impression

Concentration of critical infrastructure (industries, port & airport)
High-density city centre close to the sea
Firm but vulnerable hard defence line
Monotonous and isolated beach nourishment



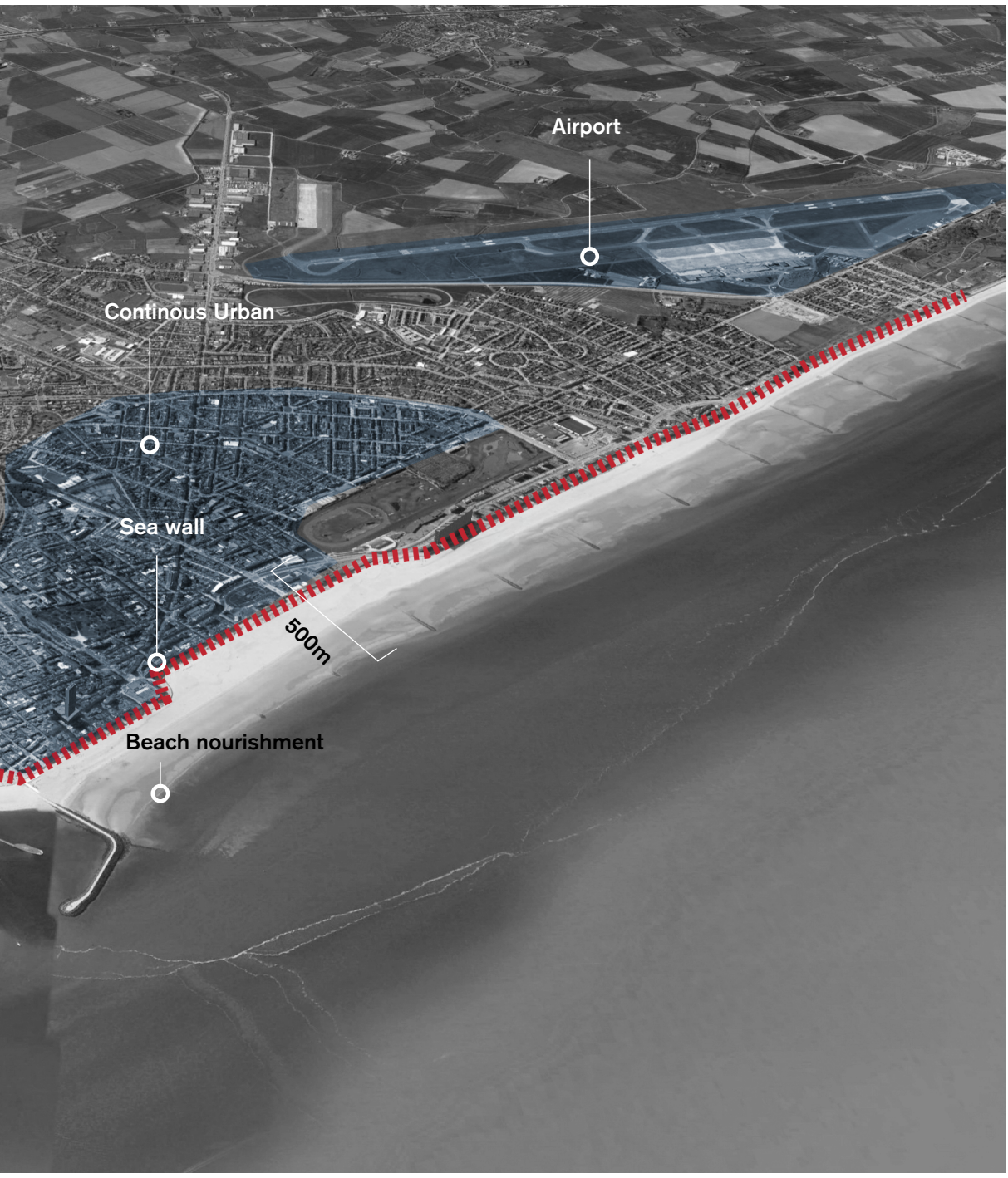


Fig.2-14 Current coastal defence system and urban structure in Ostend

Source: Made by author

2.2 Problem Statement

The coastal areas always play essential roles in the world. This importance mainly due to the dynamics of sea, which includes the maritime ecosystem and biodiversity, trading and transportation, fossil fuels and sustainable energy, tourism and living environment. On the other hand, there is also the dynamic of risks that exist in the sea. Climate change has been carrying out effects such as sea level rise and the extreme weather, which has made us pay more attention to the coastal defence system.

Nowadays, conventional coastal engineering such as sea walls are still the most widely used solutions which is inflexible and single-functional. On the other hand, with the population growth and urbanization acceleration, critical urban systems like ecology, energy, food and habitancy also seek their development and expansion within such limited land resources in the coastal area. This challenge is more pronounced in the Belgian coastal plain (BCP), where almost the entire coastline is concentrated by high-density urbanization and heavy infrastructures. The static coastal defence system is lacking of resiliency, and more nature-based solutions are needed.

However, nature-based solutions always need a lot of space and a long period of time, which is very hard to apply them in extreme dense urban areas. For example, city of Ostend, lying in the central of the belgian coastline, is the city with the highest population density, the fastest population growth rate and essential infrastructures (the port and the airport) of the BCP. Currently the coastal defence is still largely relied on the coastal engineering (the sea walls) and is very hard to transfrom to nature-based due to the lack of space.

Thus, the contradictions between built environment and nature, between different urban systems, between static defence system and dynamic of sea and urban, between nature-based solutions and limited space are particularly intense in the Belgian coastal plain especially in the city of Ostend. Confronting the specific situation, the defence system in these areas should be more resilient, nature-based and dynamics for disaster preventing, nature protection and urban developing. And the Nature-based solutions also need to be adapted under the extreme dense urban context.

Therefore, The defence system in the future can become a medium, by adapting nature-based solutions, integrating the dynamics of sea to mitigate climate risks, and integrating the city's critical network to also take on some urban functions. So it becomes a transitional buffer zone to link a sea and urban instead of a sharp and hard barrier. The main focus of defence in coastal urban areas shift from resistance to coexistence.



Fig.2-15 Urbanized and heavy Belgian coast line

Source: Photo by Marc Ryckaert

2.3 Research Question

Main research question

SQ1

How can we create a more resilient, adaptive and nature-based coastal defence system in extreme urban areas integrated with the dynamics of the sea and critical urban systems, benefits both nature and urban development?

SQ2

SQ3

Sub research questions

SQ1 Background and Theoretical base

Q1
· What are the definitions of resiliency and adaptability for the coastal defence systems?

Q2
· What is the meaning of nature-based coastal defence solutions and why can it bring resiliency and adaptability?

Q3
· What are the limitation and potentialities of applying natrure-based solutions in extreme dense urban areas?

SQ2 Research and design in BCP and Ostend context

Q4
· What are the dynamics of the sea and the urban systems in BCP and city of Ostend, and what challenges will be brought about by these dynamics?

Q5
· What is the specific situation of the current coastal defence system in city of Ostend and what is the people's behaviors and awareness towards the risks?

Q6
· What are the local impacts caused by the main challenges in city of Ostend?

Q7
· How to use nature-based solutions to transform the coastal defence system in Ostend and let it be a medium of integrating the dynamics of nature and urban systems?

SQ3 Further impacts and reflection

Q8
· What kind of values and broader influences can the new coastal defence system bring to the BCP and the North Sea areas?

2.4 Research Aims

Research objectives

Based on the research questions, it is clear that the project aims at figuring out a more resilient and adaptive paradigm of coastal defence system in city of Ostend by adapting nature-based solutions and integrating dynamics of the sea and crucial urban systems.

Thus, the research objectives are as follows:

Dynamics of the sea
Sea level rise, storm surge, currents movement, patterns of erosion and accumulation.

Dynamics of the urban
Urbanization process, infrastructure, urban landscape, geological situation (soil type, elevation and permeability), economic situation (density, landuse, water management, social patterns).

Transition of the coastal defence system
Critical review of current situation, potential of future transition.



Relation among sea, urban and coastal defence system
Natural relation (topography and ecosystem) and artificial relation (human activities)
The role that coastal defence system plays now and can play in the future, the different functions it can take on.

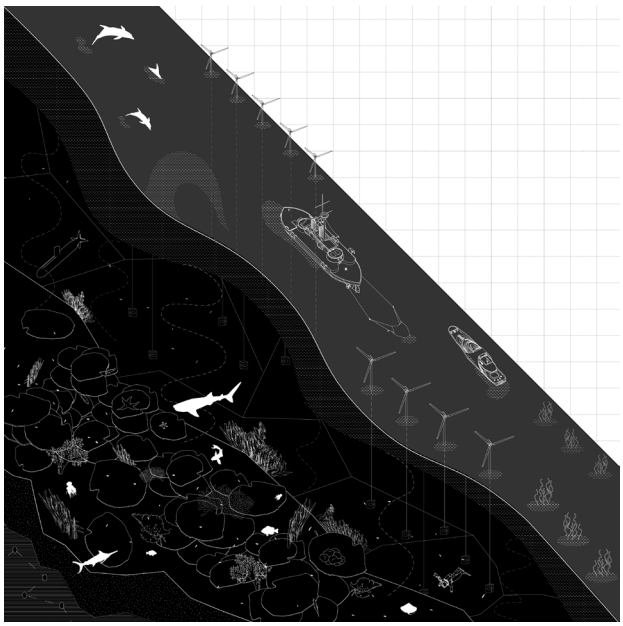


Fig.2-16 Dynamics of the sea

Source: Made by author

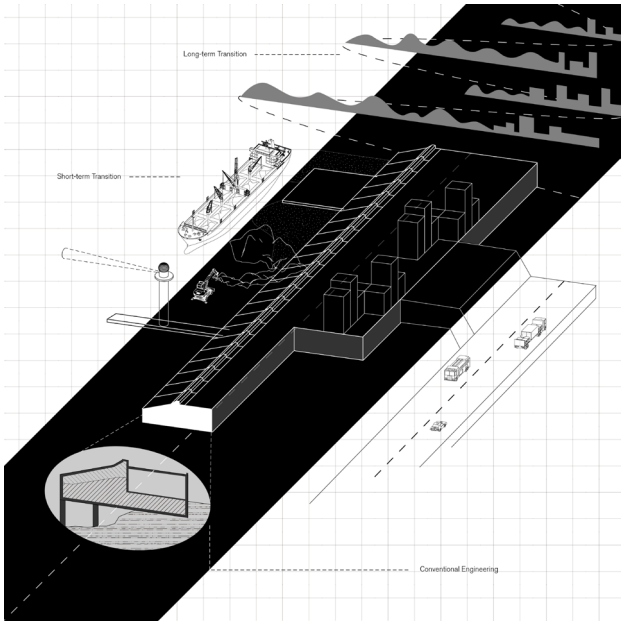


Fig.2-17 Transition of the coastal defence system

Source: Made by author

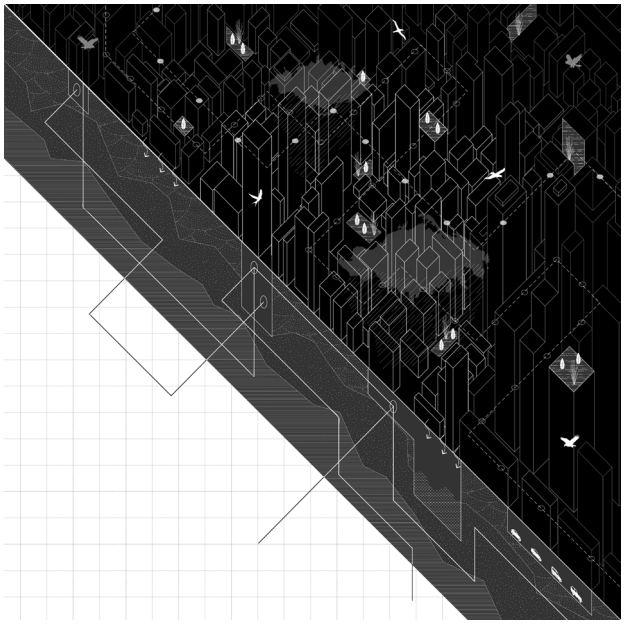


Fig.2-18 Dynamics of the urban

Source: Made by author

2.5 Conceptual Framework

The conceptual framework shows that currently, due to the climate change effects, the risks from sea side will be larger. At the same time, the ongoing urbanization process and water management of inland city also bring certain pressures to the coastal cities. However, the current defence strategy is heighten the current line, further blocking the natural connection between the sea and land, causing greater uncertainty.

In the future transition, by applying nature-based solutions, the coastal defence system becomes a gradient buffer zone instead of a sharp and hard barrier, integrating the dynamics of sea to mitigate climate risks, and integrating the city's critical network to also take on some urban functions.

The conceptual model also shows that the potentiality of the coastal defence system to connect the dynamics of sea and urban networks. Thus, form Resistance to Coexistence.

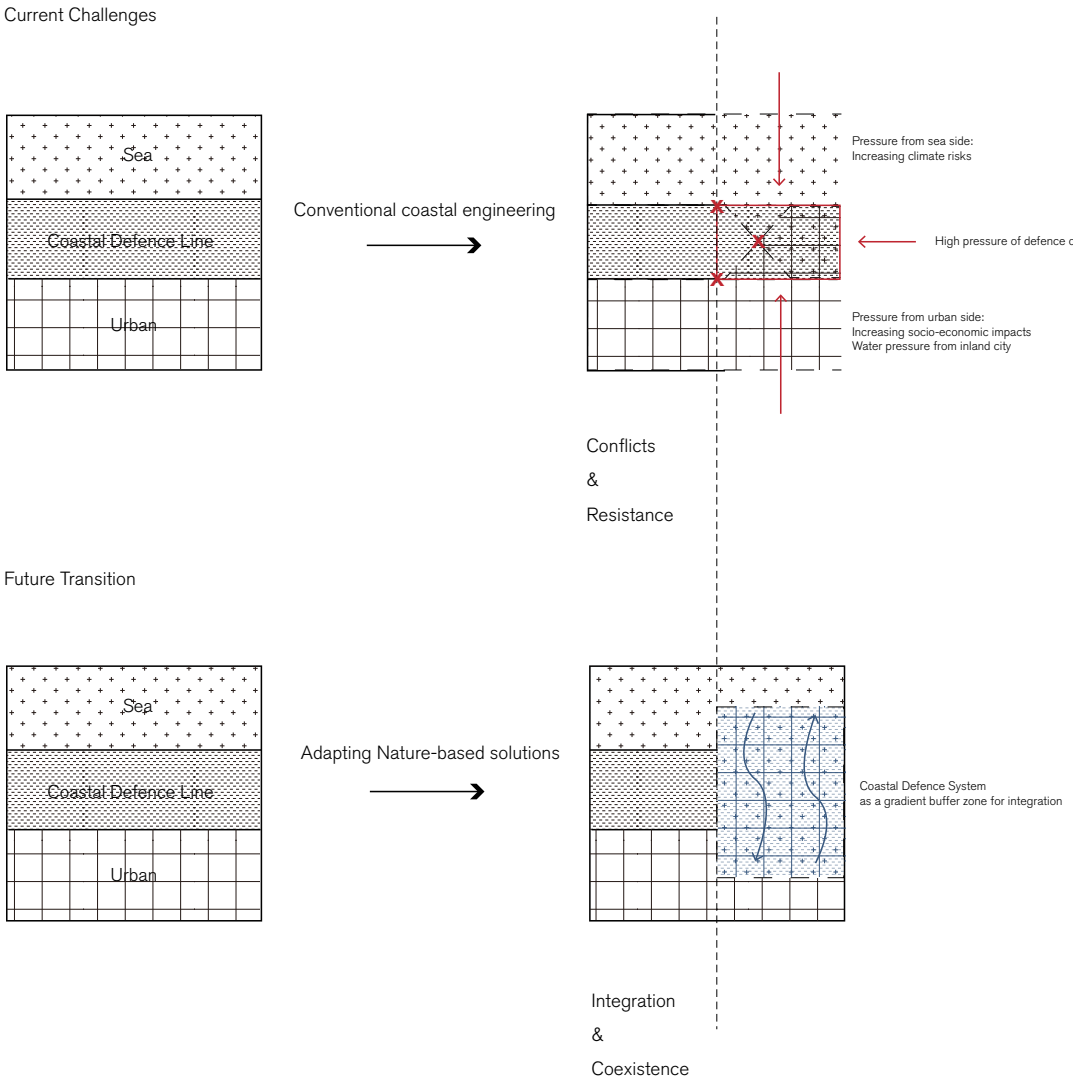
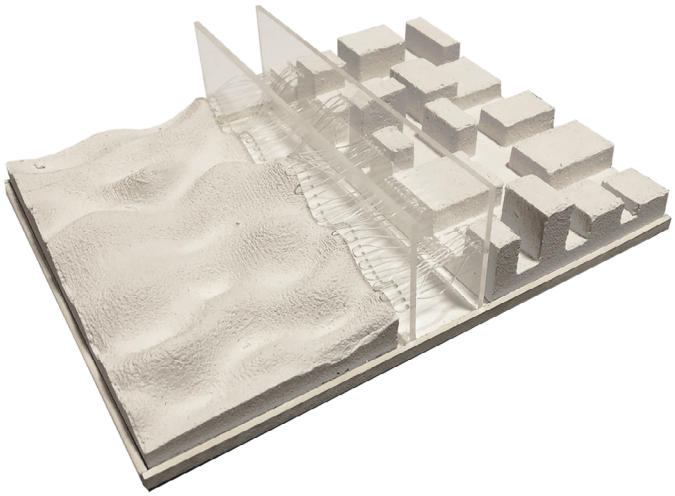
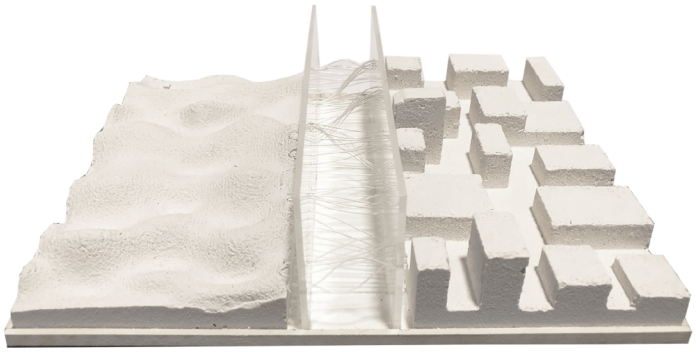


Fig.2-19 Conceptual framework

Source: made by author





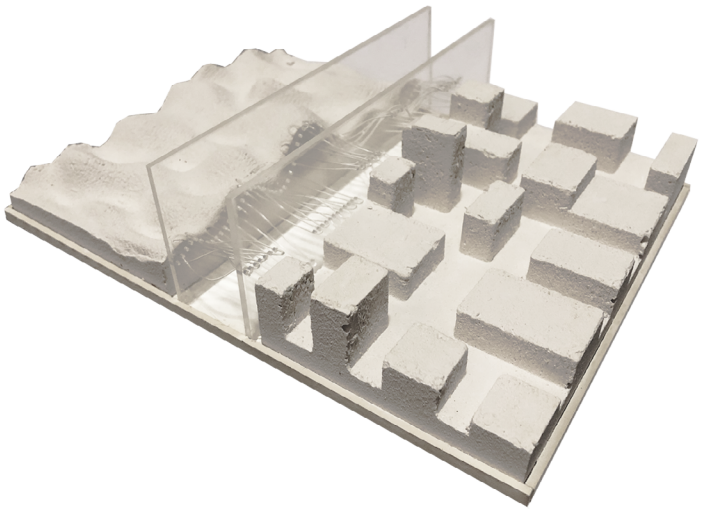


Fig.2-20 Conceptual model

Source: made by author

2.6 Research Methods

The project aims at undertaking the systematic approches in transforming the current coastal defence system, providing new opportunities for climate risks mitigation, ecosystem creation and urban development. So the methods of the project include a thorough analysis of the current theories and concepts, the dynamics of sea and urban on the scale of the Belgian Coastal Plain and city of Ostend, the status of the current coastal defence system, and the relation among sea, urban and defence system.

The main research methods used are listed below, which will be carefully explained in the corresponding research questions.

- **Literature Review**
- **Mapping**
- **GIS Analysis**
- **Transect**
- **3*3*3 Analysis**
- **Interview & Questionnaires**
- **Overtopping Calculation**
- **Observation**
- **Design Testing**
- **Risks Reduction Estimate**

SQ1 Background and Theoretical base

Q1
· What are the definitions of resiliency and adaptability for the coastal defence systems?

Q2
· What is the meaning of nature-based coastal defence solutions and why can it bring resiliency and adaptability?

Q3
· What are the limitation and potentialities of applying natrure-based solutions in extreme dense urban areas?

↓

Main Methods

Literature Review

Literature review in this stage aims to figure out the current challenges of conventional coastal engineering and why they are not resilient and adaptive. Thus the meaning of definitions of resiliency and adaptability for the coastal defence systems could also be clear. (Q1)

Another aim of this method is studying the transition of the Nature-based coastal defence solutions (NBS). In order to do so, related concepts such as Building with Nature, Ecosystem-based Coastal Defence solutions and Integrated Coastal Zone Management should also be reviewed, as well as the relation among them. By doing so, the deeper understanding of Nature-based solutions can be obtained. (Q2)

Besides, for filling the knowledge gap and broadening its range of applications, the limitation of NBS and its adaptation in extreme dense urban areas should be explored with the supportive theories like Delta Urbanism, Green and Blue Infrastructure, System Exploration Environment & Subsurface, etc. As a result, the theory paper would be written and the theoretical framework would be put forword for the future research. (Q3)

SQ2 Research and design in BCP and Ostend context

Q4
· What are the dynamics of the sea and the urban systems in BCP and city of Ostend, and what challenges will be brought about by these dynamics?

Q5
· What is the specific situation of the current coastal defence system in city of Ostend and what is the people's behaviors and awareness towards the risks?

Q6
· What are local impacts caused by the main challenges in city of Ostend?

Q7
· How to use nature-based solutions to transform the coastal defence system in Ostend and let it be a medium of integrating the dynamics of nature and urban systems?

Main Methods

- **Mapping**
- **GIS Analysis**

For the dynamics of the sea, the using of the GIS tool is necessary. By analyzing the sea level rise, storm surge, currents movement, patterns of erosion and accumulation, the main challenges from the sea side and the most vulnerable areas regard to these challenges can be mapped. (Q4)

- **Mapping**
- **3*3*3 Analysis**

For the dynamics of the urban, 3*3*3 analysis can be applied to analyze the urbanization process, the transition of infrastructure and landscape. Besides, the geological situation (soil type, elevation and permeability) and the economic situation (density, landuse, water management, social patterns) should also be mapped for identifying the most risky areas in the urban side. (Q4)

- **Transect**
- **Observation**

Interview & Questionnaires

The current defence system can be studied by transect and observation, to figure out what it includes, how it works and what is the relation between the defence system, the sea and urban.

As for the people's behaviors and awareness, the methods such as observation and interview & Questionnaires have been used through two field trips. The Interviewees include a local resident, a holiday person and a person from municipality of Ostend. (Q5)

Overtopping Calculation

The calculation of the maximum individual overtopping volume per meter run of the seawall can be used for the quantification of local impacts caused by the challenges. (Q6)

Design Testing

Risks Reduction Estimate

Based on the the theoretical framework and the above analysis, the micro & nano scale design tests can be carried out to find out how to apply Nature-based Solutions in extreme dense urban areas pratically. After that, the method of Risks Reduction Estimate could be used for evaluation. (Q7)

SQ3 Further impacts and reflection

Q8
· What values the broader influences can the new coastal defence system bring to the BCP and the North Sea areas?



Main Methods

Mapping

Summarize and analyze the different values brought by the testing design areas and reflect them on larger scale maps to show the broader impacts and influences. (Q8)

2.7 Methodological Framework

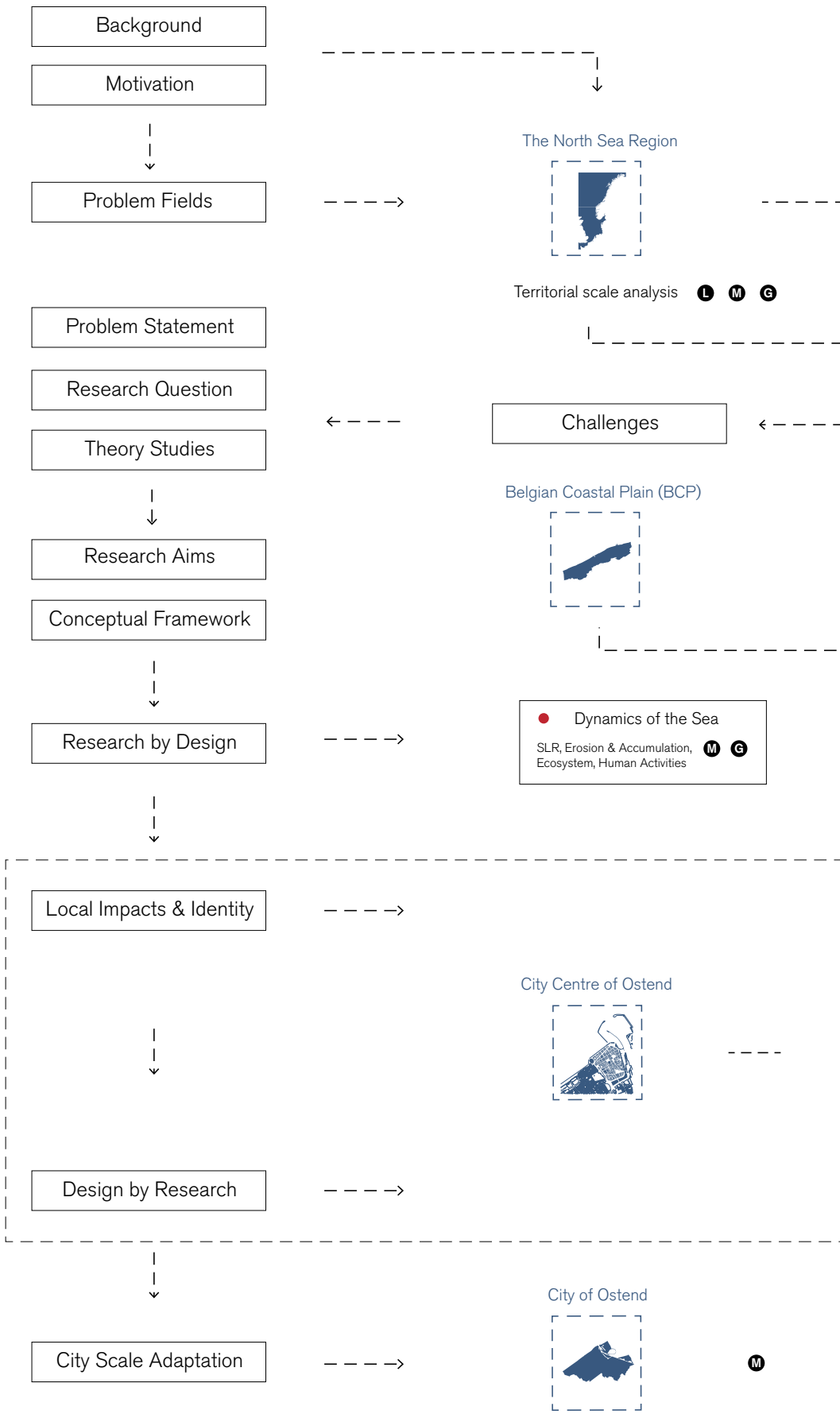


Fig. 2-21 Methodological framework

Source: made by author

Belgian Coastal Plain (BCP)



Macro scale analysis L M G

City of Ostend



Meso scale analysis L M G

City of Ostend



Dynamics of the Urban

Expansion, Density, Functionality, Landscape M G 3

Transition of the Coastal Defence

Current Situation, Existing Projects, Challenges M T O

Local Impacts

Local overtopping calculation under different senarios M C T

Local Identity

Spatial characteristic, Societal characteristic, Human behavior O I

Periods Division

Transitional Period, Strengthening Period, Risky Period, Limited period

Design Testing

Concept, Strategies, Interventions D

Transition Projection

Coastline, Coastal landscape, Risks reduction, Human experience M R

Conclusion

L Literature Review
O Observation
M Mapping
D Design Testing
G GIS Analysis
3 3*3*3 Analysis
T Transect
C Overtopping Calculation
I Interview & Questionnaires
R Risks Reduction Estimate



Fig.3-1 Rozenburg wind wall

Source: Photo by the author

03 Theoretical Fields

3.1 Defining NBS by Existing Theories (Overview)
3.2 Theoretical Framework
3.3 Abstract and Conclusion of the Theory Paper

3.1 Defining NBS by Existing Theories (Overview)

Even though the transition from conventional engineering to more nature-based solutions has become an onging trends, the specific definition, requirements and scope of application of the Nature-based Coastal defence solution should be discussed more deeply and comprehensively. In order to explore it, related theories and concepts has been studied and the highlights has been pointed out.

Building with Nature

· The new Dutch approach to coastal and river works.
· The natural forces (e.g. the hydraulic forces, geological forces and atmospheric forces) can be used as part of the intervention (IADC, 2017).
· Extra opportunities for the development of nature and ecosystem services could be provided (IADC, 2017).

Ecosystem-based Coastal Defence

· Recognizing the full array of interactions within an ecosystem, including humans, rather than considering single issues, species, or ecosystem services in isolation (Temmerman et al., 2013).
· Creating or restoring the large coastal ecosystems to attenuate storm waves and surges, accumulating sediments with sea-level rise (Temmerman et al., 2013).
· Ecosystem has its own carrying capacities, time cycle and scale of application.

Integrated Coastal Zone Management

· The process for the management of the coast using an integrated approach, regarding all aspects of the coastal zone, including geographical and political boundaries, in an attempt to achieve sustainability.
· Integrating all relevant policy areas, sectors, and levels of administration, considering the terrestrial and marine components of the target territory in both time and space, seeking over the long-term to balance environmental, economic, social, cultural and recreational objectives, all within the limits set by natural dynamics(Wescott, 2004).

Delta Urbanism

· Human territories have the ever-changing interrelations between socio-ecological systems, which requests complex thinking about the uncertainties (Meyer et al., 2015).
· The essence of the complex adaptive system (CAS) approach is that an urbanized delta is perceived as a complex and dynamic whole made up of different component parts (sectors) which continually influence one another and together as a whole are influenced by many different types of social, biological and physical developments (Giacomoni, Kanta & Zechman, 2013)
· The 'CAS' is a dynamic open system integrated with different subsystems.

Green and blue infrastructure

· The integration of urban landscape and water management that contributes to the climate adaptation, biodiversity, air quality, sustainable energy production, etc (Pötz & Bleuzé, 2012).
· Consists of small interventions based on green & blue patches in the urban areas.

System Exploration Environment & Subsurface

· The subsurface is a technical space, the "engine room of the city," that incorporates the vital functions of water and energy supply, communication systems, sewers and drainage (Hooimeijer & Maring, 2018).
· The integration of the surface and the subsurface systems in urban planning and design can offer us more potentialities to tackle the current trends such as climate change and energy transition (Hooimeijer & Maring, 2018).
· The surface and subsurface should not only coexist but work together (Hooimeijer & Maring, 2018).
· The System Exploration Environment and Subsurface (SEES) is an innovative systems approach that can help us gain a better understanding of the relation between surface and subsurface (Hooimeijer & Maring, 2018).

3.2 Theoretical Framework

Through the above theoretical research, the theoretical framework of the thesis can be formulated by two parts in the context of climate change effects and socio-economic change impacts.

The first is about the original understanding of Nature-based coastal defence solution, includes the different typologies, the Principle – 'Building with Nature', Spatial implementation – 'Ecosystem-based Coastal Defence', Governance – 'Integrated Coastal Zone Management' and the key factors (carrying capacities, time cycle and scale) that need to be taken into consideration.

The second part is when it is applied to the dense urban contexts, a broader and more comprehensive theoretical basis is needed. Thus, related theories like Delta Urbanism, Green & Blue Infrastructure and System Exploration Environment & Subsurface can be studied and considered for the adaptation.

At the same time, due to the complexity and uncertainty of the coastal urban system, the theories of Open-ended Design and Complex adaptive system will run through all stages of research and design.

In order to further explain the origin of this framework and the relationship between the different elements within it, a theory paper is written and showed following.

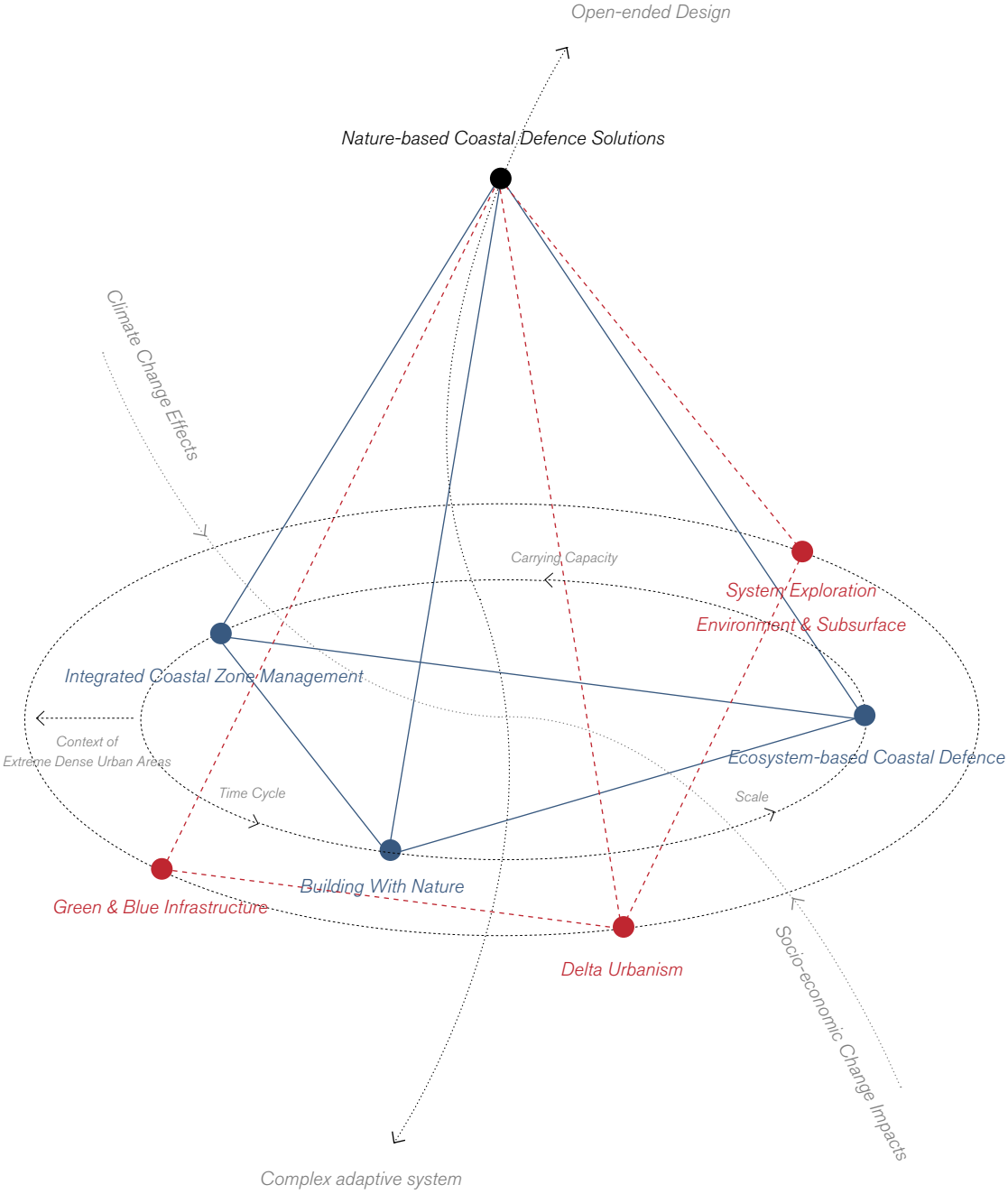


Fig.3-2 Theoretical framework

Source: Made by the author

3.3 Abstract and Conclusion of the Theory Paper

Title

From resistance to coexistence:
The transition to nature-based coastal defence solutions and their adaptation in extreme dense urban areas

Abstract

The coastal areas always play a crucial role in the economic, social and political development of most countries; they support diverse and productive coastal ecosystems that provide valuable goods and services (Airoldi et al., 2005). On the other hand, climate change as an existing and accelerating fact, carrying out a series of ripple effects such as sea level rise and extreme weather. Because of the particularity of geographical location, such climate changes effects have the most direct and strong impacts on the coastal zone, which includes but not limited to coastal erosion, flooding, salinization and landward retreat. In many coastal areas, the conventional coastal engineering solutions such as sea walls are increasingly challenged by these changes and their maintenance may become unsustainable (Temmerman et al., 2013). To cope with this challenge, the transition to more nature-based coastal defence solutions has already taken place by integrating the ideas of Building with Nature, Ecosystem-based Coastal Defence and Integrated Coastal Zone Management. However, these interventions mainly rely on the dynamics of large-scale natural and ecological systems, which requires relatively large and open space for implementation. When they are applied to extreme urban areas, there are always certain knowledge gaps and limitations.

This paper firstly introduce the existing coastal defence approaches and two concepts of solutions based on these approaches. Then, it addresses the current challenges faced by conventional coastal engineering due to the climate change effects. Further, on the basis of theoretical research, the current transition to nature-based defence solutions are put forward as well as their limitations. Following that, the paper discusses the particularities of coastal extreme urban areas and the key elements to be taken into consideration when applying these solutions. As a conclusion, the theoretical framework and principles of adaptation of nature-based coastal defence solutions in extreme dense urban areas are proposed for new direction for the future research.

Key words

Coastal defence, coastal urbanization, nature-based solutions, ecosystem services

Conclusion

Because of the climate change effects and socio-economic demands, the coastal defence solutions are facing the transition. The concept of Nature-based Coastal Defence Solutions (NBS), as a new trend of defence system intervention, has been experiencing a wider and frequent application due to its long-term sustainability. However there are still limitations especially when it is applied in the extreme dense urban areas. As a result of the natural dynamics and processes, the limitations lie in two aspects, the spatial limits and the temporal limits.

On the other hand, after studying the coastal urban system and its related theories, it is also clear that there are potentialities of overcoming the limits.

Based on the discussion, the first conclusion can be summarized by the diagram of theoretical framework. Basically, NBS has its own theoretical basis (Building with Nature, Ecosystem-based Coastal Defence and Integrated Coastal Zone Management) and the main factors (carrying capacities, time cycle and scale) that need to be taken into consideration.

And when it is applied into the dense urban contexts, related theories like Delta Urbanism, Green & Blue Infrastructure and System Exploration Environment & Subsurface can be supportive for the adaptation.

Secondly, based on the theoretical framework, the proposal principles of this adaptation are put forward for further research.

1. Combination of 'sustainable' engineering and NBS.
Transforming the conventional coastal engineering to be more sustainable and multifunctional (For example, it can be integrated with energy production, creatures habitats and recreational function). Combining engineering and ecology to provide short-term urgent defence and long-term eco-services and development.

2. Multi-scale strategies and local, small-scale, scattered intervention.
Because the creation and effects of ecosystems can not limited to single scale, strategies in different scales are needed. When it comes to the urban scale, the existing blue-green system and underground space can be made use of to build up the whole ecosystem by small parts, combining small- scale intervention with large-scale connectivity. For example, buffer stripes, habitat connection and wildlife corridors are common approaches to create the ecosystem in the urban context.

3. Coastal defence system as a transitional zone between sea and urban.
Regarding the sea and coastal urban areas as a whole ecosystem, so the coastal defence system can act as a gradient medium that integrate the dynamics of both sea and urban, mitigating the coastal risks and at the same time taking on some urban functions.

4. From Integrated Coastal Zone Management (ICZM) to Adaptive Integrated Coastal Zone Management (AICZM).
As the integration of NBS and urban systems should be a long-term vision, AICZM offers the evaluation and adaptation stage based on multiple scenarios making, long-term modelling and monitoring, ensuring the consistent and coherent governance after the implementation and offers experience for future improvement.

Full version of the paper in Appendix 1



Fig.4-1 Wadden sea

Source: Photo by the author

04 Dynamics of the Sea

4.1 Climate Change Effects
4.2 Coastal Flooding
4.3 Coastal Change
4.4 Coastal Ecosystem

4.1 Climate Change Effects

CLIMAR-project projection

The effects of a changing climate are already perceptible and predictable. Despite uncertainties about the timing and magnitude of the changes associated with global warming, the problem of global climate change has become one of the most important environmental issues facing the world today. Scientific research has revealed that even when the emission of greenhouse gases decreases the impacts of climate change will be inevitable (Solomon et al. 2007). Therefore it is necessary to assess which climate change effects the Belgian coast will undergo.

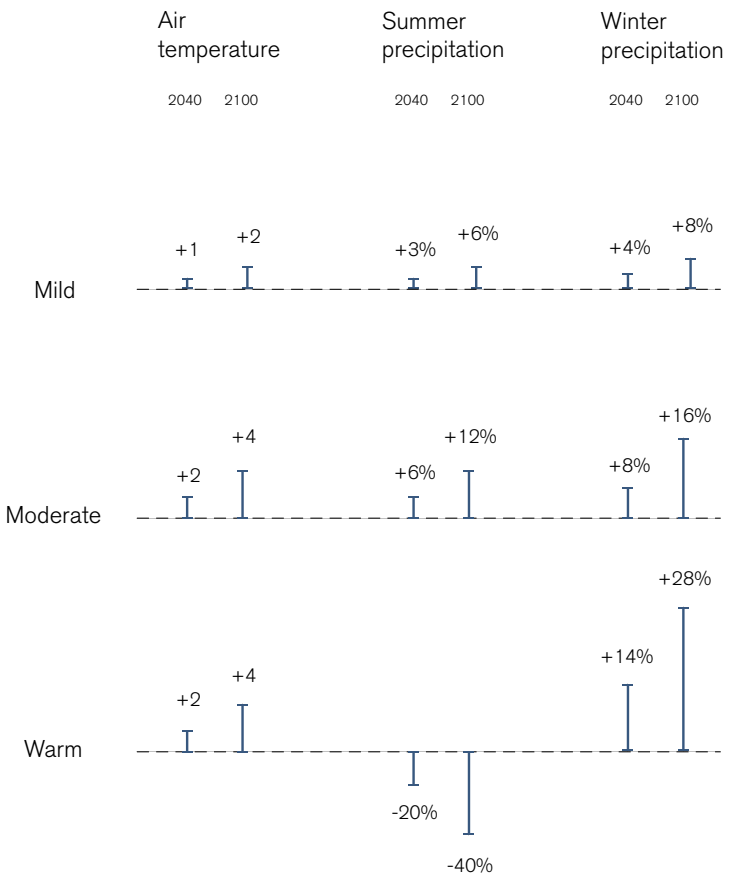
Almost 85% of the Belgian coast lies under 5m elevation, which makes the Belgian coast one of the most vulnerable coastlines in Europe, and makes the question: how to deal with climate change, even more pressing. It is now known that climate change will make coastal zones even more hazardous. The most consistent effects will be due to sea level rise.

A Study carried out within the CLIMAR-project by the Management Unit of the North Sea Mathematical Models (MUMM) to assess the impacts of climate change for the Belgian part of the North Sea shows that it is likely to experience a greater incidence of storm damage and flooding in vulnerable coastal areas.

Though the exact impacts of climate change are difficult to predict, the study has made use of scenarios to make assumptions on the future. According to this study, 3 main scenarios for 2040 and 2100 are concluded in this thesis: a mild scenario, a moderate scenario and a warm scenario.

In the mild and moderate scenarios, there is no significant change in air circulation patterns, and the precipitation increases both in summer and in winter with about 3% per °C of air temperature increase. The expectations are that in 2040 the sea level will rise up to 30 cm in the mild scenario, in the moderate scenario up to 40 cm and in the worm case scenario up to 50 cm. The expectations for 2100 are a sea level rise of 60 cm in the mild scenario, 90cm in the moderate scenario and 2m in the warm scenario (CLIMAR 2008a).

Sea level rise is an important indicator of climate change in coastal regions. At the Belgian coast it will increases the likelihood of flooding and coastal erosion.



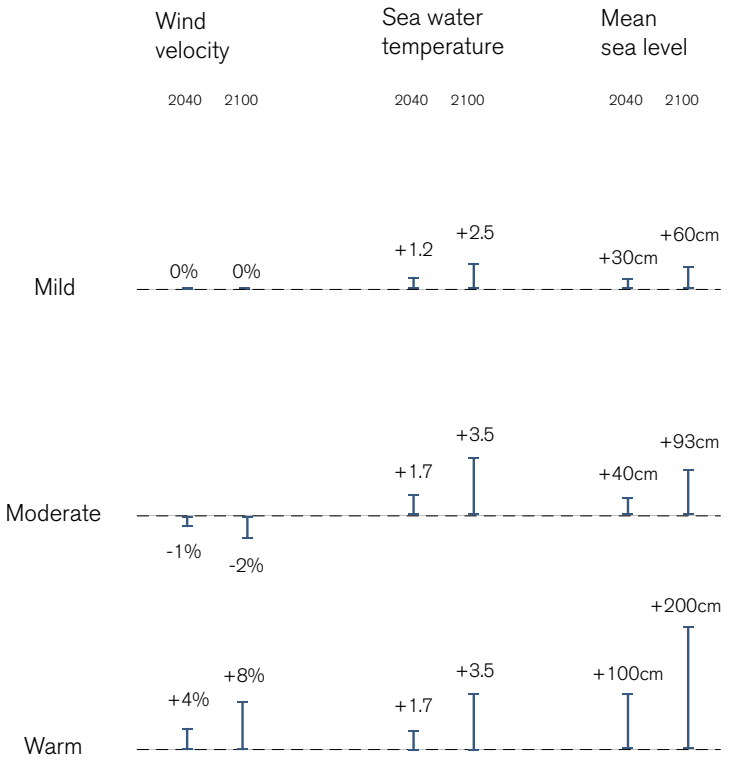


Fig.4-2 Climate change senarios in CLIMAR-project

Source: Made by the author based on CLIMAR 2008

Jim Hansen projection

The more extreme climate senarios comes from Jim Hansen. He and his research team also predicted the future climate change and sea level rise by using numerical climate simulations, paleoclimate data, and modern observations to study the effect of growing ice melt from Antarctica and Greenland.

They hypothesize that ice mass loss from the most vulnerable ice, sufficient to raise sea level several meters, is better approximated as exponential than by a more linear response. Doubling times of 10, 20 or 40 years yield multi-meter sea level rise in about 50, 100 or 200 years (Hansen et al, 2016).

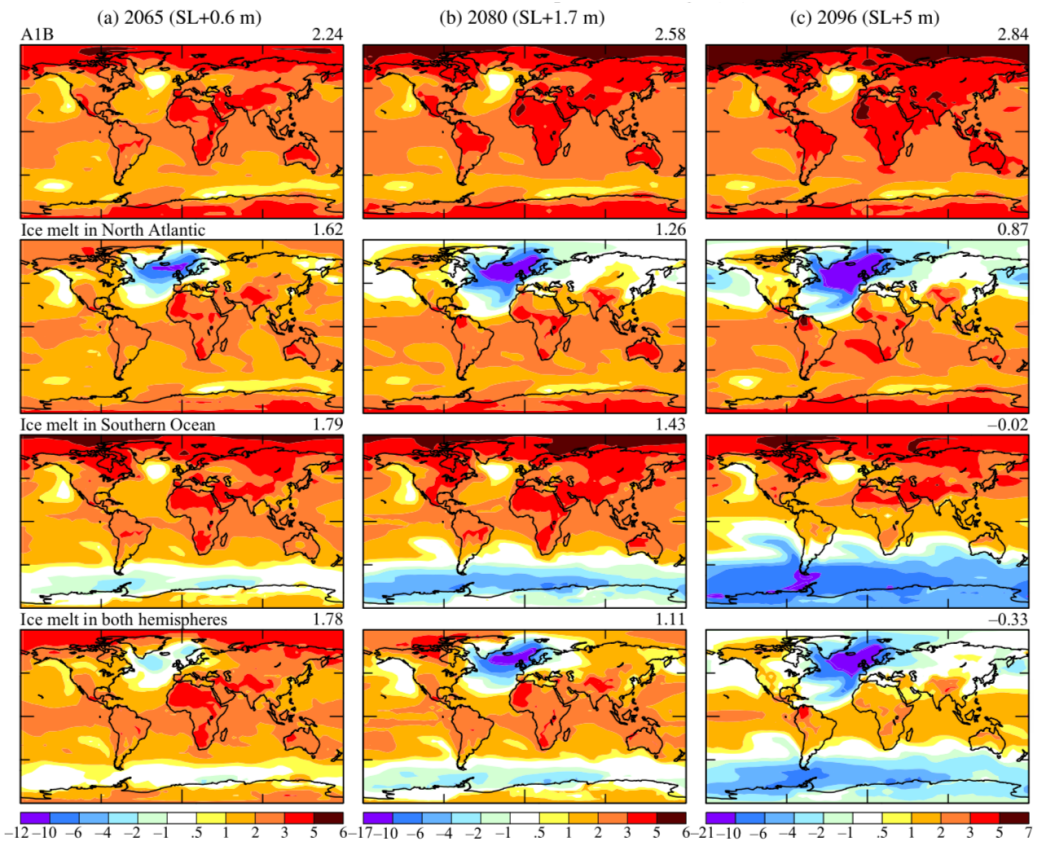


Fig.4-3 Surface air temperature (◦ C) relative to 1880–1920

Source: Hansen et al, 2016

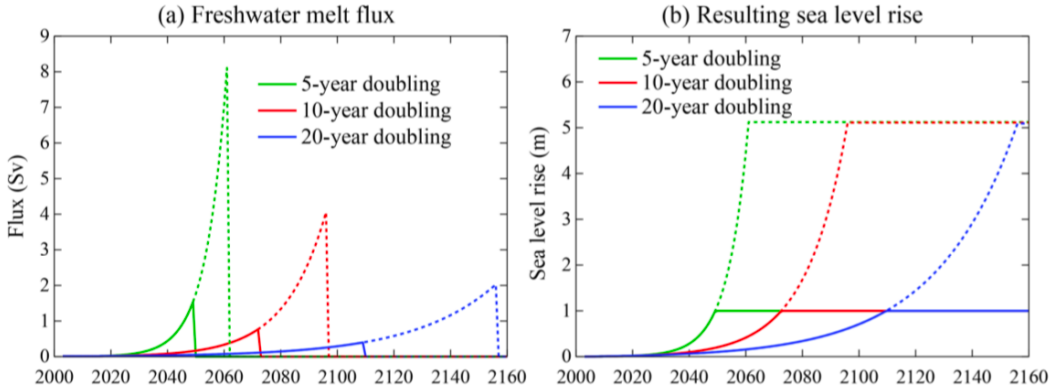


Fig.4-4 Jim Hansen sea level rise projection

Source: Hansen et al, 2016

Alexander Nauels projection

In addition to exploring the impact of the physical environment on climate change, another prediction from Alexander links the future sea level rise with socio-economic elements under the SSP model (Shared Socioeconomic Pathways).

Based on the SSP-FT framework, the research team not only analyzing future sea level rise under societal and economic developments, but also distinguishing between sea level rise projections for the baseline scenarios (with no mitigation measures) and scenarios with different levels of mitigation measures.

After the study, they made the SSP scenario-specific sea level rise projections for global mean sea level rise in 2100.

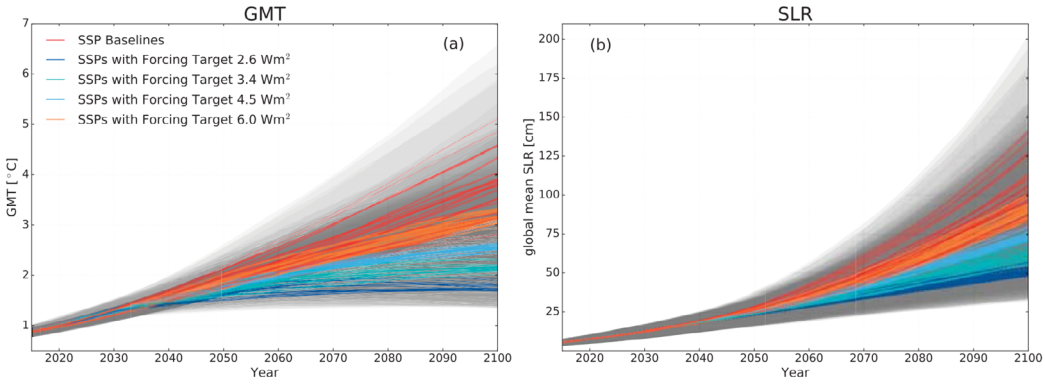


Fig.4-5 Probabilistic MAGICC global mean temperature (GMT) (a) and global mean sea level rise (SLR) projections (b).

Source: Nauels et al, 2017

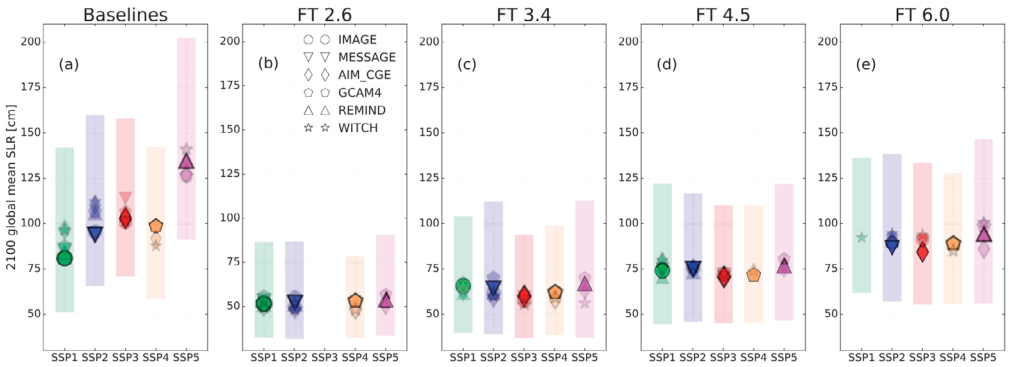


Fig.4-6 Flooding areas during an extreme storm in the current situation

Source: Nauels et al, 2017

Conclusion of the current climate change projection

From these predictions, we can see that the most extreme forecast of sea level rise is five meters rise in 2100.

4.2 Coastal Flooding

Historical storm surge events in Belgium

There are three serious storm surge events that are recorded in Belgium, respectively 1953, 2007 and 2013.

The 1953 North Sea flooding was a major flooding event caused by a heavy storm from 31 January night to 1 February morning. The floods mainly affected the Netherlands, Belgium, UK. During this event, the Flemish coastal defence was severely damaged. Near Ostend, Knokke and Antwerp, a lot of breaches was created to the sea wall. 28 people died in this event in Belgium.

In early November 2007 (8-9 November), an European windstorm Cyclone Tilo affected northern and western Europe. Combining the remnants of previous Hurricane Noel, this storm surge caused the serious flood event, affecting the coastal areas of the Netherlands, UK, Belgium, Germany, Norway and Denmark.

The Sinterklaas Storm was a heavy storm over 5 and December 6, 2013 Northern Europe drew, sometimes with hurricane force. In Belgium, Bredene evacuated 2083 residents of the neighborhood Sas Slijkens. Ostend was faced with the highest water level since the Flood of 1953. The water came up to 6.33 m TAW.

The historical strom surge events show that basically, the hightest water level during the storm events can reach nearly +7m TAW[1], around 3m higher than the high tide in the normal time. And the duration of the extreme water level before returning to the normal levels is more or less 48 hours.

1 TAW
Tweede Algemene Waterpassing
TAW is the reference point for which an altitude is expressed in Belgium. TAW +0 m equals the average sea level at low tide in Ostend, and it is 2.03m below MSL (mean sea level).

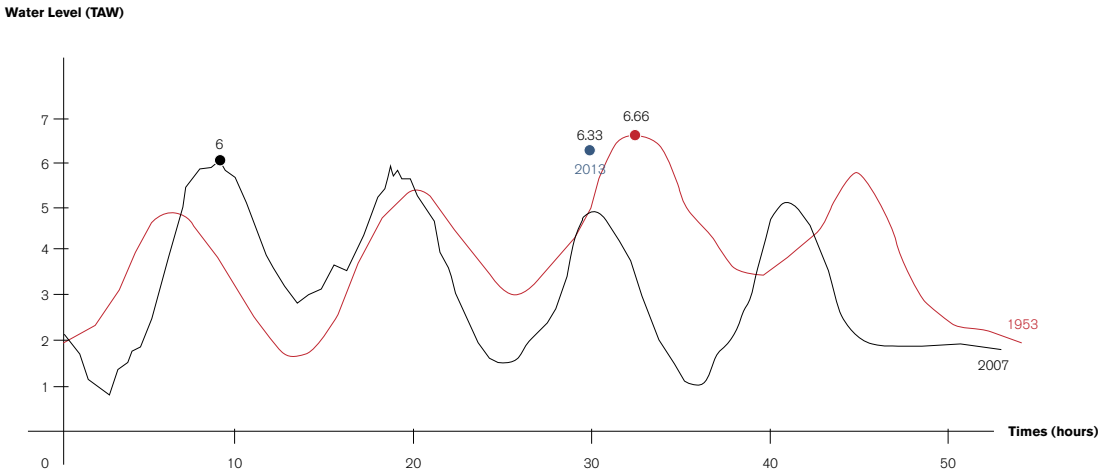




Fig.4-7 Ostend during 1953 strom

Source: https://www.deplate.be/trefwoorden/overstroming-1953



Fig.4-8 Overtopping event in Ostend

Source: Gysens et al, 2011



Fig.4-9 The pier and the seawall in Ostend during the Sinterklaasstorm in 2013

Source: http://www.planeetzee.be/lesmodule/8?page=8

Coastal flooding in Belgian Coastal Plain

In the light of the CLIMAR-project the Flanders Hydraulic Research has made some flood models to assess the effects of flooding at the Belgian coast. The flood models are calculated for an extreme storm with a flood level of +7 m TAW in Belgian Coastal Plain. This storm is the most extreme but still a realistic super storm.

By comparison, the known worst storm of the past 100 years, namely the storm of February 1, 1953, reached a flood level at Ostend of +6.66 m TAW. This is only 0.34 m lower than the +7 m TAW storm. Statistically, this Super storm has a return period of 1,000 years[1].

Here, the maps of flooding areas during the extreme storm based on different senarios of sea level rise (+7 TAW)

1 Storm return period in Belgium
+5 TAW year return
+5.5 TAW 5-year return
+6 TAW 20-year return
+6.5 TAW 110-year return
+7 TAW 1,000-year return
+7.5 TAW 4,000-year return
+8 TAW 17,000-year return

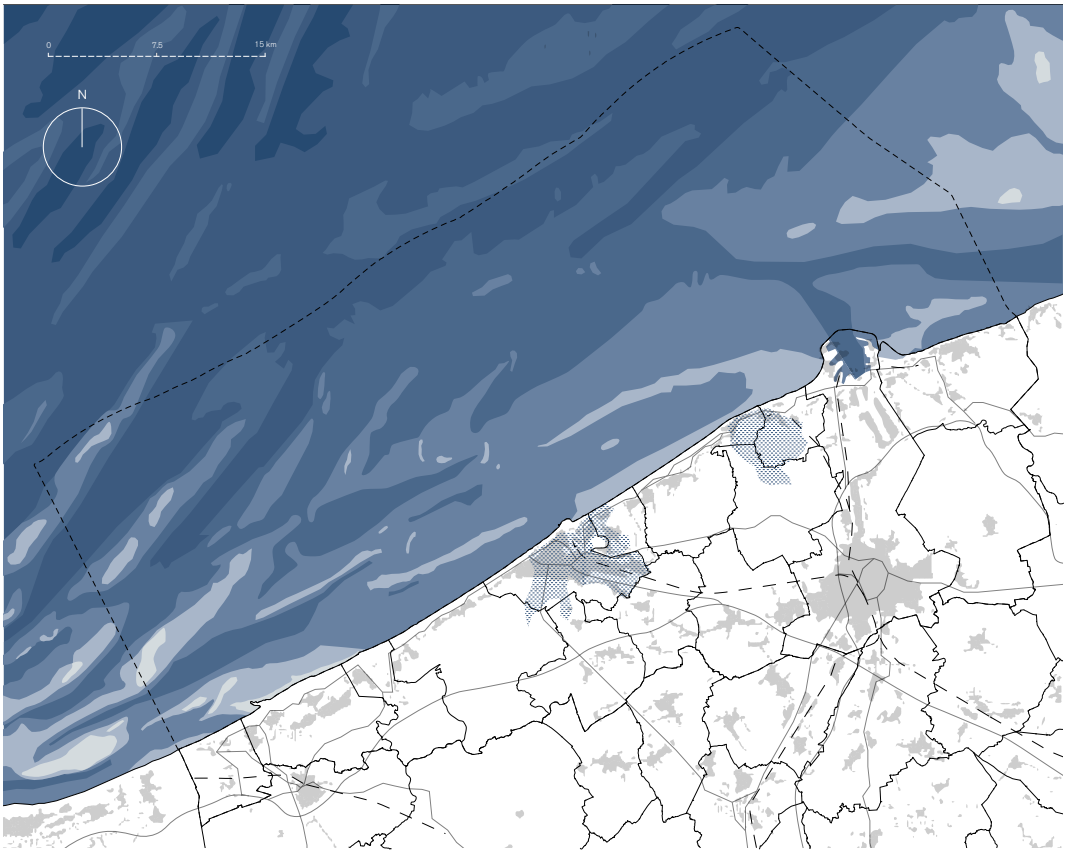


Fig.4-10 Flooding areas during an extreme storm in the current situation

Source: Made by the author based on kustportaal.be

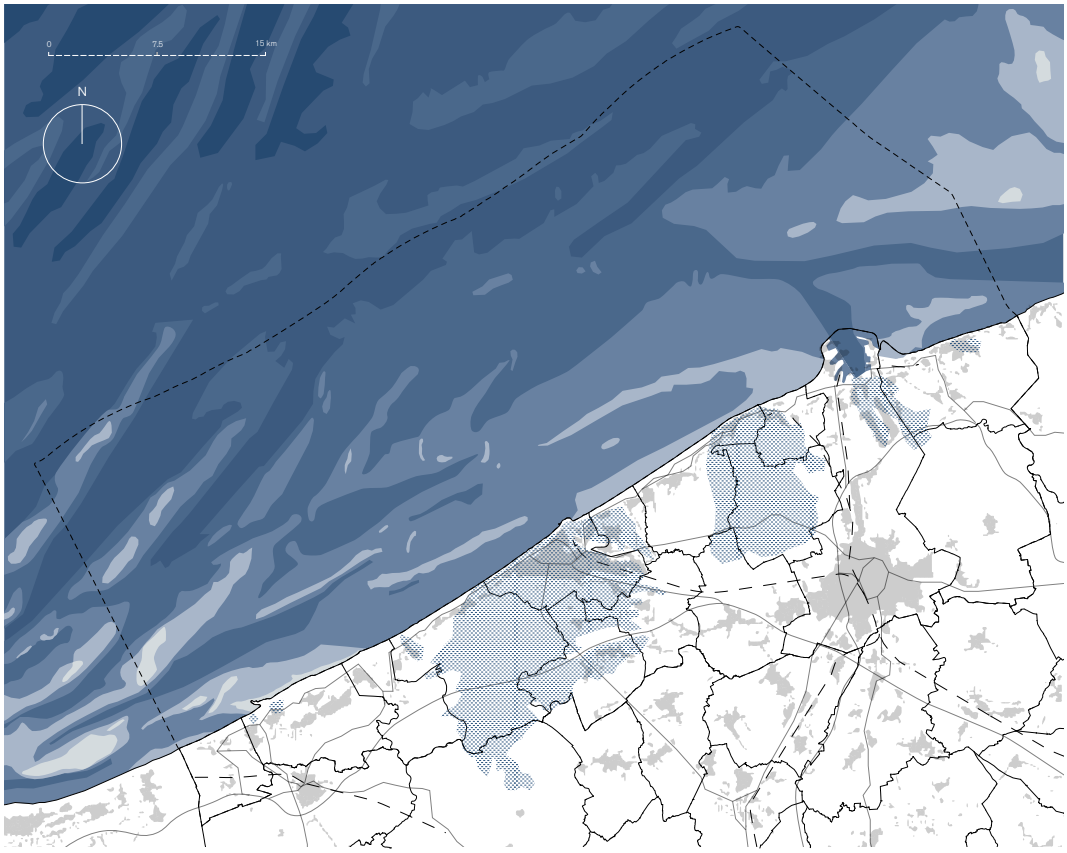
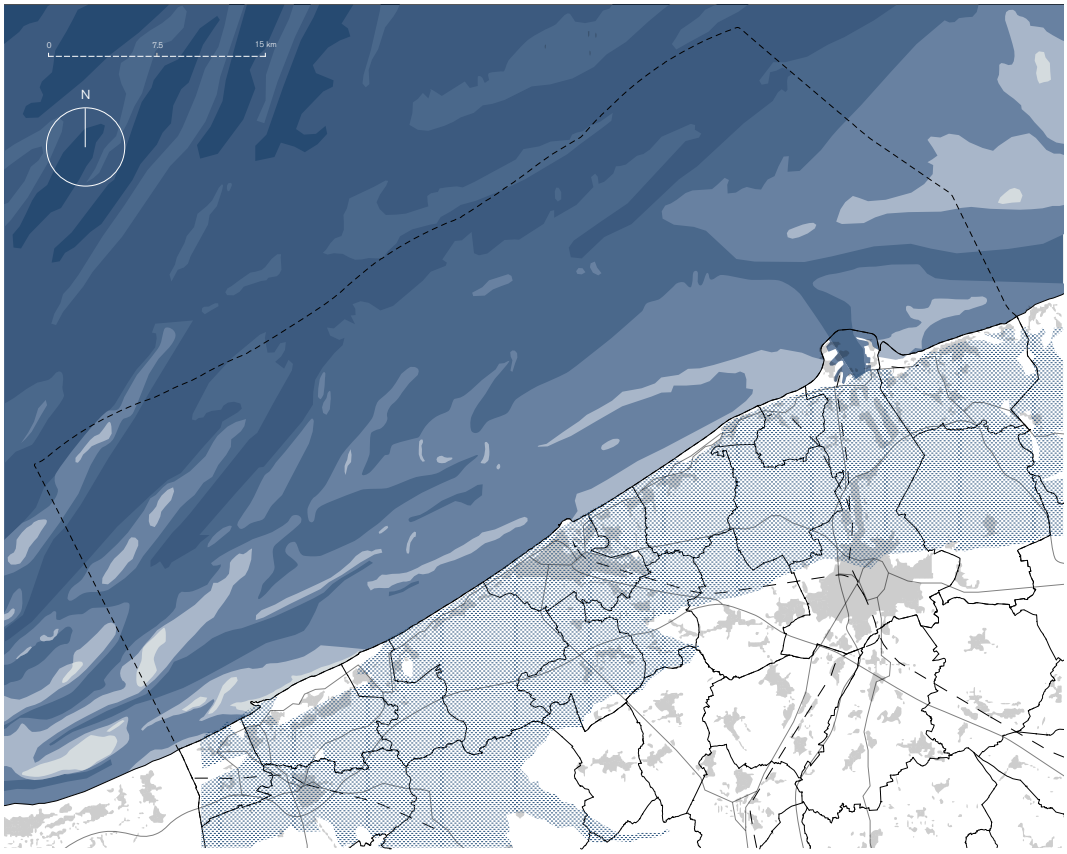


Fig.4-11 Flooding areas during an extreme storm with 1m SLR

Source: Made by the author based on kustportaal.be



1m

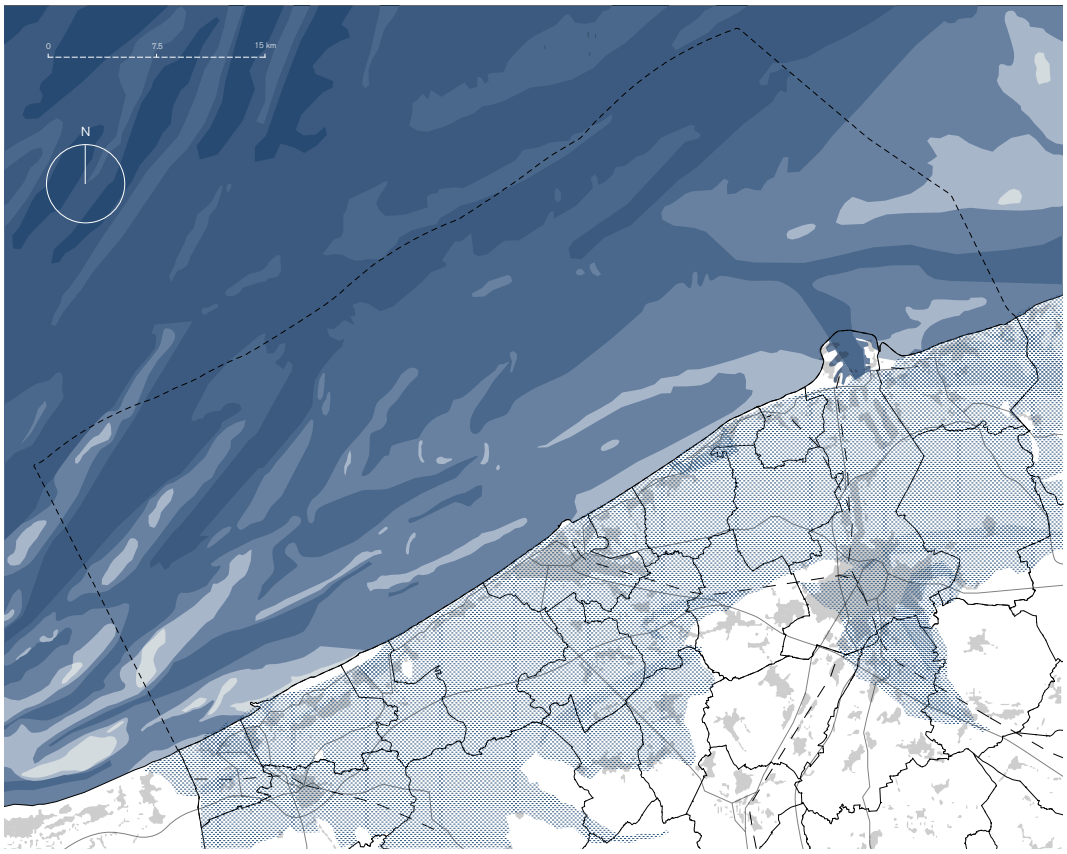
30m

Bathymetry

Flooding area

Fig.4-12 Flooding areas during an extreme storm with 2m SLR

Source: Made by the author based on kustportaal.be



1m

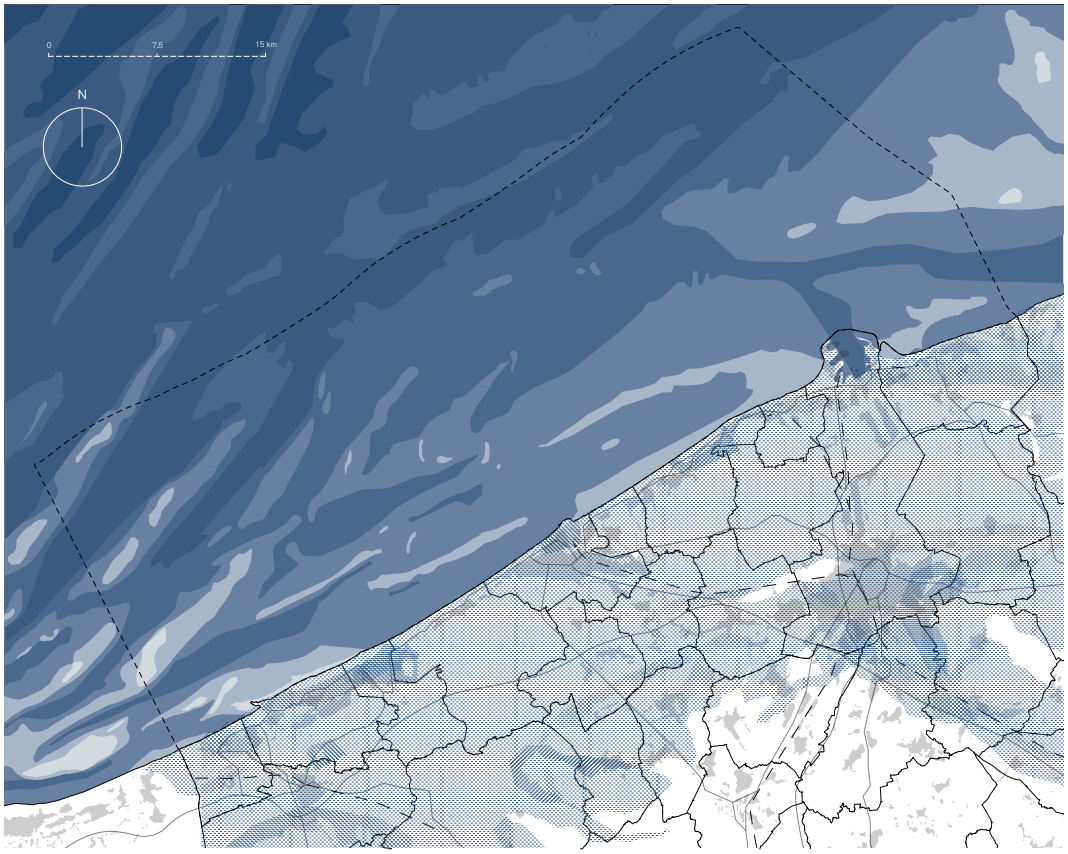
30m

Bathymetry

Flooding area

Fig.4-13 Flooding areas during an extreme storm with 5m SLR

Source: Made by the author based on kustportaal.be



1m

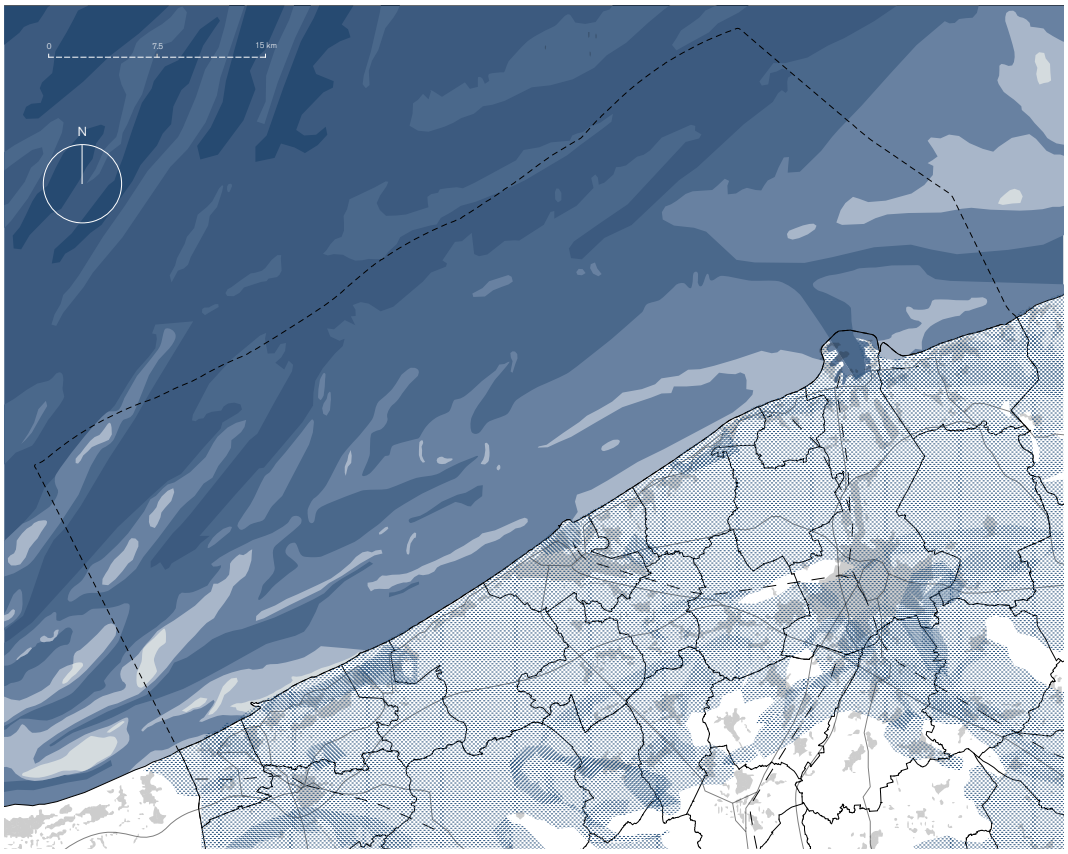
30m

Bathymetry

Flooding area

Fig.4-14 Flooding areas during an extreme storm with 7m SLR

Source: Made by the author based on kustportaal.be



1m

30m

Bathymetry

Flooding area

Fig.4-15 Flooding areas during an extreme storm with 10m SLR

Source: Made by the author based on kustportaal.be

Coastal flooding in city of Ostend

In order to balance protection and the investment and construction of coastal defence, the current minimum safety stantard in Belgium is preventing the strom with 1,000-year return period, which is +7m TAW storm surge.

Based on this standard, in the city of Ostend specifically, the coastal flooding risks are huge due to the breaches in the sea defences.

Here the flooding maps in Ostend with the SLR of current situation, 1m and 2m are presented. From these maps we can see clearly that even without the SLR, more than 30% areas in Ostend are under the risk of coastal flooding.

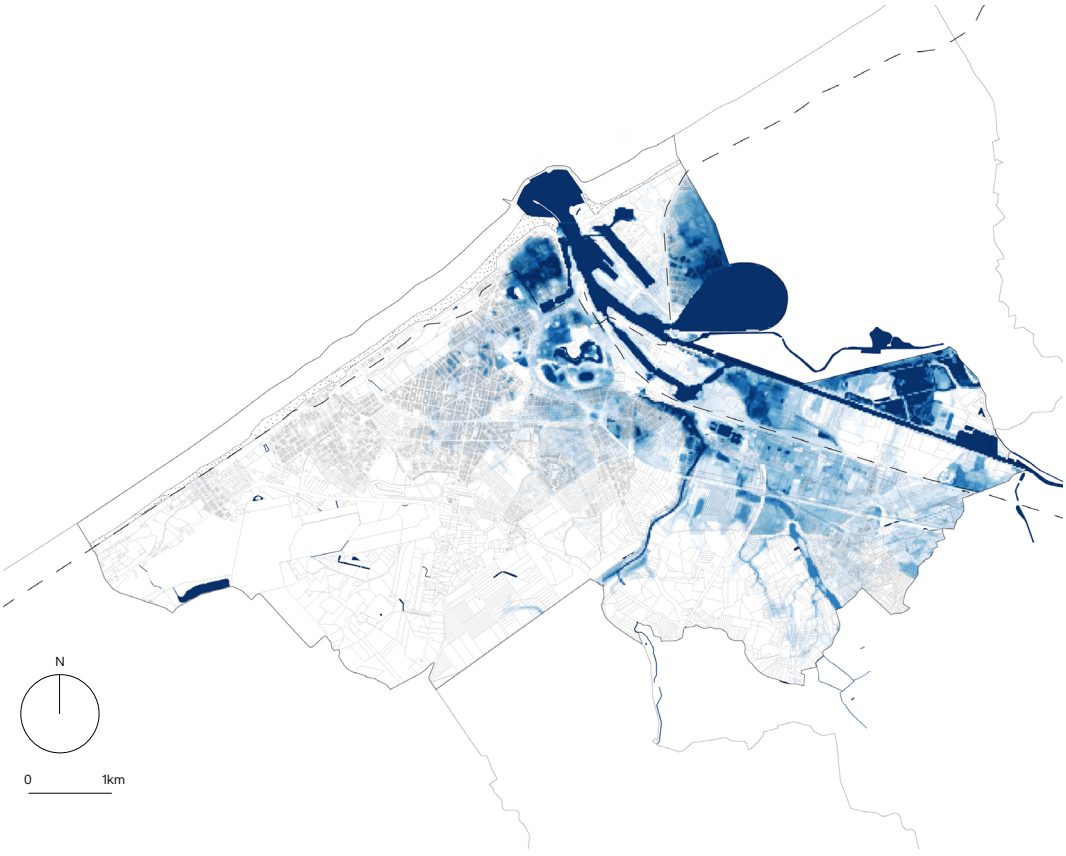
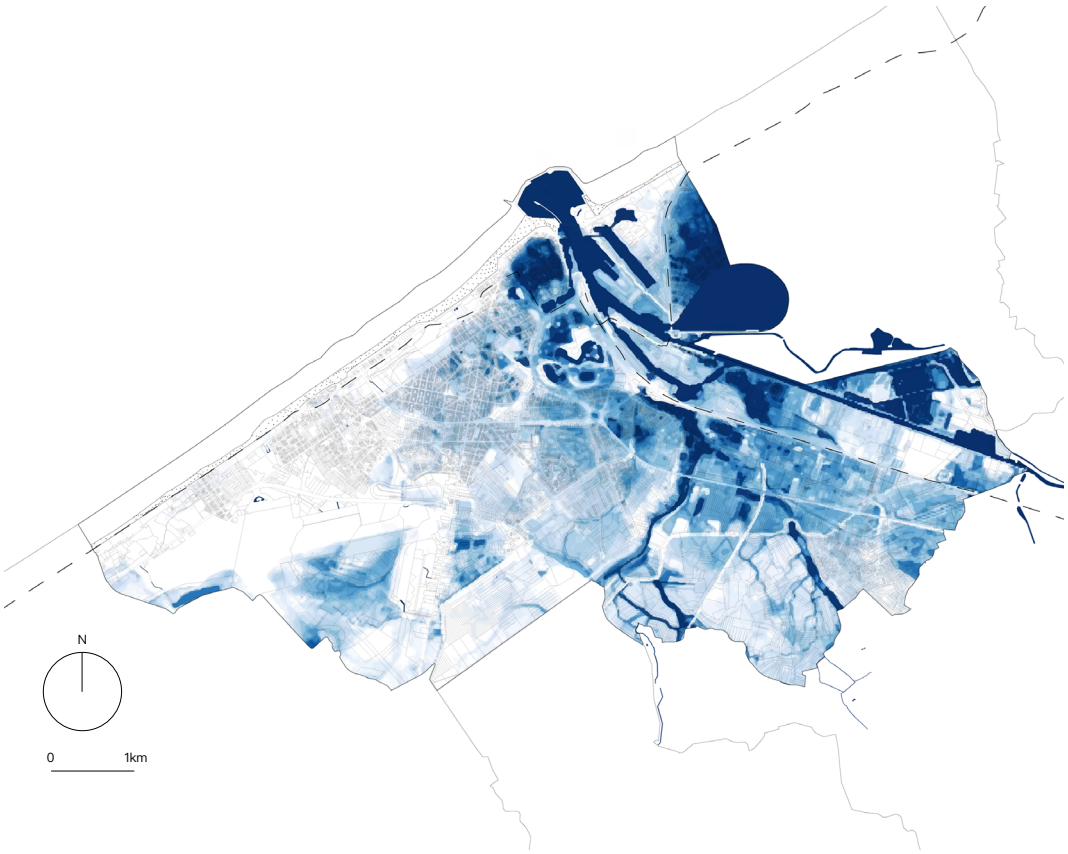


Fig.4-16 Flooding areas during a +7 TAW storm in the current situation

Source: Made by the author based on kustportaal.be

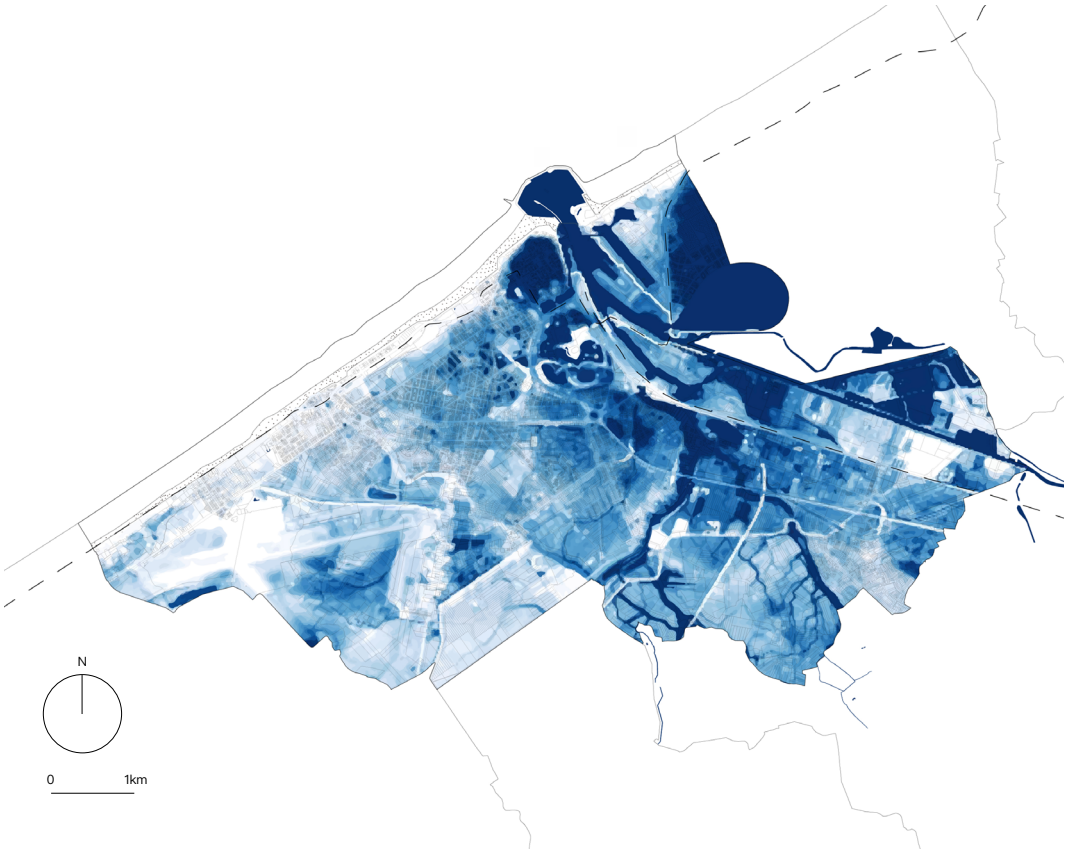


Municipality border

Flooding area

Fig.4-17 Flooding areas during a +7 TAW storm with 1m SLR in Ostend

Source: Made by the author based on kustportaal.be



Municipality border

Flooding area

Fig.4-18 Flooding areas during a +7 TAW storm with 2m SLR in Ostend

Source: Made by the author based on kustportaal.be

Trends

The Ostend MVB tidal station is one of the numerous gauging stations in Flanders that keep close watch on the Flemish watercourses, continuously registering water levels, flows and precipitation.

According to the data from MVB station, we can clearly see the trends of tidal height from 2000-2019.

The charts show that the frequency of abnormal water levels is rising significantly, which means even though theoretically speaking, the +7 TAW storm is with 1000-year return period, it could happen more frequent in the future.

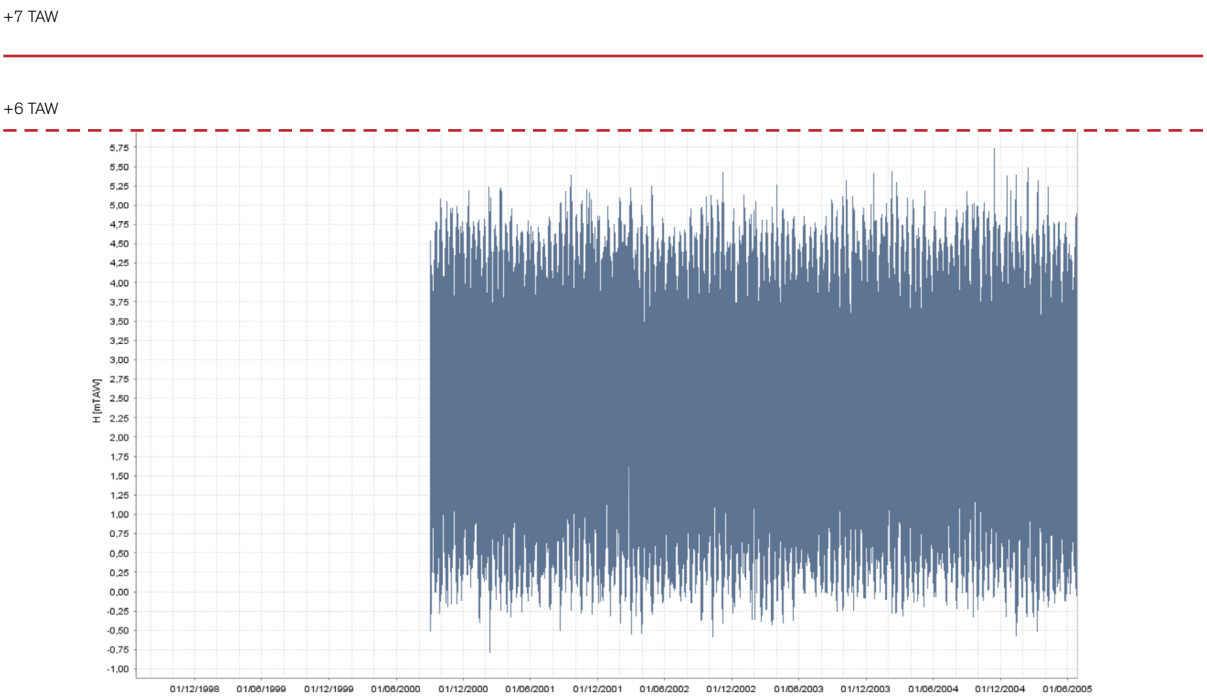


Fig.4-19 Tidal height in Ostend during 2000-2005

Source: waterinfo.be

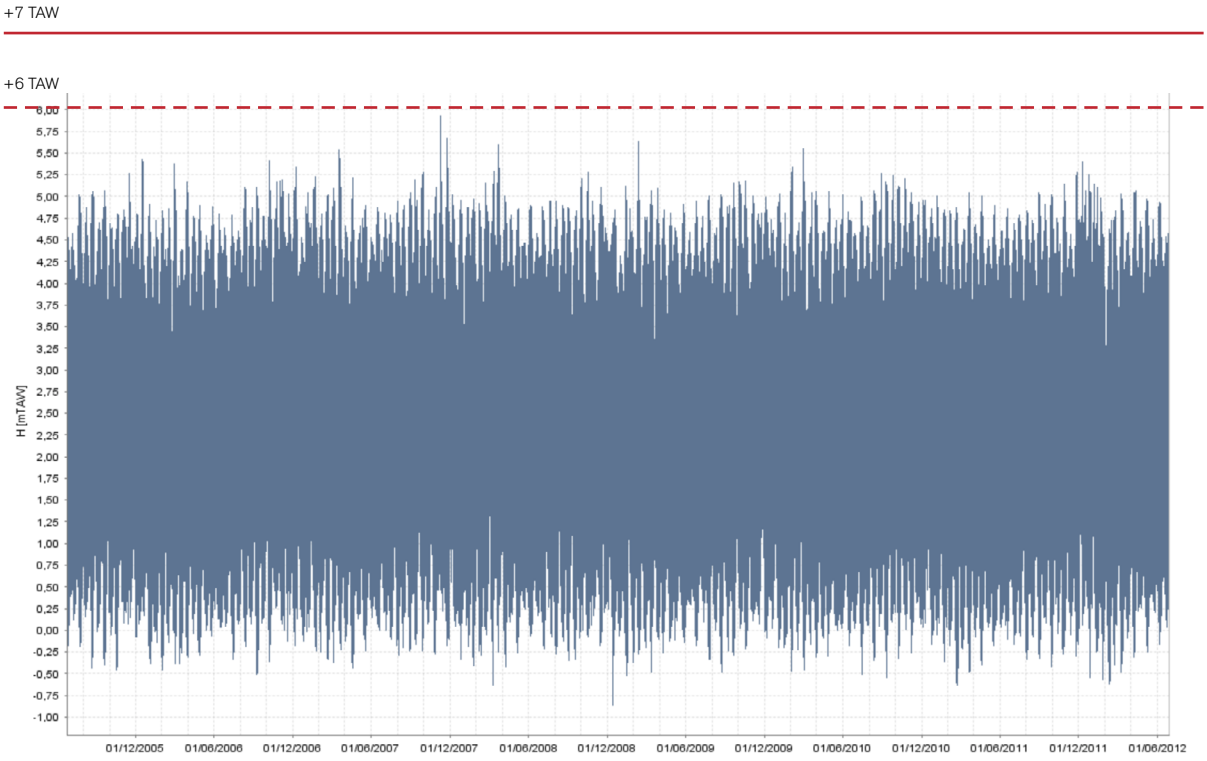


Fig.4-20 Tidal height in Ostend during 2005-2012

Source: waterinfo.be

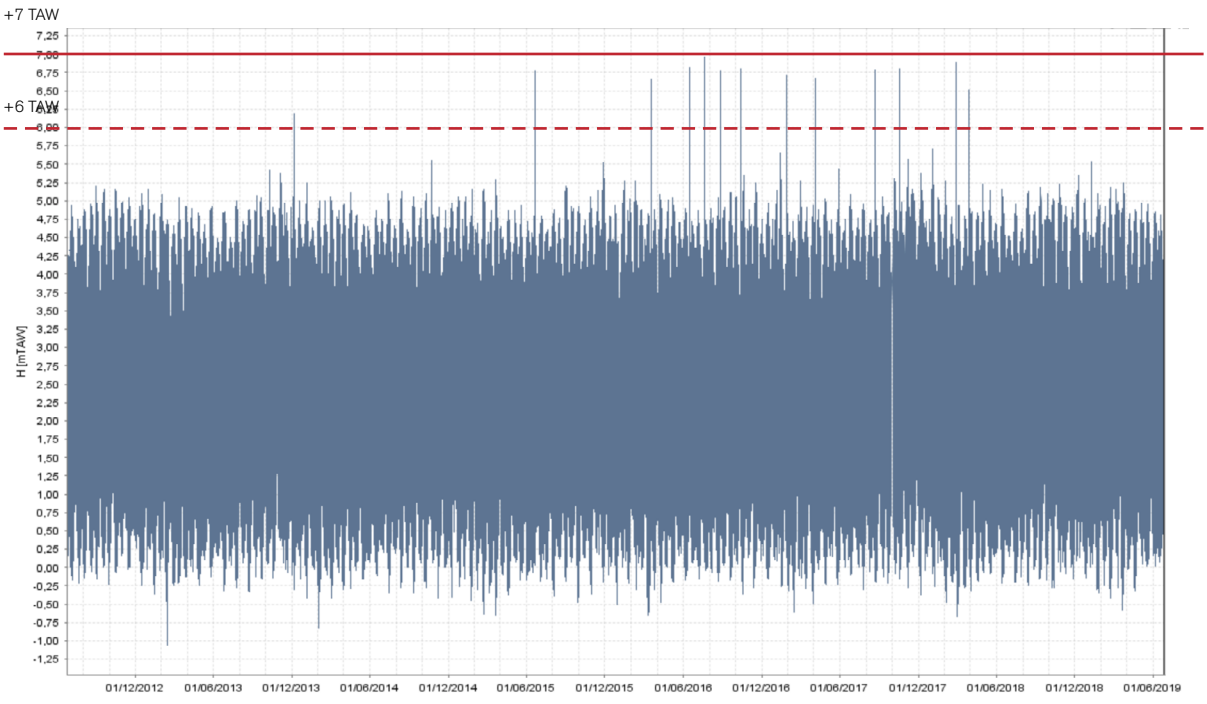


Fig.4-21 Tidal height in Ostend during 2012-2019

Source: waterinfo.be

4.3 Coastal Change

Geomorphology

The evolution of Belgian Coastal Plain is a process from the dynamics to the fixture. Based on the dominant way of influencing the coastline, the evolution of the coastline is mainly divided into three periods here, namely Natural dominant period, Balancing period and Human dominant period.

Natural dominant period

· Intertidal influences resulted in the diverse original landscape in the Belgian Coastal Plain (sand banks, dunes and intertidal zones).

· Due to the development of settelments and agriculture, land reclamations happened and polders and dikes came into being for development and protection. In this stage, the dikes were built according to the natural land form.

Balancing period

· With the development of human society, people began to further use the coastal areas, and the construction of dikes was closer to the shoreline also with other functions such as promenade.

· Some settlements were abandoned or rebuilt due to coastal flooding.

· Due to early land reclamation, a large number of forest landscapes emerged in the coastal plain close to the inland.

Human dominant period

· Due to the further development of human society, the coastal defence line moved further to the shoreline for the reasons of protecting the city. In the end, the shape of the coastline is basically the same as the artificial coastal defence line.

· High urbanization has reduced the diversity of the original landscape, while the rapid development of tourism, urban recreational industry and the change of coastal defence strategies have led to an increase in artificial sandy beach landscapes.



Fig.4-22 Belgian Coastal Plain in 500

Source: Made by the author

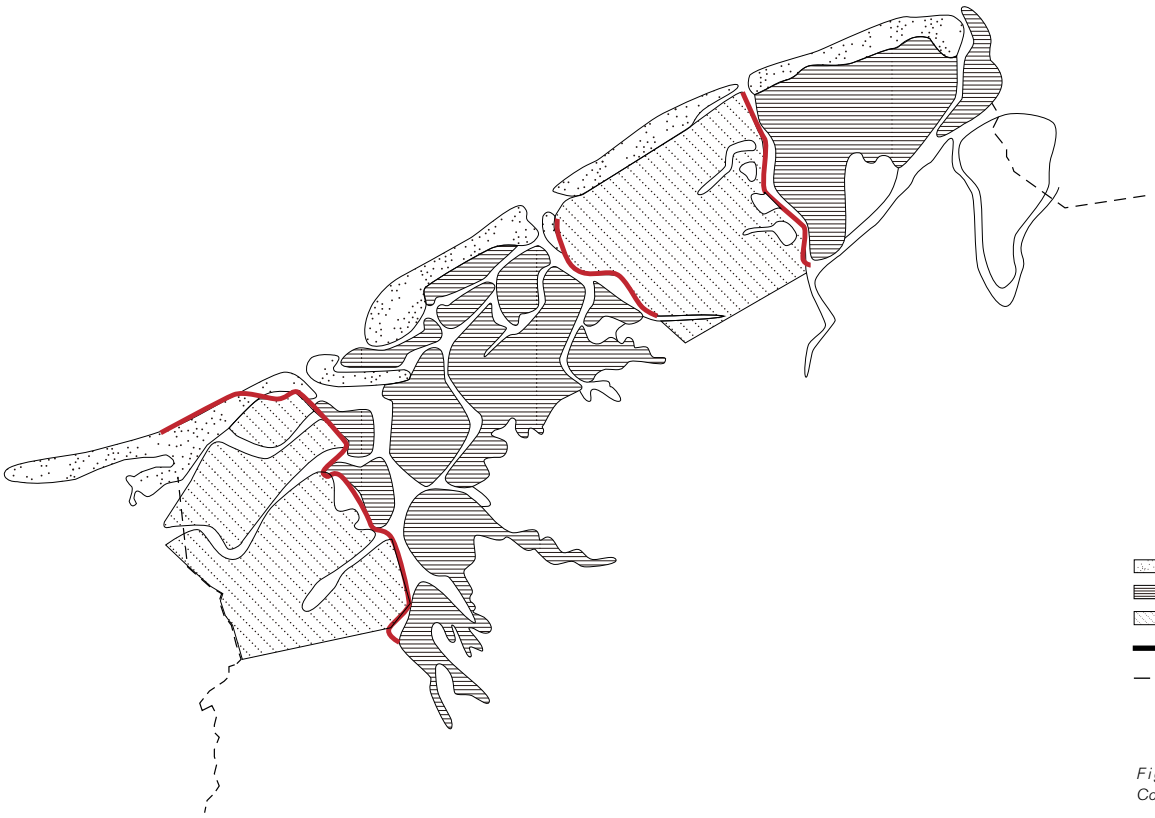


Fig.4-23 Belgian Coastal Plain in 1300

Source: Made by the author

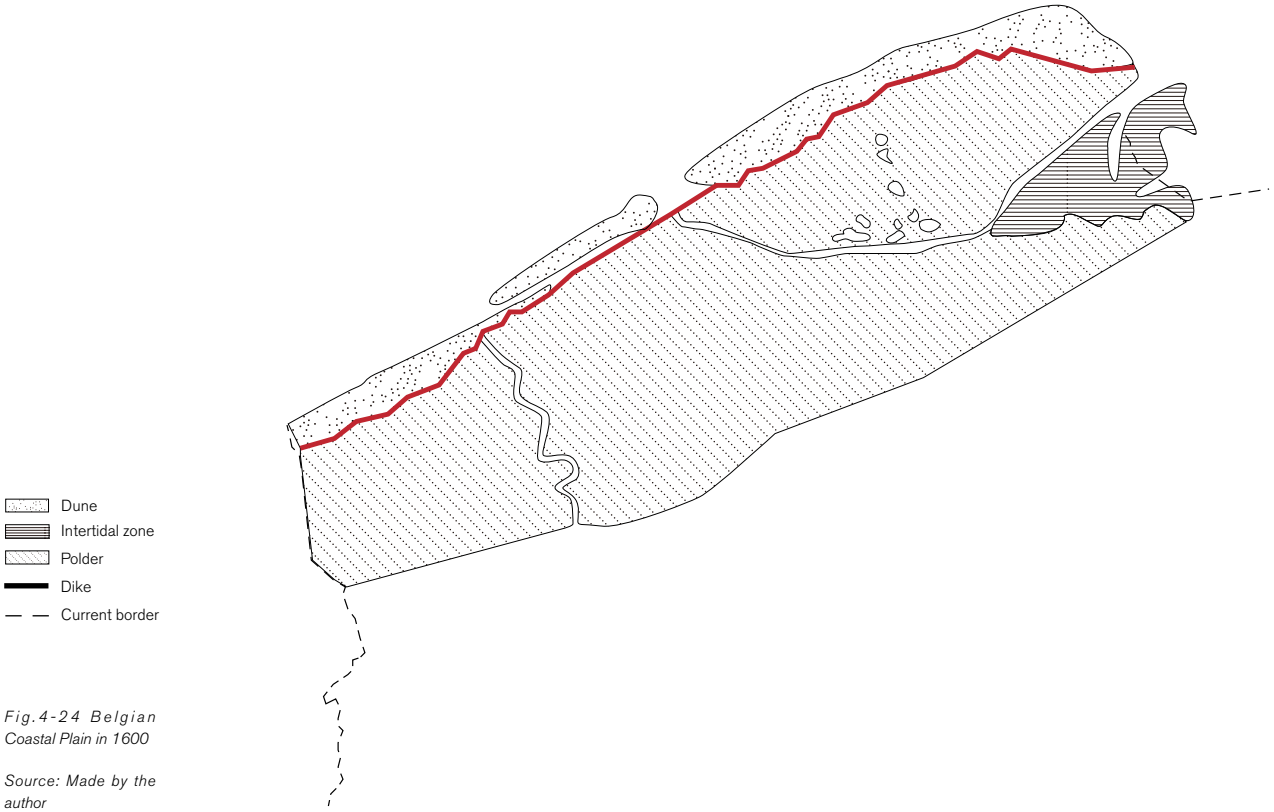


Fig.4-24 Belgian Coastal Plain in 1600

Source: Made by the author

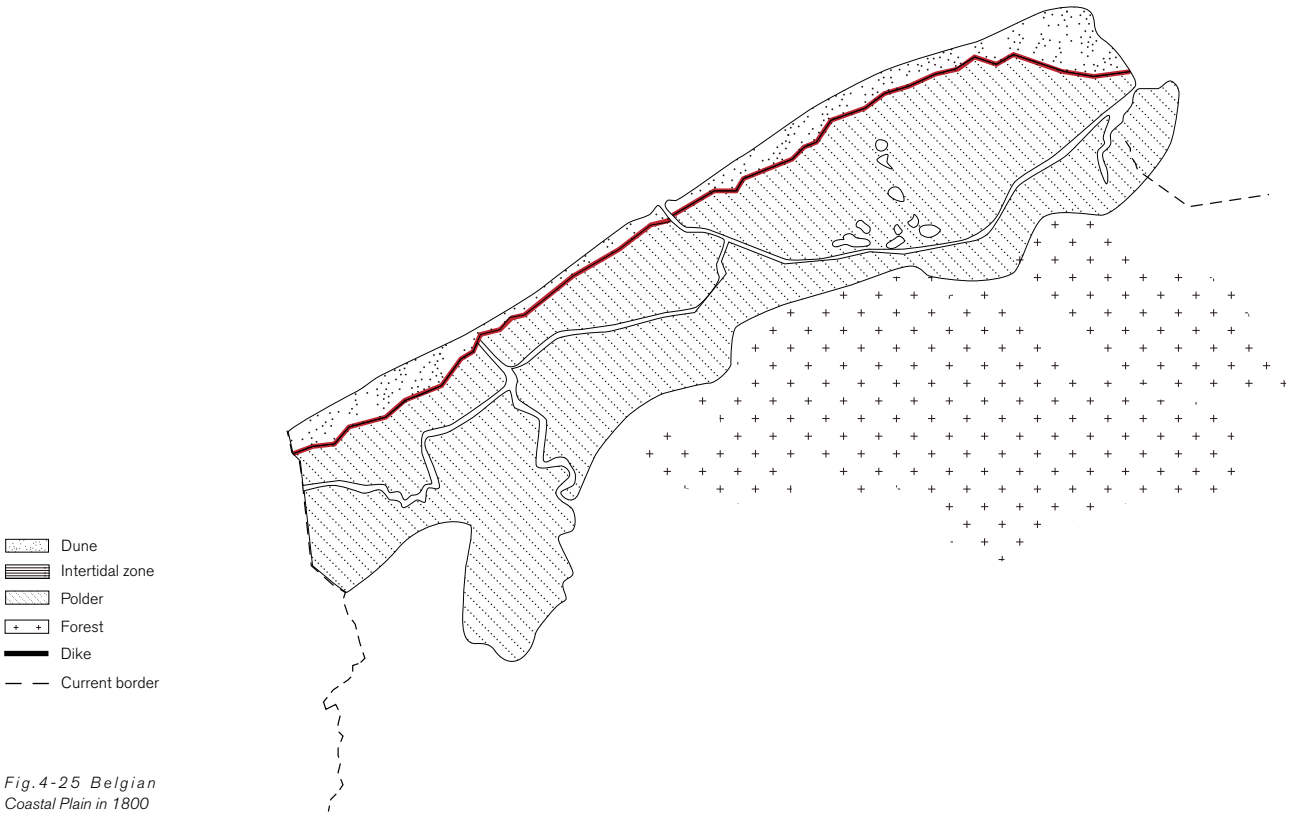


Fig.4-25 Belgian Coastal Plain in 1800

Source: Made by the author



Fig.4-26 Belgian Coastal Plain in 1900

Source: made by the author

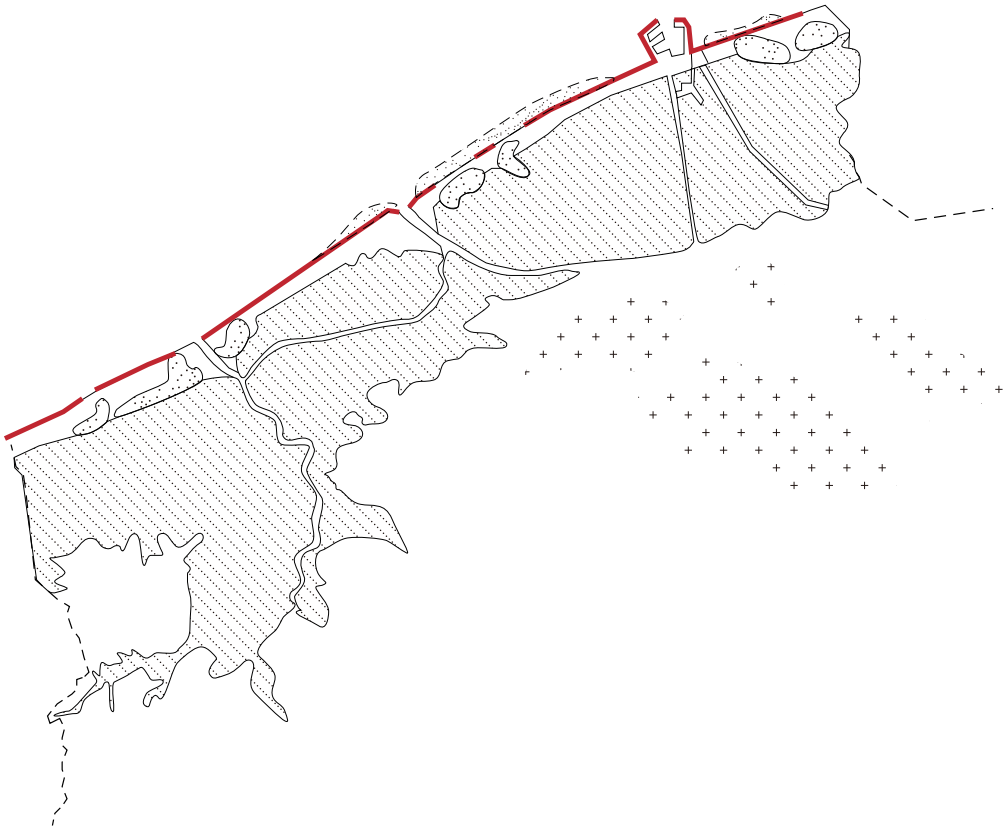


Fig.4-27 Belgian Coastal Plain in 2018

Source: made by the author

Patterns of tides, waves and currents

In order to predict the future changes of the coastline, research on natural forces that influence the coastal areas is necessary. And the main natural forces from the sea selected here are tides, waves and currents.

Tides

The Belgian coast is subjected to a tidal regime with a half day schedule. The Belgian coast has two high tides and two low tides every day, with an average tidal range of 4 metres. The tide wave moves along the coast from west to east. The tidal difference decreases in the same direction by ± 0.5 m. Spring tides occur twice a month (after every new and each full moon) when the tidal variation has reached its maximum (± 5 m); neap tides occur twice a month when the tidal difference has reached its minimum (± 3 m).

Waves

Because of the shallow seas and the short fetch, waves are tipically short crested at the Belgian coast (waves with periods less than approximately 20 s).

Short waves are waves, generated by the wind that propagate towards the beach. They can be either actively forced by the wind (wind waves) or they can have left their generation area (swell waves).

Wind waves, also called storm waves, or sea. These are waves generated and influenced by the local wind field. Wind waves are normally relatively steep (high and short) and are often both irregular and directional, for which reason it is difficult to distinguish defined wave fronts. Wind waves tend to be destructive for the coastal profile because they generate an offshore (as opposed to onshore) movement of sediments, which results in a generally flat shoreface and a steep foreshore.

Swell are waves, which have been generated by wind fields far away and have travelled long distances over deep water away from the wind field, which generated the waves. Their direction of propagation is thus not necessarily the same as the local wind direction. Swell waves are often relatively long, of moderate height, regular and unidirectional. Swell waves tend to build up the coastal profile to a steep shoreface.

In Belgium, wind set-up can generate water elevation at the coast of more than 2 m.

Currents

The gulf stream passes the Belgium coast in a northern direction. This causes a net long shore current in northern direction along the entire Belgian coast, which also influences the movement of the sediments.

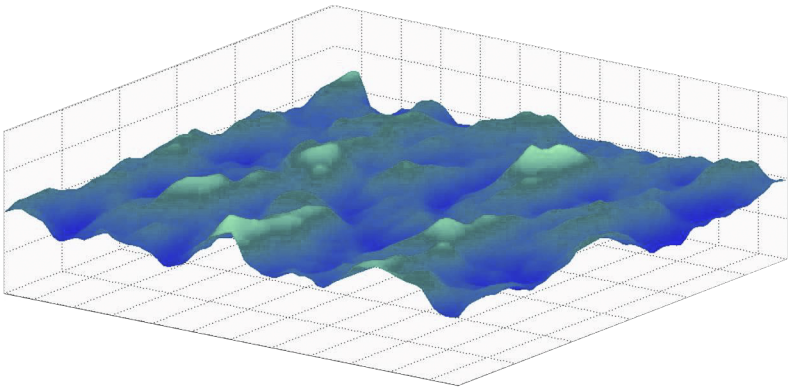


Fig.4-28 Wave patterns in Belgian Coastal Plain

Source: made by the author

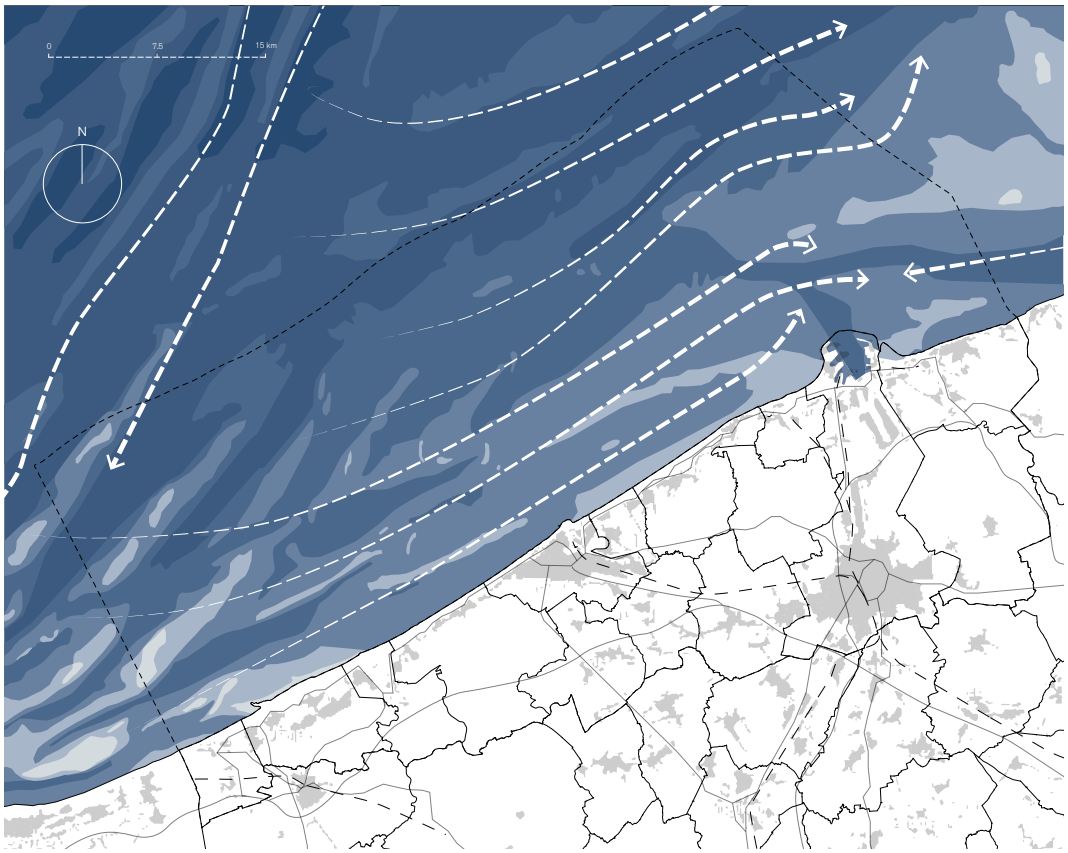


Fig.4-29 Currents patterns in Belgian Coastal Plain

Source: made by the author

Erosion & accumulation patterns in Belgian Coastal Plain

The review of the historical change of coastline and the nature forces that have direct or indirect impacts on it indicates the future change of the Belgian coastline.

Together with the research made in 'Metropolitan Coastal Landscape 2100' project, the patterns of erosion and accumulation can be concluded and the future change of coastline can be preliminary projected.

Overall, about 20% of the coastline is sedimentary, 40% is erosive, and the remaining part is relatively stable.

Specifically, the dune areas in Knokke-Heist and De Haan are facing more risks of erosion. And in 2100, the coastline in these areas may retreat by around 2 meters. The most significant coastal growth happends on the west side of Bruges port, and it is predicted that there will be an increase of about 5 meters in the future.

The patterns of erosion and accumulation give us the basis for the strategies of future development in coastal areas and the transition of coast defence system.

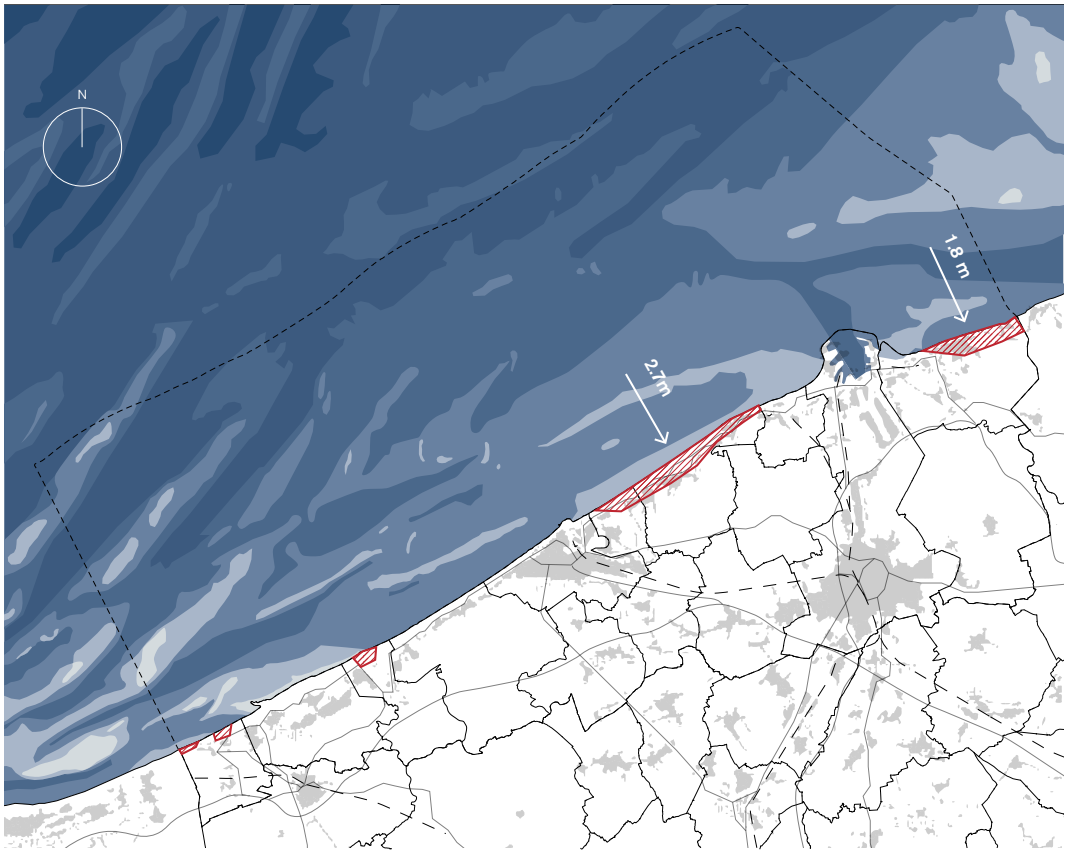


Fig.4-30 Projection of erosion in Belgian Coastal Plain in 2100

Source: made by the author based on Metropolitan Coastal Landscape 2100

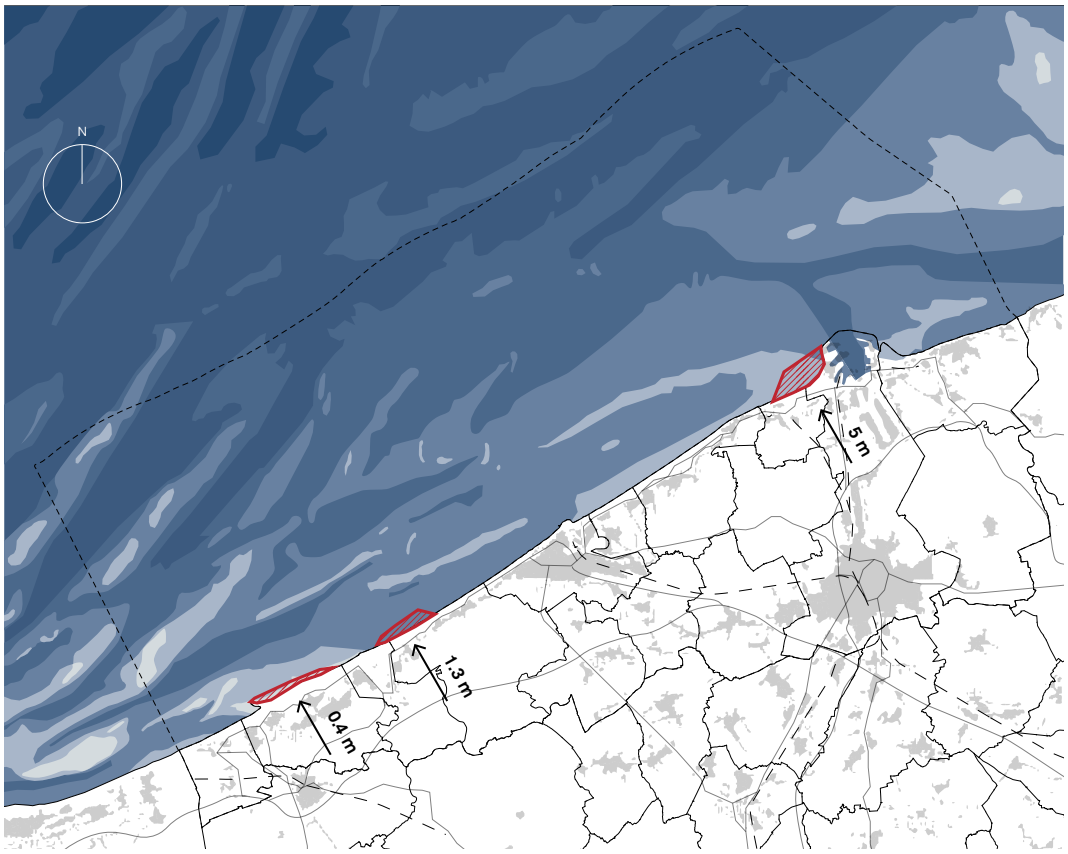


Fig.4-31 Projection of accumulation in Belgian Coastal Plain in 2100

Source: Made by the author based on Metropolitan Coastal Landscape 2100

Local wind patterns in Ostend

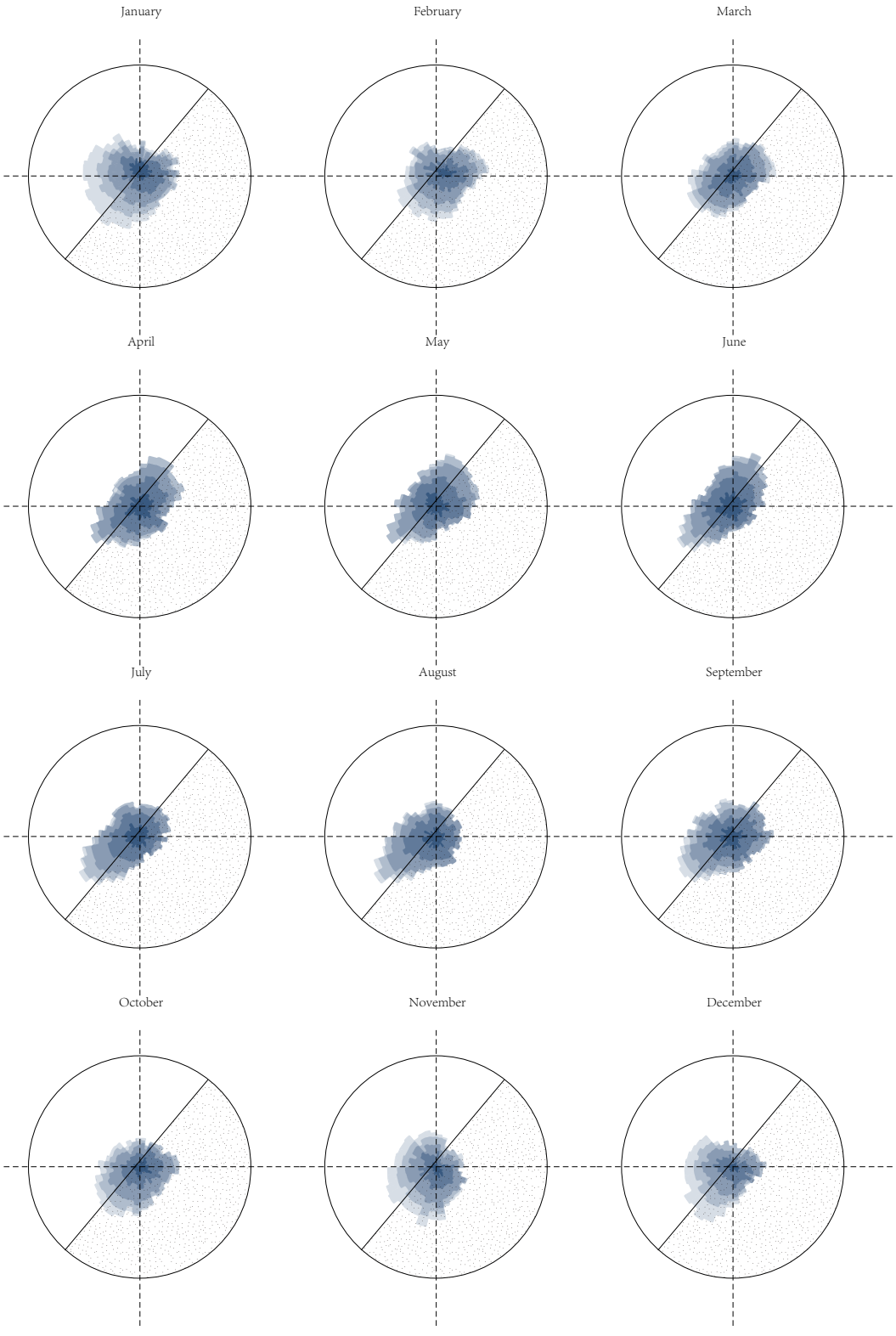


Fig.4-32 Wind pattern in Ostend

Source: Made by the author based on surf-forecast.com

Local wave patterns in Ostend

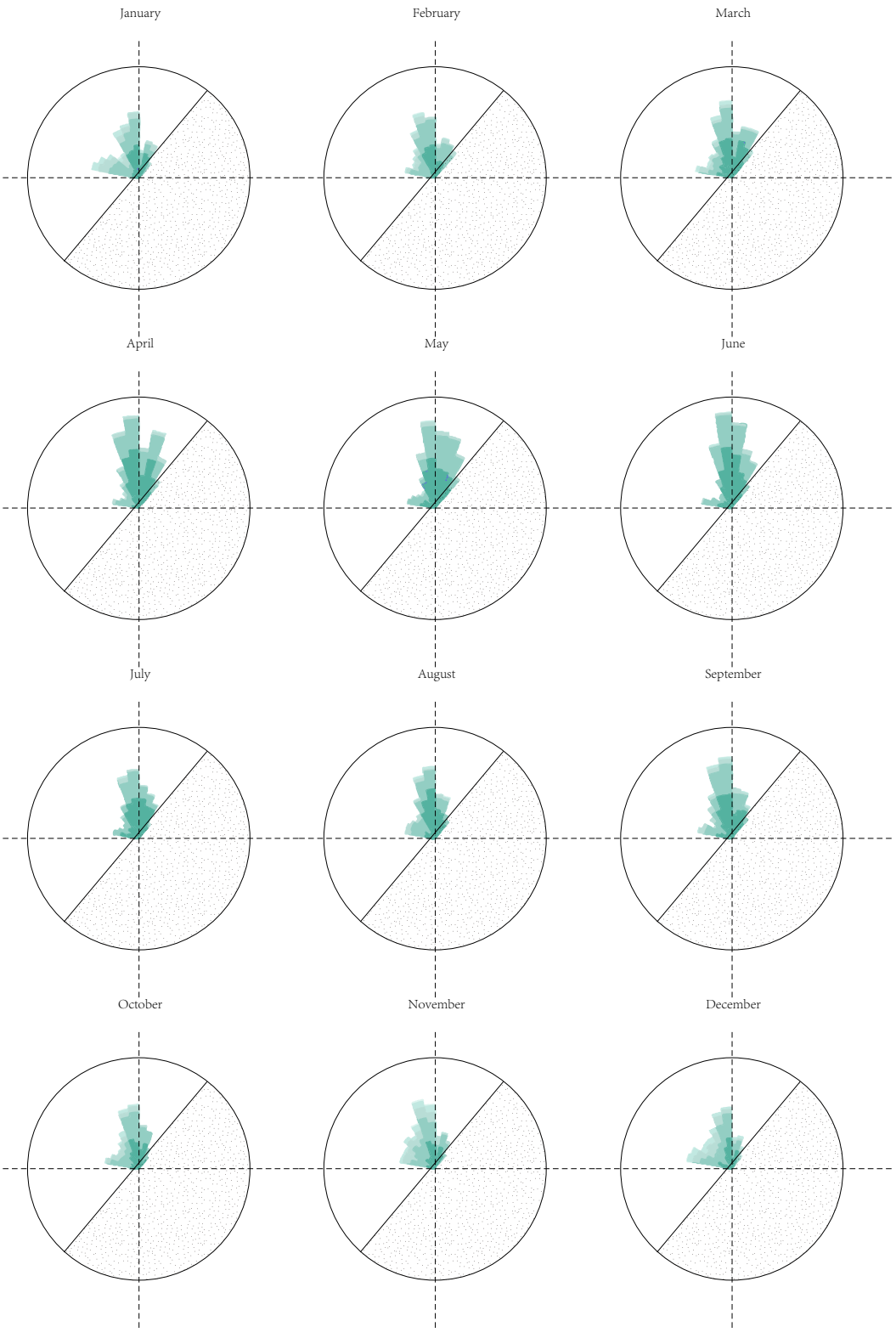


Fig.4-33 Wave pattern in Ostend

Source: Made by the author based on surf-forecast.com

Erosion & accumulation patterns in city of Ostend

More specifically, the erosion and accumulation patterns are analyzed in MICORE project in 2011 based on the Xbeach software simulation.

Compared to the other areas of the Belgian sea, the sea in front of the Ostend city centre has a relatively steep topography, varing between 8m to -8m height within 1km distance. This means the supplyment of the sand is easier to be washed away by waves and storm.

And the result of software simulation also confirms that even though the erosion & accumulation of sea near Ostend is quite balanced, small scale of erosion or accumulation is still happening.

Together with the wind and wave patterns in Ostend, it can be seen that the area 100-200 meters away from the dike has the most chance to get eroded. And after the construction of the breakwater, the area between two breakwaters can naturally get more sediments.

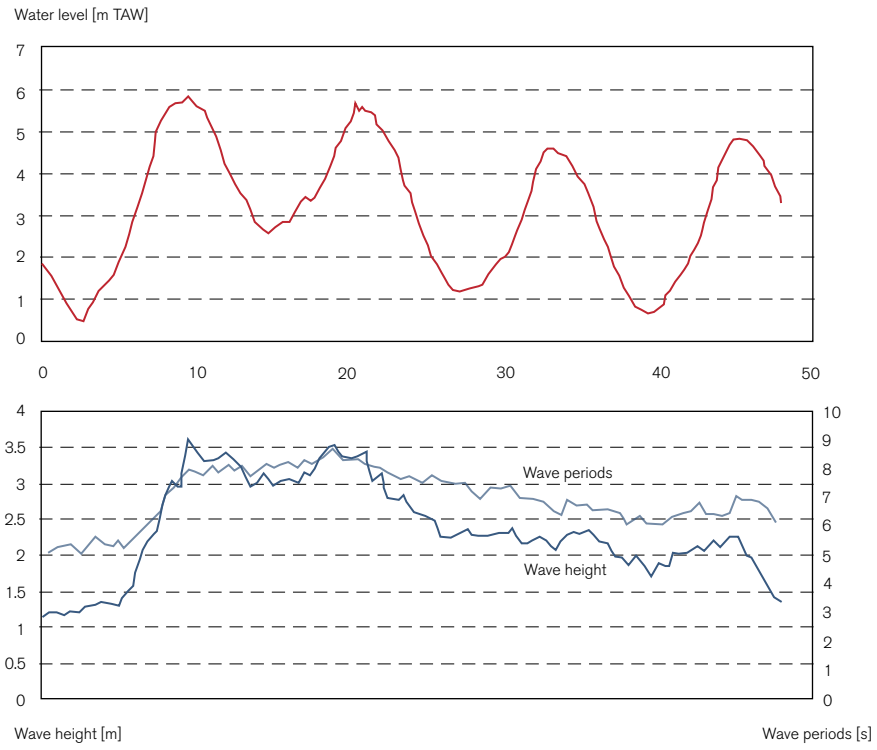


Fig. 4-34 Hydrodynamic conditions at Ostend during the 100-year return period storm

Source: Made by the author based on the Xbeach simulation in 2011

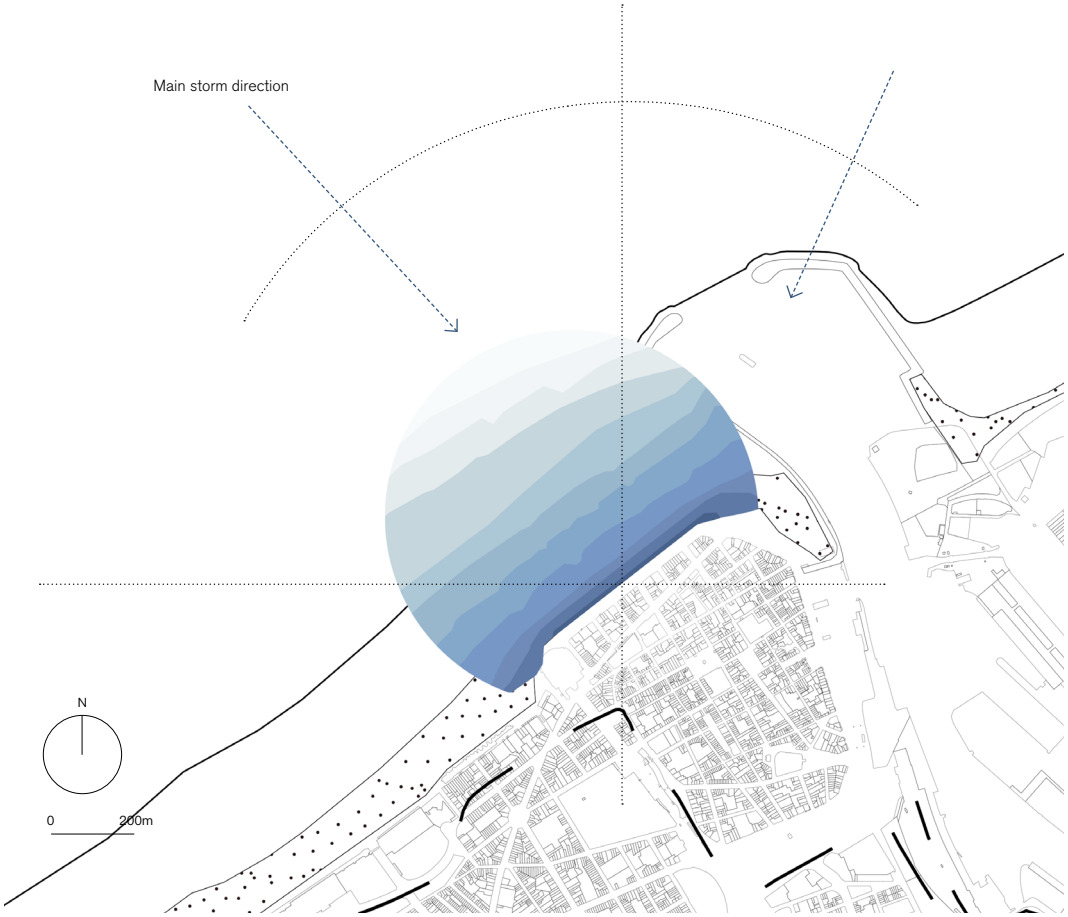


Fig.4-35 Bathymetry in the centre of Ostend

Source: Made by the author based on the Xbeach simulation in 2011



Fig.4-36 Erosion/ sedimentation patterns in the centre of Ostend

Source: Made by the author based on the Xbeach simulation in 2011

4.4 Coastal Ecosystem

Topography & Geology

The Belgian part of the North Sea is characterised by a limited water depth and a small seabed gradient. The water depth ranges between 0 meters at the coast and a maximum of 25-30 meters in the Belgian territorial sea and 40-45 meters in exclusive economic zone (north-western part). 10 to 20 kilometers from the coast the maximum depth amounts to 15 meters.

The substrate in the Belgian sea consists of strata of different ages. The basic straum dates from the Palaeozoic. A limestone stratum deposited on this layer, followed by a Palaeogene overburden, and the surface of the seabed consists of Pleistocene/ Holocene sediments

Despite its small size, the North Sea off the Belgian coast is characterised by several valuable habitats. This, in part, has to do with the presence of a complex system of sandbanks. The sandbank area stretchs out from Zeeland in the Netherlands to Calais in France. The sandbanks in the Belgian part of the North Sea are situated more or less parallel with the coast and some of them surface during extreme low tides. Together, they form a fascinating underwater dune landscape with a large biological value.

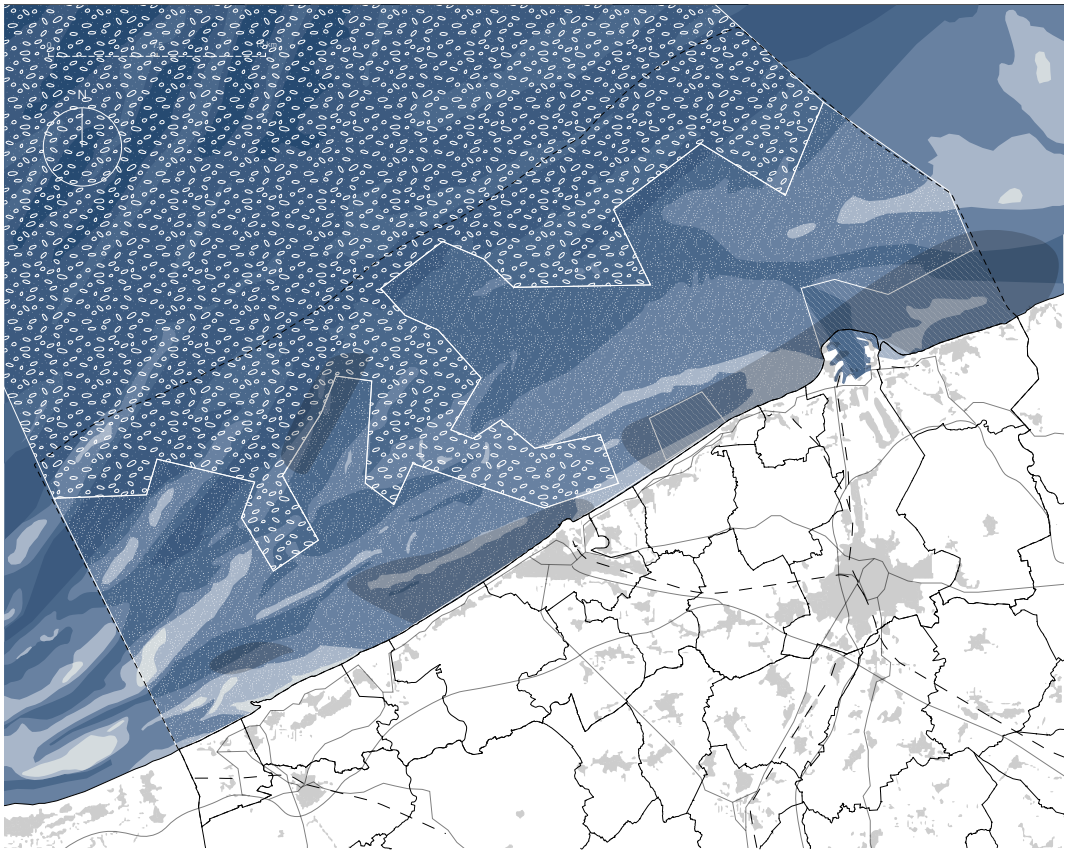


Fig.4-37 Substrate of the Belgian sea

Source: Made by the author based on Belgian Science Policy, 2005

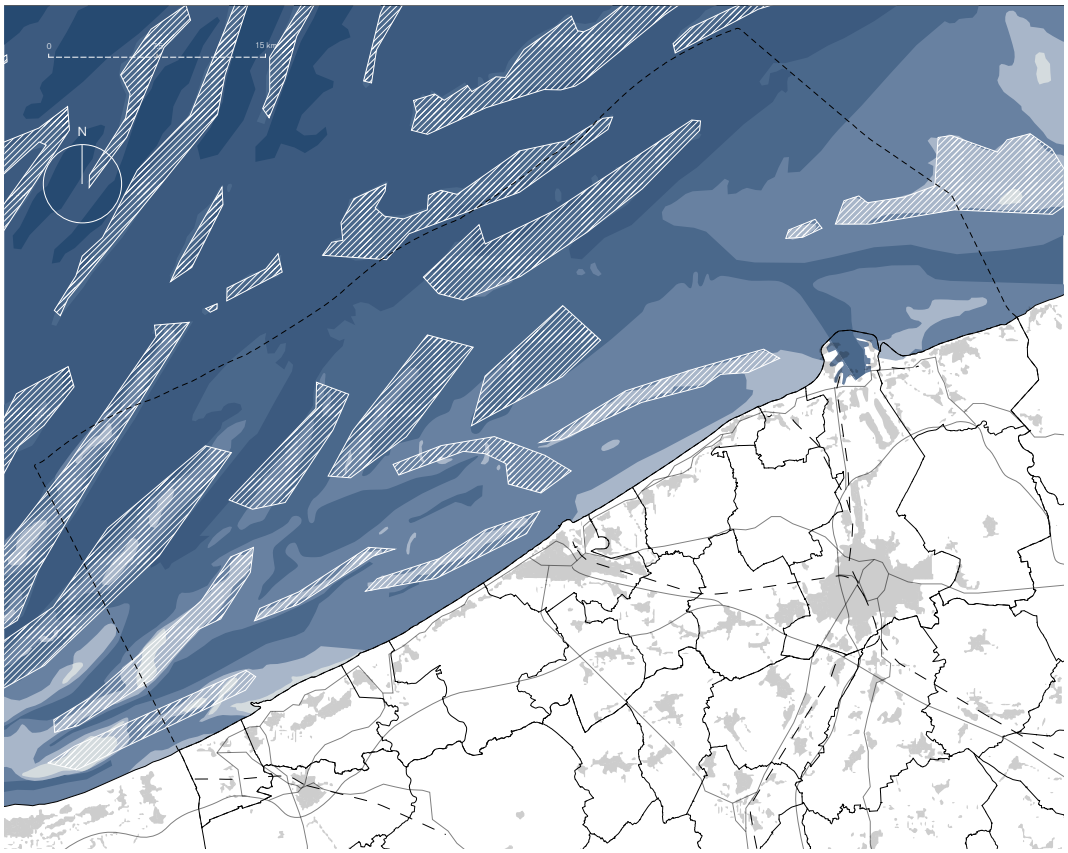


Fig.4-38 Sandbanks in the Belgian sea

Source: Made by the author based on Belgian Science Policy, 2005

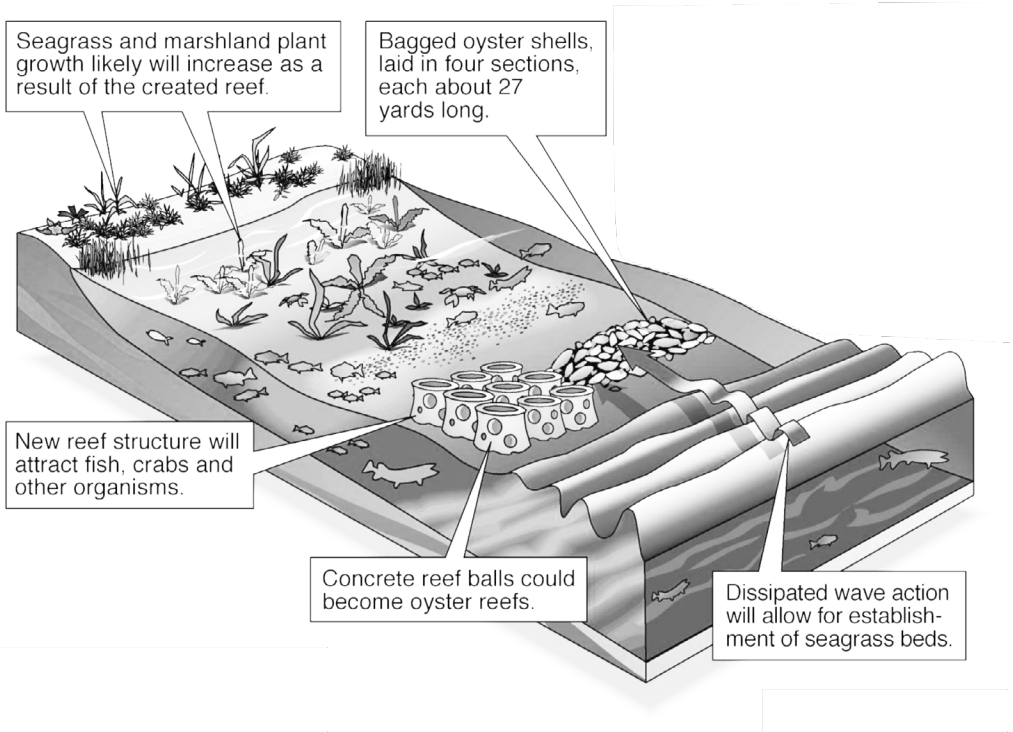
Coastal protection by 'ecosystem engineers'

Marine ecosystem is not just a cluster of marine creatures, it can actually help us to protect the coastal areas by reducing the wave energy, traping the sediment and grow with sea level rise, delivering many other ecosystem services and etc. The creatures that have benefits on coastal protection are called 'ecosystem engineers'.

The main 'ecosystem engineers' that are found nowadays include mangroves, sea grasses, marsh plants, coral reefs, mussel beds, oyster reefs, etc.

In the case of Belgium, the ecological values in near shore areas are pretty high, which mean the environment there is suitable for creation and development of 'ecosystem engineers' and optimization the whole marine ecosystem.

Because of environmental characteristics, in the above mentioned several 'ecosystem engineers', sea grasses, coral reefs, mussel beds and oyster reefs are more suitable for the Belgium Coastal Plain.



F i g . 4 - 3 9
Representation of the role of reef structures

Source: Dauphin Island Sea Lab, The Nature Conservancy, Alabama Dept. of Conservation

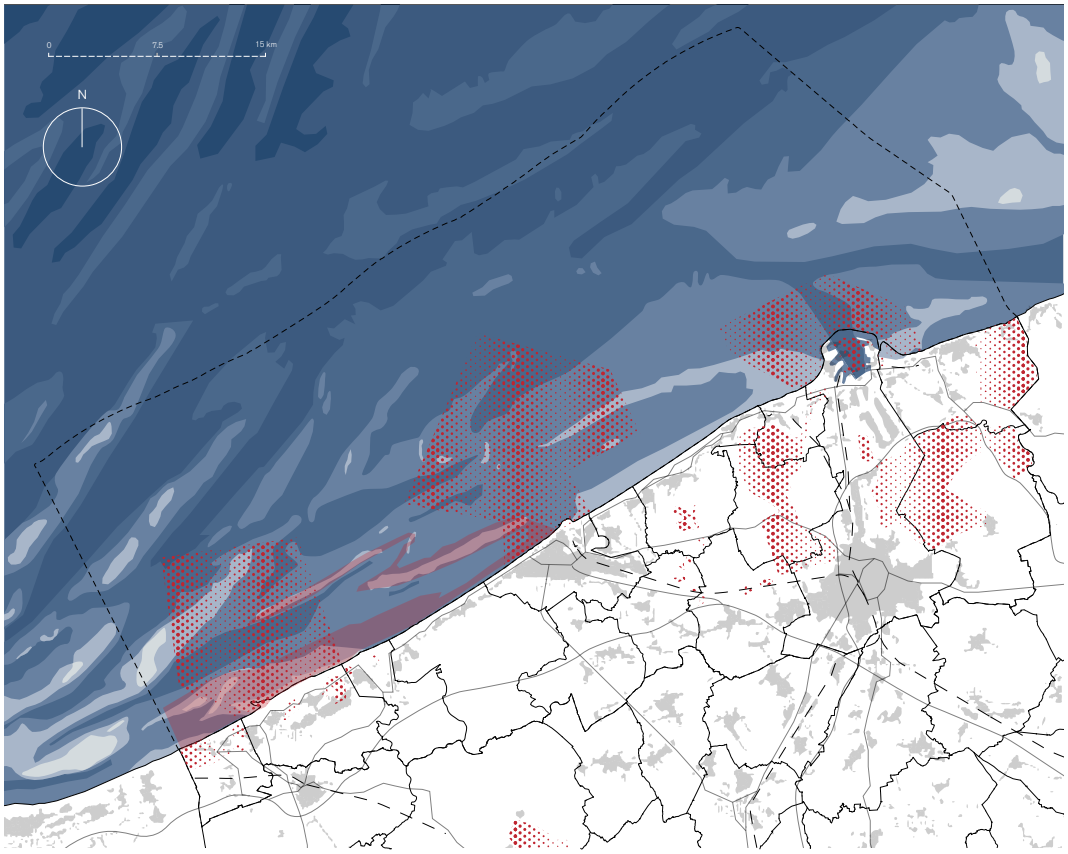


Fig.4-40 Main protected areas in Belgian Coastal Plain

Source: Made by the author based on Nature 2000

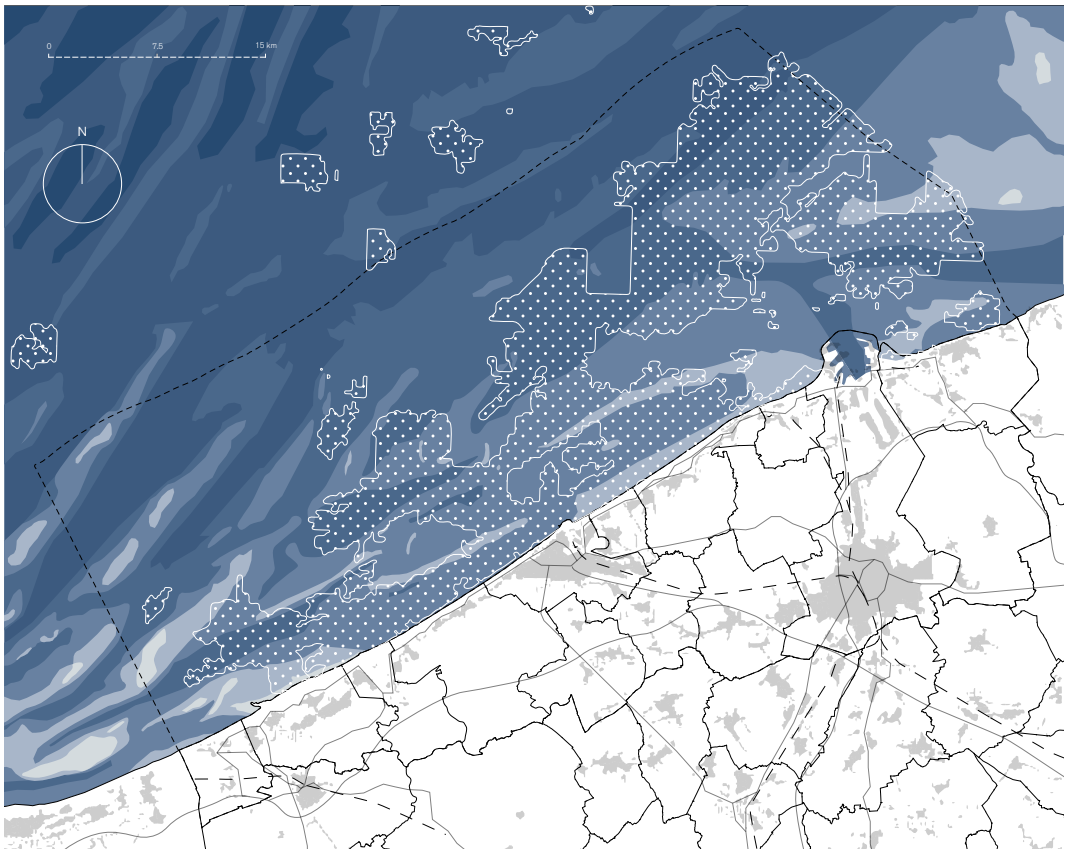


Fig.4-41 Areas of high ecological values in Belgian sea

Source: Made by the author based on kustportaal.be

Oyster reef

Oyster reefs and mussel beds are essential for a healthy, rich underwater life. They can filter the seawater and form a resting and spawning area for fish such as plaice, cod and sea bass. In their turn, they attract sharks, rays, porpoises and seals. These shellfish beds provide a hard substrate where e.g. dead men's thumb, a soft coral, can settle. Sharks, rays, smaller fish and also the common cuttlefish can attach or deposit their eggs. In addition, all kinds of birds forage on the many small fish and shrimp that live on and around shellfish bed.

Over a century ago, the whole Belgian coastline was covered with European flat oyster beds, but those have completely disappeared because of over-fisheries, coastal engineering, diseases and pollution.

Because of its high ecological value and the significance in the past, some restoration of hard substrates on the seabed is therefore a focus in the Dutch policy (Natuurambitie Grote Wateren, Uitvoeringsagenda Natuurlijk Kapitaal). Wageningen Marine Research collaborates with other parties to recover European flat oysters reefs in the Netherlands. In recent years, a number of studies have been completed on the conditions under which reintroduction of the flat oyster in the North Sea can be carried out successfully. A number of reintroduction projects are already taking place.

From this perspective, along the Belgium coastline, there is also the potentialities of the oyster reef restoration.

Important fish species

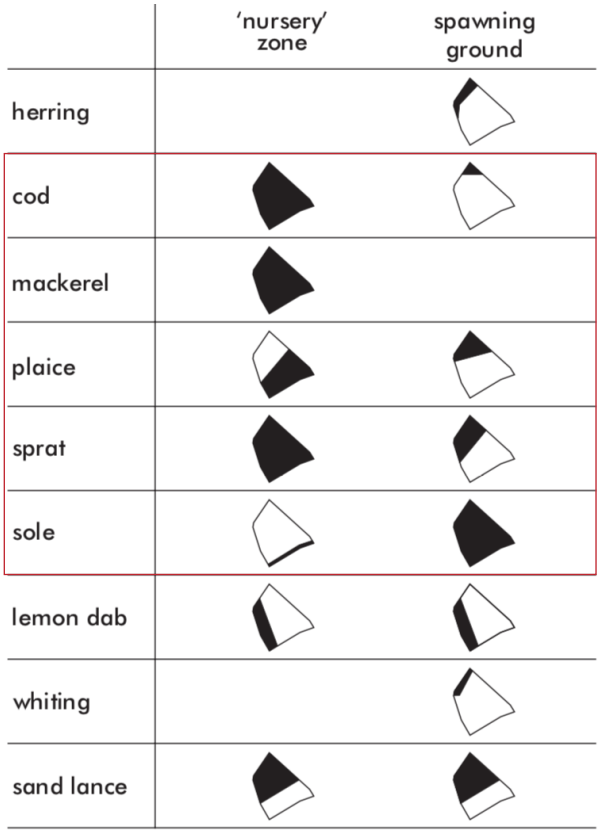
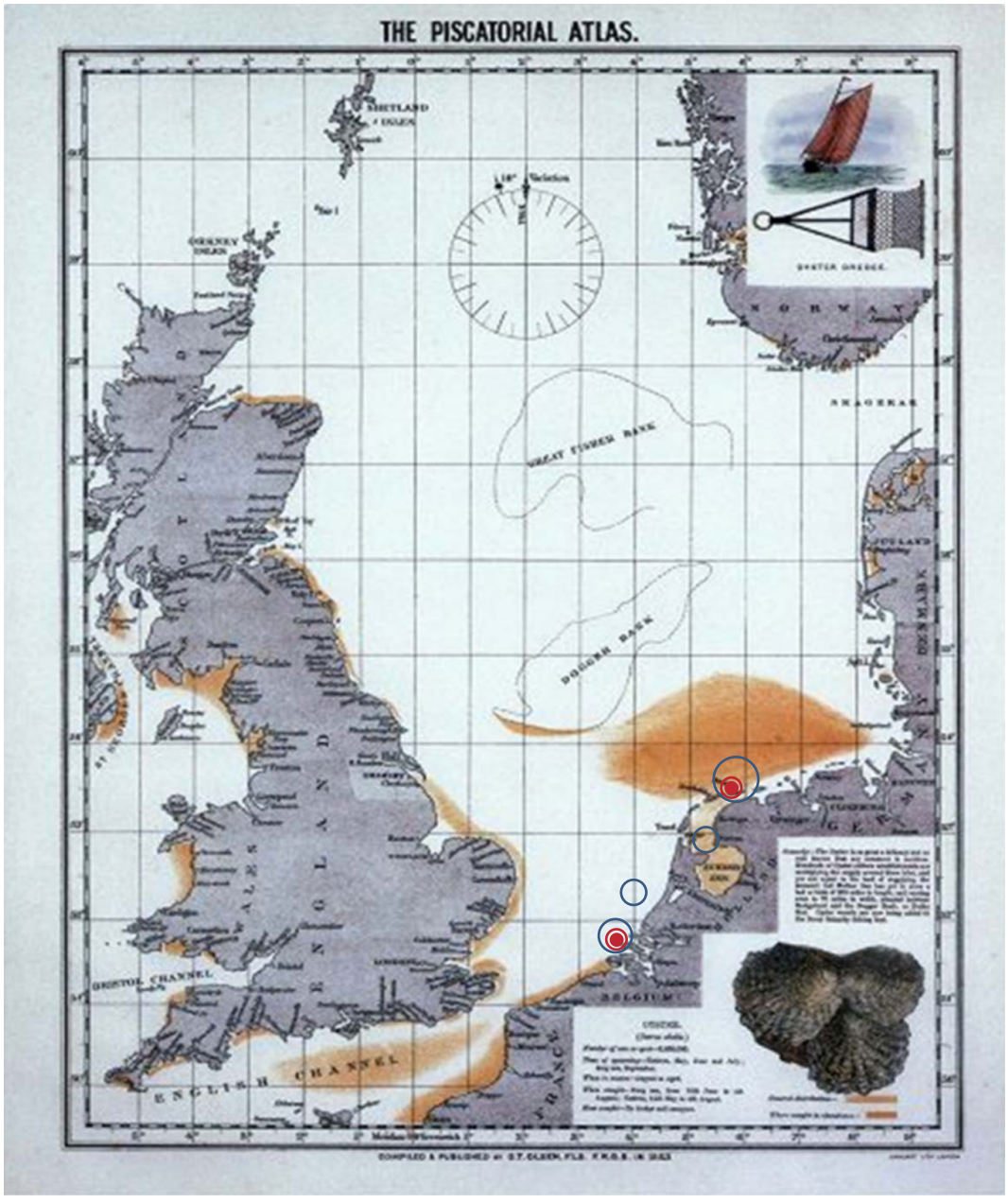


Fig.4-42 Different fish species distribution in Belgian sea

Source: Belgian Science Policy, 2005



Present distribute of flat oyster

Ongoing restoration projects

Fig.4-43 Historical distribution of the flat oyster

Source: Olsen, 1883



Fig.5-1 City centre of Ostend

Source: Photo by the author

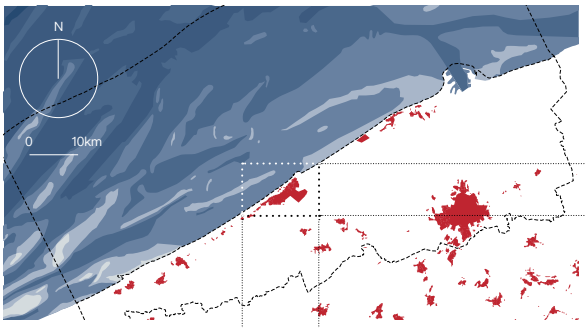
05 Dynamics of the Urban

5.1 Urbanization process
5.2 Coastal Economy
5.3 Occupation
5.4 Infrastructure
5.5 Green & Blue Network
5.6 Urban Premeability

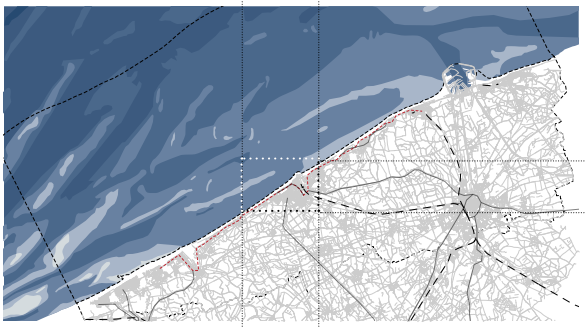
5.1 Urbanization Process

1900

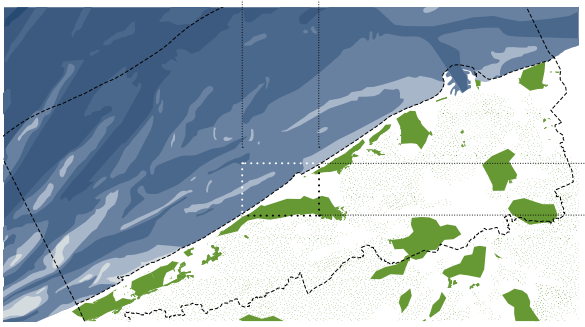
Occupation



Infrastructure



Landscape



Highway
Main road
Other road
Railway
Coastal tram

Farmland and grassland
Natural landscape
Urbanized area

1950

2018

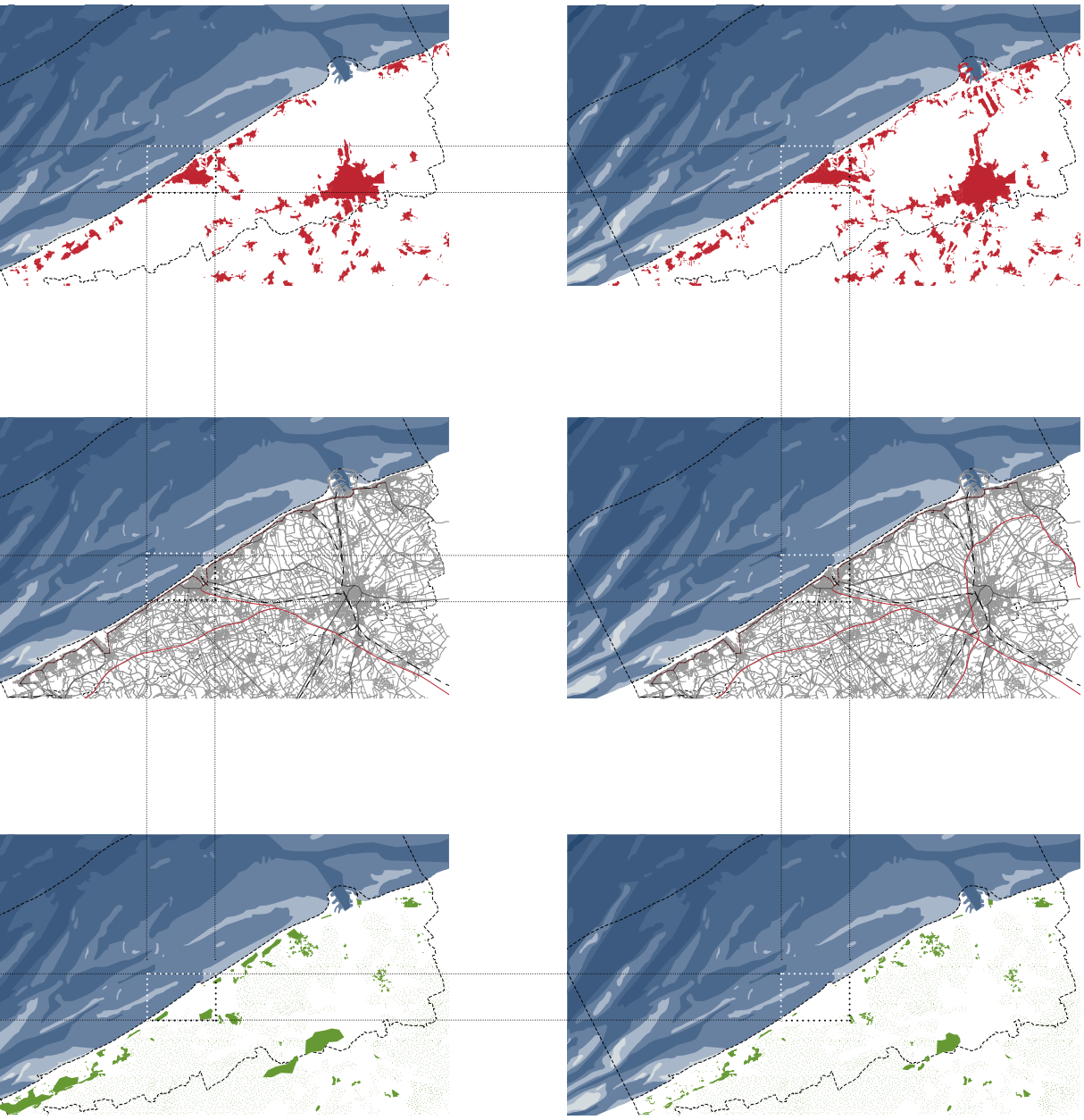


*Fig.5-2 3*3*3 analysis of Belgian Coastal Plain*

Source: Made by the author

5.2 Coastal Economy

The coast of Belgium is buzzing with many types of business. The main economy is showed as following.

1.Tourism
Tourism involves the coastal marinas and some water recreation.

2. Fisheries

3. Ports and transport
The three main ports in BCP is

4. Dredging and sand extraction
One of the main usage for the sand extraction is beach nourishment.

These industries are the main drivers of coastal economy and coastal urban development in Belgium, and also the main sources of income for workers in coastal cities.

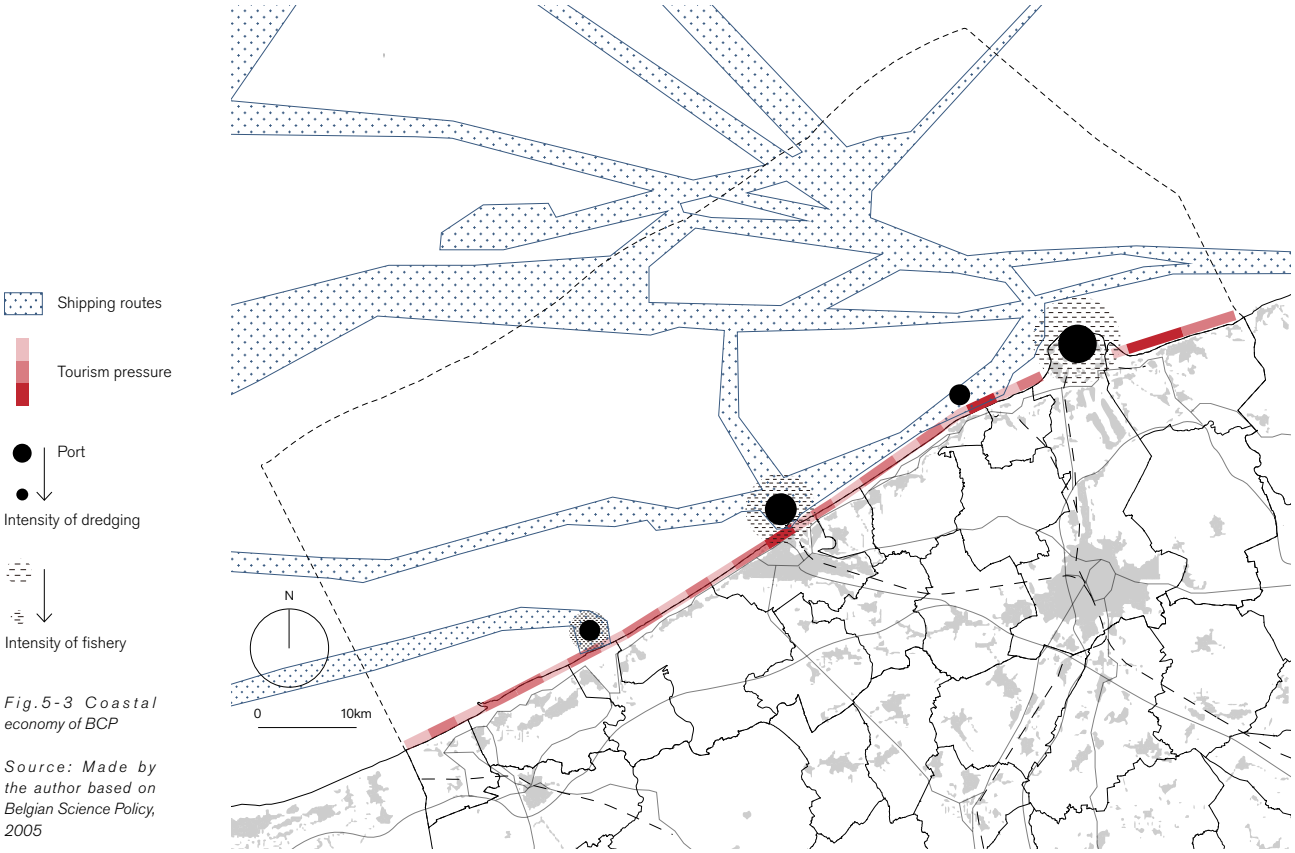


Fig.5-3 Coastal economy of BCP

Source: Made by the author based on Belgian Science Policy, 2005

In city of Ostend, specifically, these main business reflects in different parts of the city.

The tourism concentrates on the city centre and the beach area, including attractions and supporting facilities like holiday housing.

The port of Ostend was once Belgium's largest passenger harbour, but this activity has reduced sharply in recent years. A major part of the traffic consists of sand and gravel dredged from the sea for the local building industry and sandy beach nourishment.

From the chart of Value of landings of Belgian fishing vessels in Belgian ports we can see that even though the Ostend's share of the total value has declined, it still accounts for one-third of the national total value.

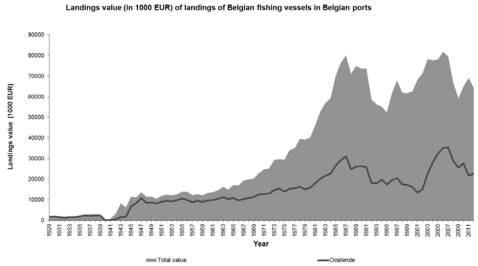


Fig.5-4 Value of landings (euro) in Oostende (1929-2012)

Source: HiFi database, De Belgische Zeevisserij

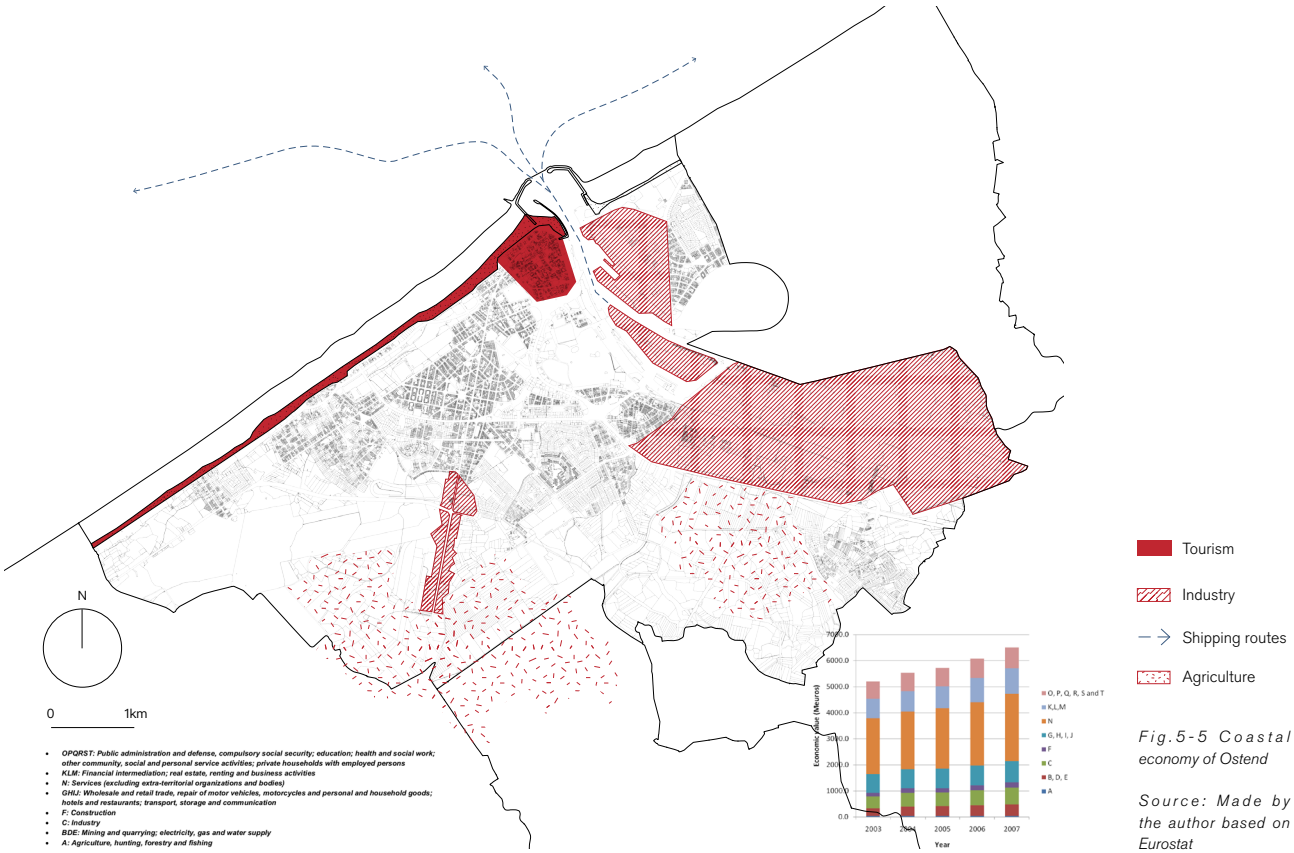


Fig.5-5 Coastal economy of Ostend

Source: Made by the author based on Eurostat



Fig.5-6 Dredging and beach nourishment along Belgium coastline

Source: https://www.magotteaux.com/solutions/dredging



Fig.5-7 Port overview in Ostend

Source: http://www.4allports.com/port-overview-oostende-belgium-pid17.html



Fig.5-8 Beach tourism during summer in Ostend

Source: https://tech2.org/belgium/3-5-million-day-trippers-provide-top-month-on-coast-ostend/



Fig.5-9 Fishery boat in Ostend

Source: http://www.flanderstoday.eu/business/flemish-fishing-industry-satisfied-new-quotas

5.3 Occupation

Functionality

Urban functionality provides certain possibilities and limitation for the spatial intervention and future development. From the land use map we can see that the same functionality is relatively concentrated in the same area, and most of the public functionality is distributed in the city centre near the coastline.

On the other hand, we can see that the whole city is quite fully occupied and the space for the future development is limited.

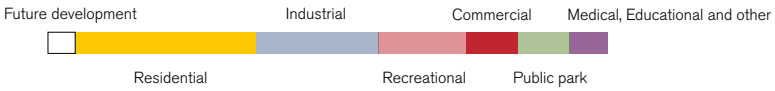


Fig.5-10 Propotion of main urban funcions in Ostend

Source: Made by the author

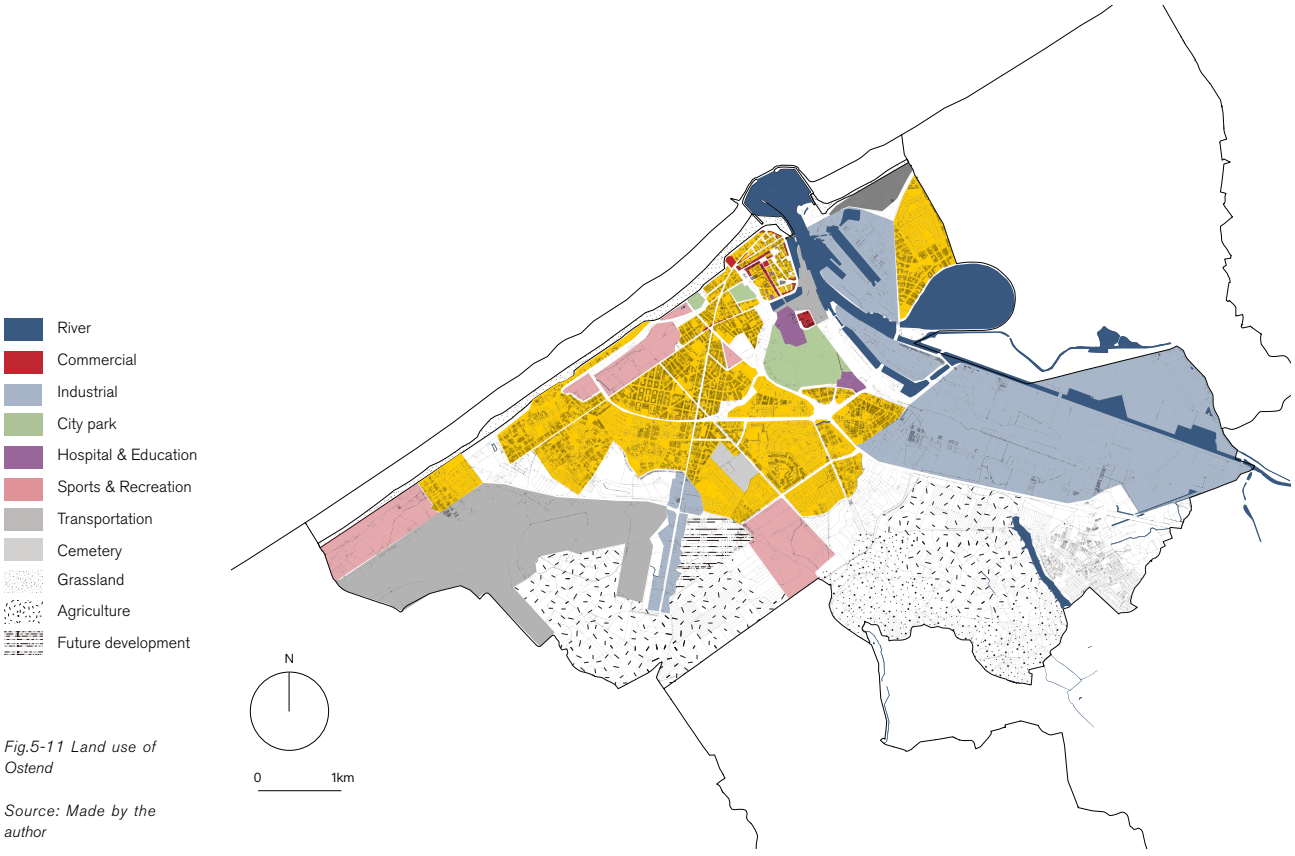


Fig.5-11 Land use of Ostend

Source: Made by the author

Low-lying occupation

Even though the whole city of Ostend is low-lying area (around +5m TAW), there are still slightly height differences which influences the natural water flow and the flooding direction.

When we overlap the digital elevation model map to the occupation layer, we can notice that there are two main areas that locate in relatively low areas with relatively high urban density. These areas have more demand for rapid drainage after flooding, especially in the area lies in the city centre, where all sides are higher than it.

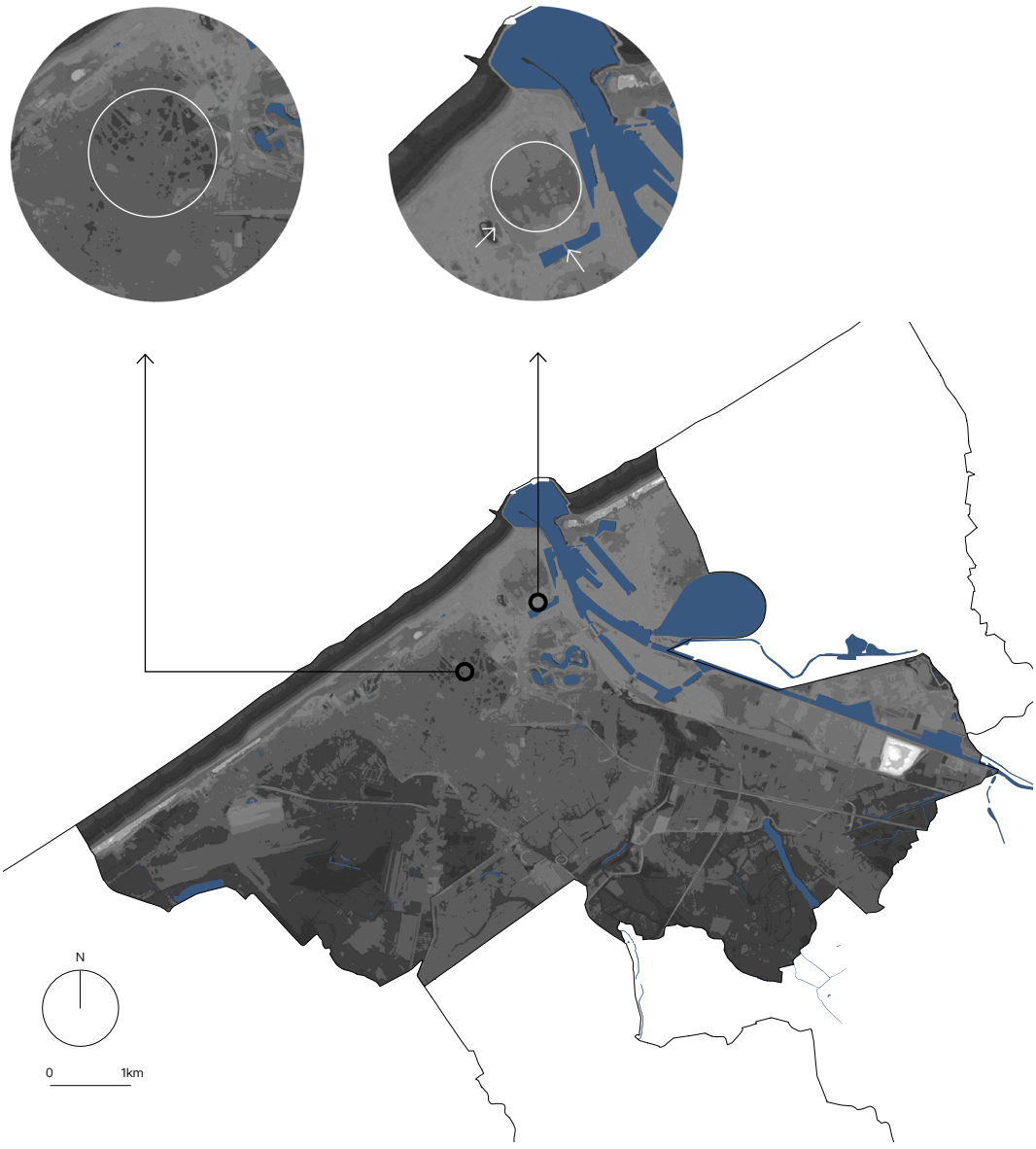


Fig.5-12 Digital Elevation Model of Ostend

Source: Made by the author

5.4 Infrastructure

Transportation network

The transportation network is quite clear can consistent with the urban structure. The core city centre is surrounded by the public transportation (coastal tram line) and the industrial area and different type of residential areas are divided by the main roads in the city. The coastal tram also makes the coastline more accessible. However, the connection between two beach areas are weak, so the beach on the industrial side is quite isolated.

There are also a lot of important transportation facilities in the city of Ostend with different service scope. The railway station mainly services the city, the Luchthaven Oostende-Brugge Airport mainly services the Flemish region and the port is for the whole nation.

Walking friendly area and bike lanes

The core centre of Ostend and together with the beach area have a relatively good walking environment and bike paths connection, which provides the high potential of tourism.

At the same time, these areas are also easier to carry out the renovation of the pavement and the intervention of greening.

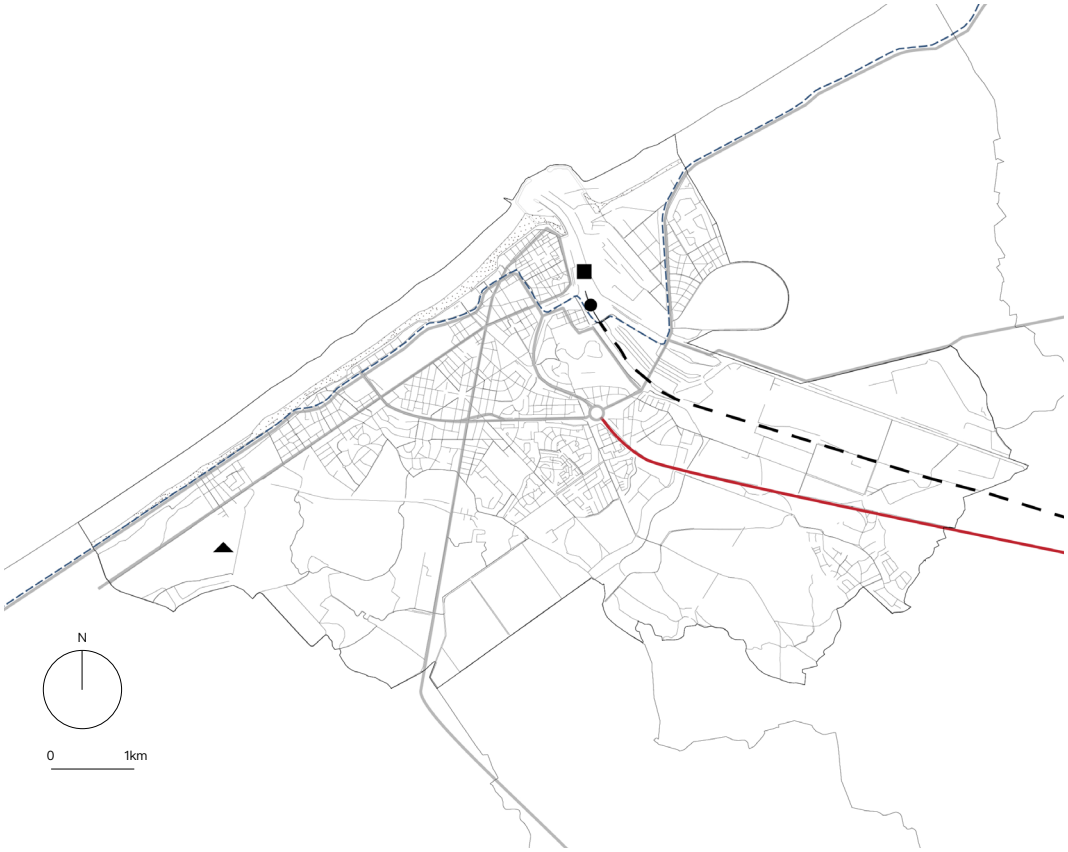


Fig. 5-13 Transportation network in Ostend

Source: Made by the author

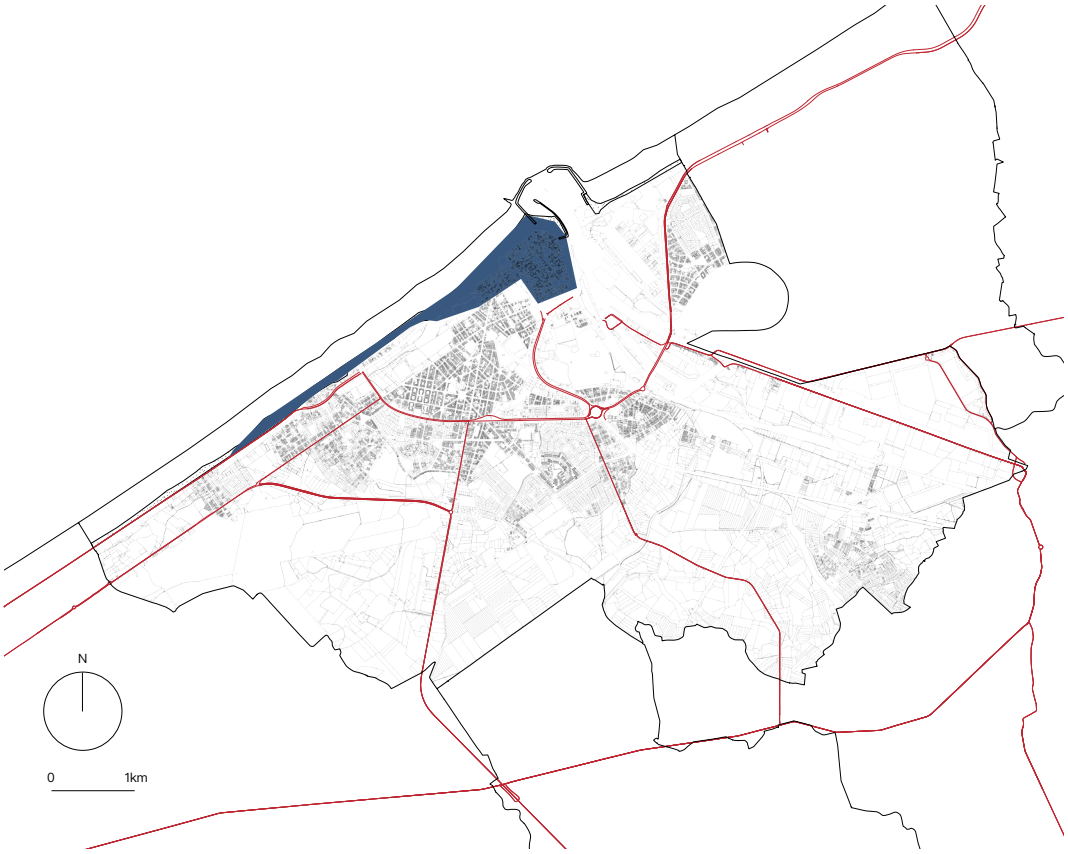


Fig.5-14 Walk and bike environment in Ostend

Source: Made by the author

5.5 Green & Blue Network

Unlike the infrastructure network, the green space system does not form a complete network. The water system mainly serves the port and the industrial area, while the green space is more scattered.

In addition, many of the current green spaces in the city are private space (sports club and recreational centre), and urban public green spaces are relatively lacking, especially at the core city centre.

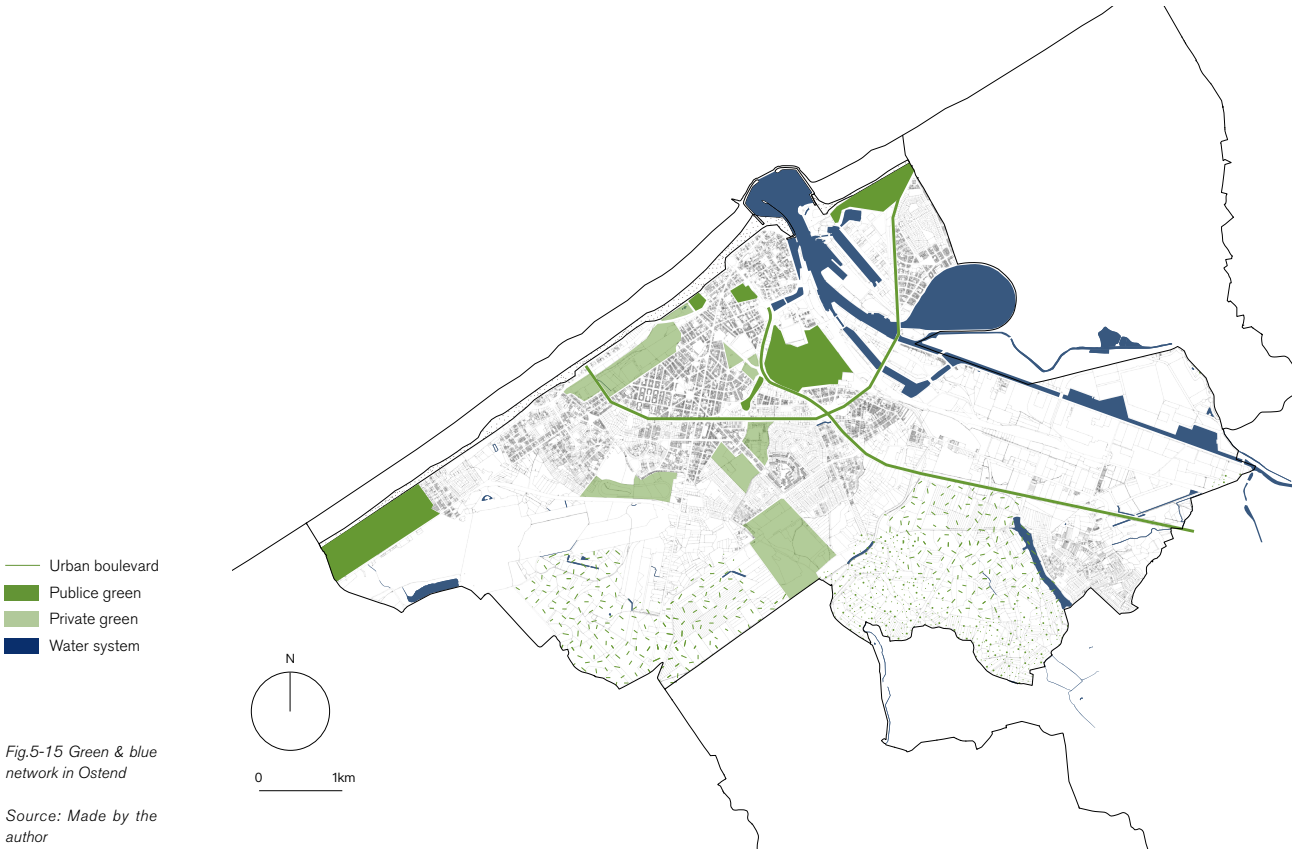


Fig.5-15 Green & blue network in Ostend

Source: Made by the author



Fig.5-16 Gated gulf club

Source: Google earth



Fig.5-17 Maria Hendrikapark

Source: Google earth



Fig.5-18 Spuikom

Source: Google earth

5.6 Urban Permeability

Double risks

Beside the risks come from the sea side, the city of Ostend also faces the risks from inland. Because of the centralized drainage system, Ostend also undertakes the function of draining for inland areas such as Brugge. The water sluice locates at the border of Ostend and Bredene discharge the water conveyed by the river Noordede from inland areas twice a day during the low tide time. However, when the water level from the sea side rises, the water inland can not be discharged, which also could cause flooding event.

This double risks require us not only to pay attention to coastal threats, but also to the city's permeability and drainage system.

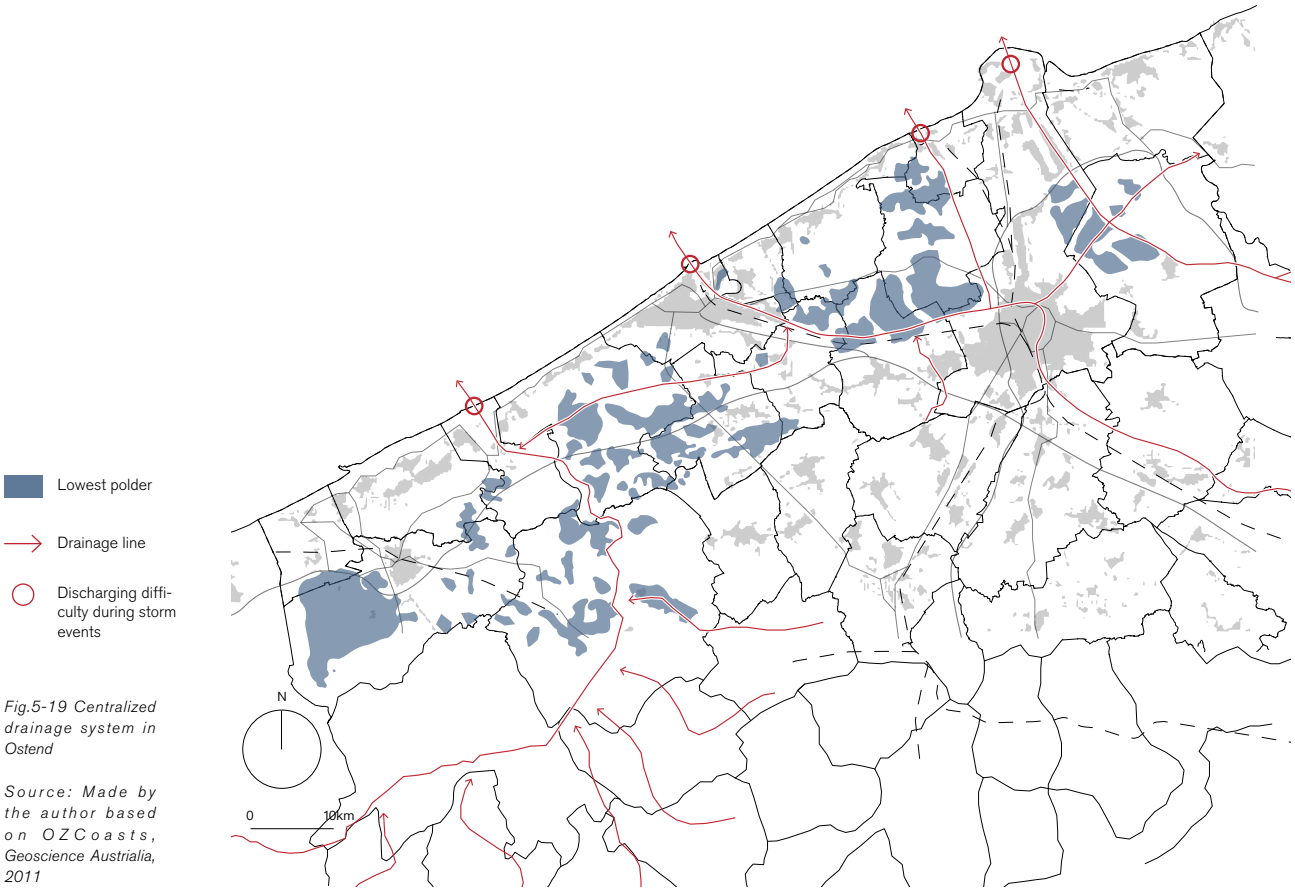
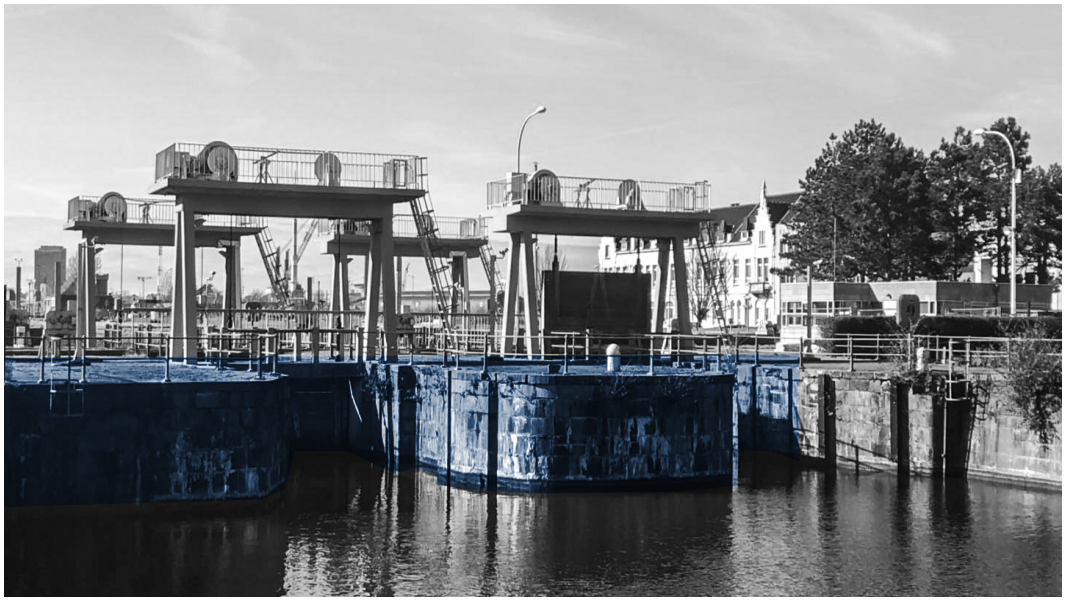


Fig.5-19 Centralized drainage system in Ostend

Source: Made by the author based on OZCoasts, Geoscience Australia, 2011



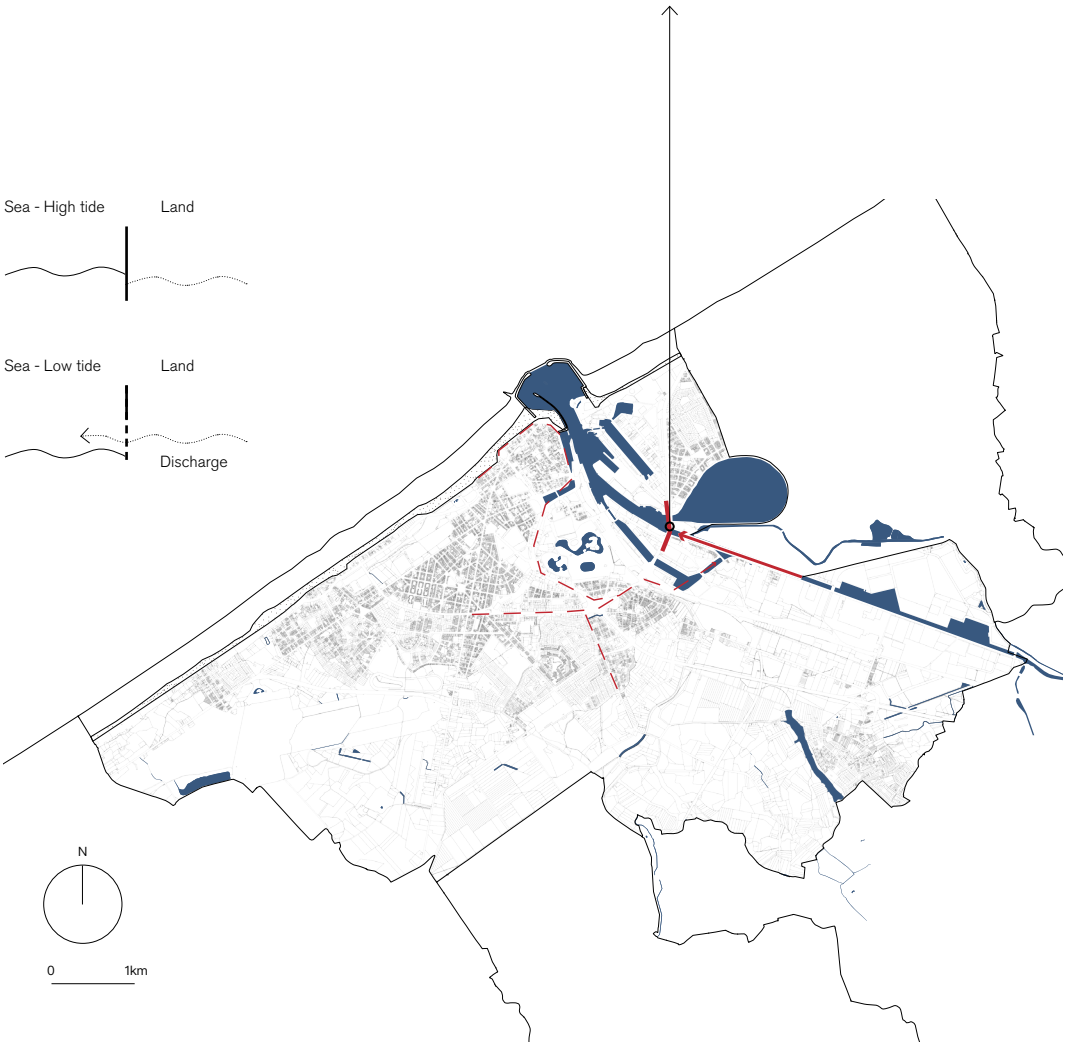


Fig.5-20 Centralized drainage system in Ostend

Source: Made by the author

Drainage system

The urban drainage network in Belgium is combined, which means wastewater and surface water from roofs and paved areas (roads, squares, parks, etc.) drain into the same underground pipe. All this water is normally taken to the wastewater treatment plant where it is treated before being discharged into the river. Although it worked well for a period, combined urban drainage systems are becoming overloading.

Moreover, the compined system also cause a lot of use of the pipelines which needs a lot of construction and maintenance input.

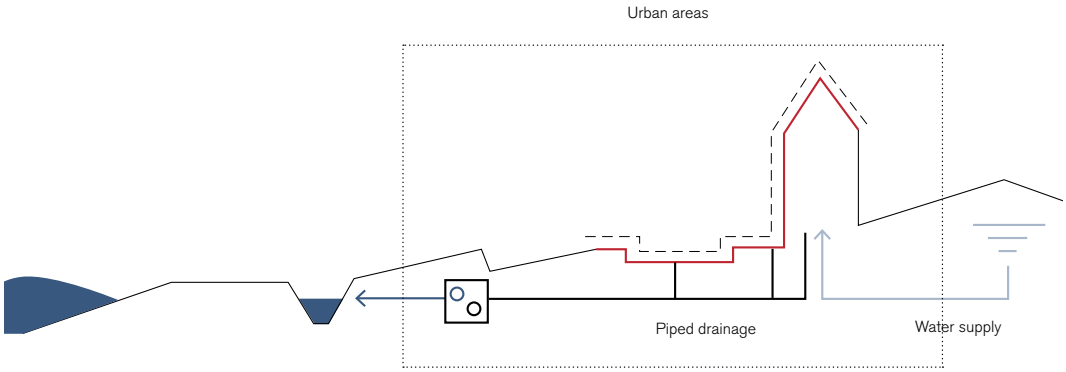


Fig.5-21 Schematic profile of the drainage system in Belgium

Source: Made by the author based on Nolf, 2013

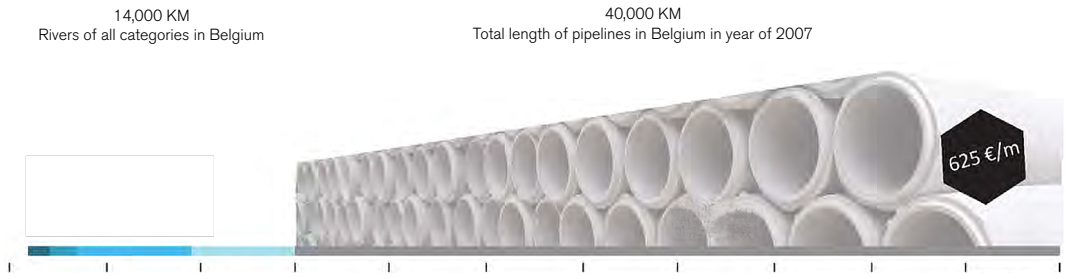


Fig.5-22 Green & blue network in Ostend

Source: Nolf, 2013

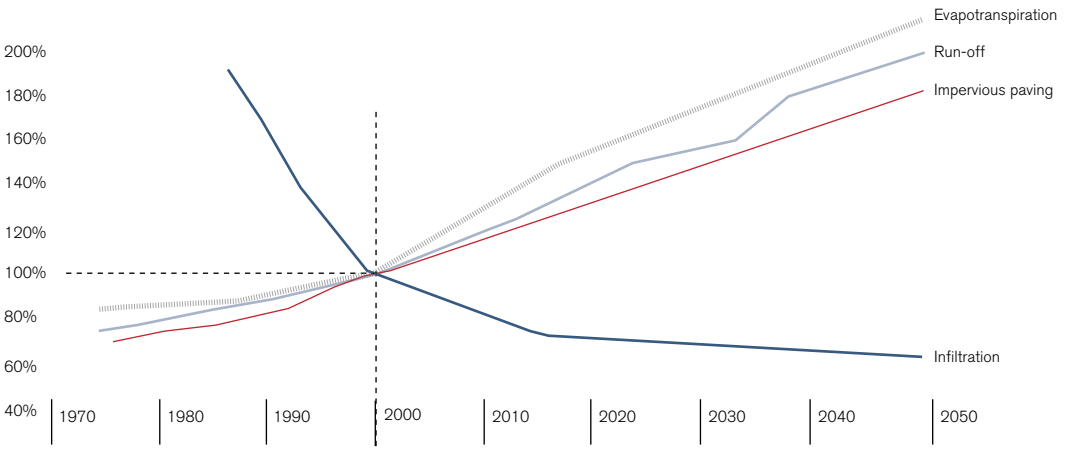


Fig.5-23 Observed (until 2000) and modelled (from 2000) evolution of impervious paved area in the Flanders-Brussels region and impact on infiltration, run-off and evapotranspiration

Source: Made by the author based on Nolf, 2013

Permeability conclusion

The main reason why the drainage system in Belgium largely relies on the underground water pipelines is that ongoing urbanization process brings the invasive paving and eventually causes soil sealing. Some studies has showed that the housing sector is the main contributor to the soil sealing.

The phenomenon of paving has significantly increased in recent decades and is expected to continue expanding in responding to the population growth. The continuing low permeability increases the risks of flooding that caused by both sea level rise and heavy rains.

From the map we can see that the areas with more residential functions face larger problem of urban permeability.

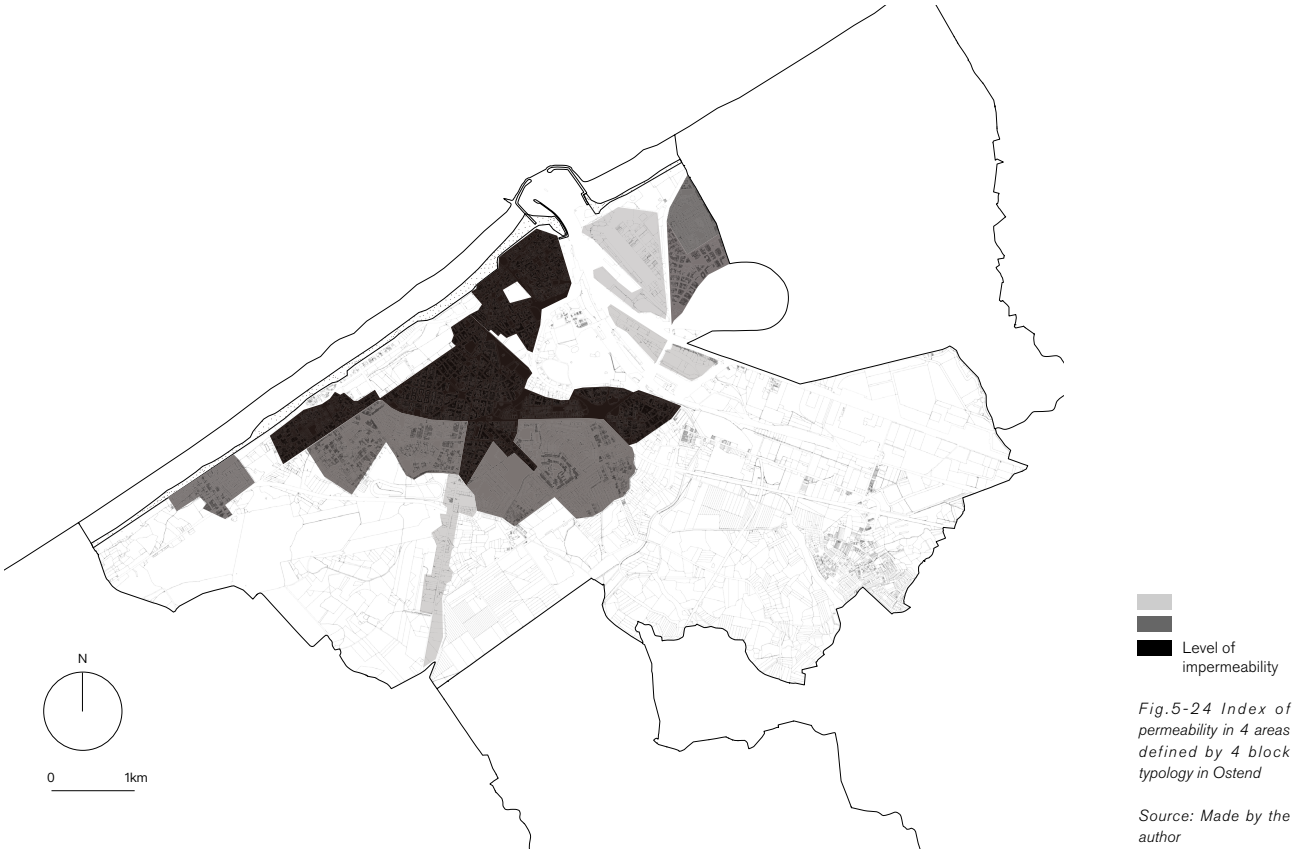


Fig.5-24 Index of permeability in 4 areas defined by 4 block typology in Ostend

Source: Made by the author



Fig.6-1 Birdview of Ostend seashore

Source: https://www.afdelingkust.be/en/'zeeheldenplein'-in-ostend

06 Transition of the Coastal Defence System

6.1 Overview of the Current Defence in BCP
6.2 Coastal Defence in City of Ostend
6.3 The Challenge of Beach Nourishment

6.1 Overview of the Current Defence in BCP

Grey defence

Along the Belgian coast no natural hard substrates (rocky shores) are found. In the framework of coastal defence several artificial coastal engineering have been built. Their most important function is the protection of the hinterland, the harbour or the safeguarding of the shipping. Furthermore they form a substrate on which specific rocky shore communities can settle.

There are three main type of grey defence can be distinguished along the Belgian coast: Sea wall, Reinforced dune and Beach Stabilization. Sea walls are usually combined with dike and piers. Dune reinforcement are solutions that prevent the movement dunes and protect the coastline. And Beach Stabilization mainly consists two ways. First is using groynes to prevent the beaches being washed away or eroded by longshore drift. Second is using geotextile tubes on the beach to fix the sand. The structure of Sea wall and Reinforced dune are usually parallel with the wave activity , while the Beach Stabilization (especially groynes) is always perpendicular to the waves.

Artificial constructions are practically found along the entire Belgian coast. Near to all Belgian coastal cities promenades are constructed and different lines of dunes (e.g. Westhoek) are separated from the beach by dune base reinforcements (Du: duinvoetverstevigingen). A continuous series of groynes are found between Westende and Bredene and between Wenduine and Knokke. They are absent near to De Panne, Oostduinkerke, De Haan and the mouth of the Zwin. Harbour-related hard constructions (e.g. moles, breakwaters, piers and groynes accompanied by piers) are found in Nieuwpoort, Ostend, Blankenberge and Zeebrugge.



Fig.6-2 Dike in Ostend

Source: Photo by the author

Green defence

In Belgium, the application of more green and natural defence is limited, mainly including beach nourishment and forshore berm.

Beach nourishment is the most commonly used method in Belgium to fight against coastal erosion and to maintain the basic coastline in a way that the natural coastal processes can proceed safely. Beach nourishment involves placing a large amount of sand on the beach.

Foreshore berm is also called feeder berm. With this method the foreshore seabed is nourished with sand. Since this zone is usually situated below the water surface the method is also called 'underwater nourishment'. This method is used to mitigate the wave activities and provide better stabilisation to an eroding beach. This technique is not frequently used in Belgium.

Eventhough these appraoches are more flexible comparing to the Grey defence, the creation and maintenance are still largely rely on engineering measures.



Fig.6-3 Beach nourishment in Ostend

Source: Photo by the author

Master plan for coastal safety

In order to cope with the climate change risks, the Flemish Government approved the Master Plan for Coastal Safety in June 2011. That proposes a series of measures to protect the 67-kilometre-long coast against a 1000-year storm surge. In the same year the Coastal Division started already with the implementation of the measures.

In the Master Plan, all flood risks are established and the risk zones charted. For each risk zone, measures and possible alternatives are studied. The emphasis is primarily put on the realisation of the chosen measures necessary to ensure the coastal safety until 2050. Thereby the expected rise in sea level (30cm) is being taken into consideration.

In addition to the implementation of the planned measures, it is important to follow closely coastal erosion and the effects of emerging storms. To that end, the Coastal Division has a plane flying over the beach twice a year and also over all dune areas once every three years. Using LiDAR technology (Light Detection And Ranging), height maps of the beaches and dunes are created. This way, the areas where erosion or sedimentation has occurred can be identified and further management can be planned.

To maintain the full sea defence structure so it continues to comply with the proposed level of security, the Coastal Division implements, amongst other, maintenance nourishments. Every six years, a test of the sea defence is made. The last test took place in 2017.

The measures of the Master Plan for Coastal Security do not only protect the cities against a 1000-year storm surge, but also against smaller storm surges. With storm surges bigger than a 1000-year storm surge, the coast is not fully protected but the impact will be smaller thanks to the measures taken.

The right table shows the risk zones from the Master Plan Coastal Safety, along with the state of play of the implementation of the soft measures in the applicable zone. The indicated maintenance of risk zones covers both scheduled maintenance as well as repairs of heavy storm damage (e.g. after the Sinterklaas storm in 2013 or the Dieter storm in 2017).

Zone	Status
De Panne Centrum	Carrying out replenishment: 2011 Maintenance: 2017
Sint-Idesbald - Koksijde Centrum	Carrying out replenishment: 2011 Maintenance: 2017
Koksijde - Gilles Scottlaan	Dune passage incremented and remade: 2013
Middelkerke - Westende	Carrying out replenishment: 2013 - 2015 Maintenance: 2017
Oostende - Mariakerke & Raversijde	Carrying out replenishment: 2014 Maintenance: 2018
Oostende Centrum	Carrying out replenishment: 2013 Maintenance: 2018
Oostende - Oosteroever	Carrying out replenishment: 2014
De Haan - Wenduine	Carrying out replenishment: 2012 Maintenance: 2014, 2016, 2017, 2018
Blankenberge	Carrying out replenishment: 2014 - 2015 + use of dredged sand from harbour channel
Knokke-Heist	prior to the planned replenishments in 2012, 2013, 2014, 2015 en 2017

Fig.6-4 Measures of Master plan for coastal safety

Source: afdelingkust.be

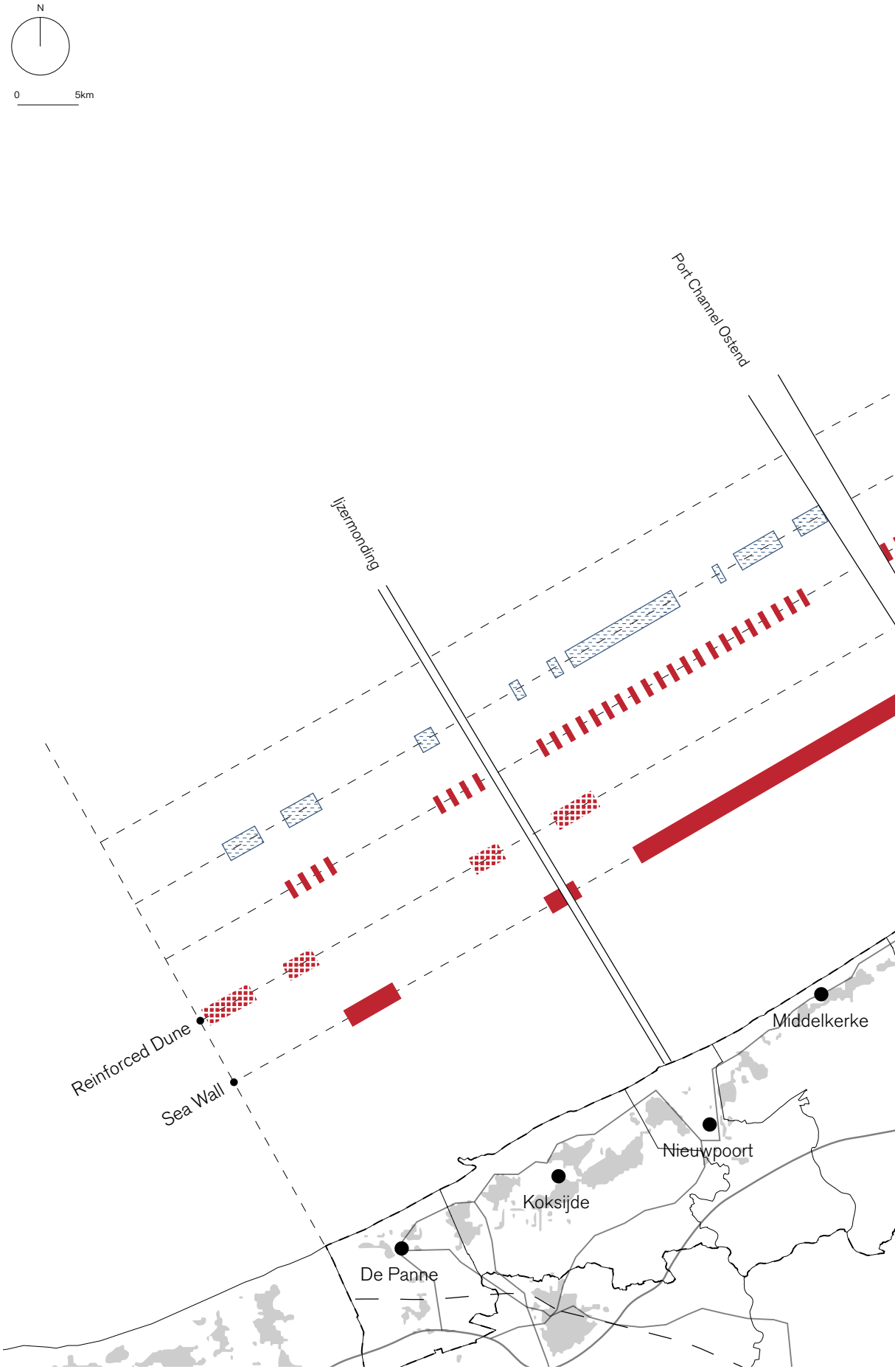
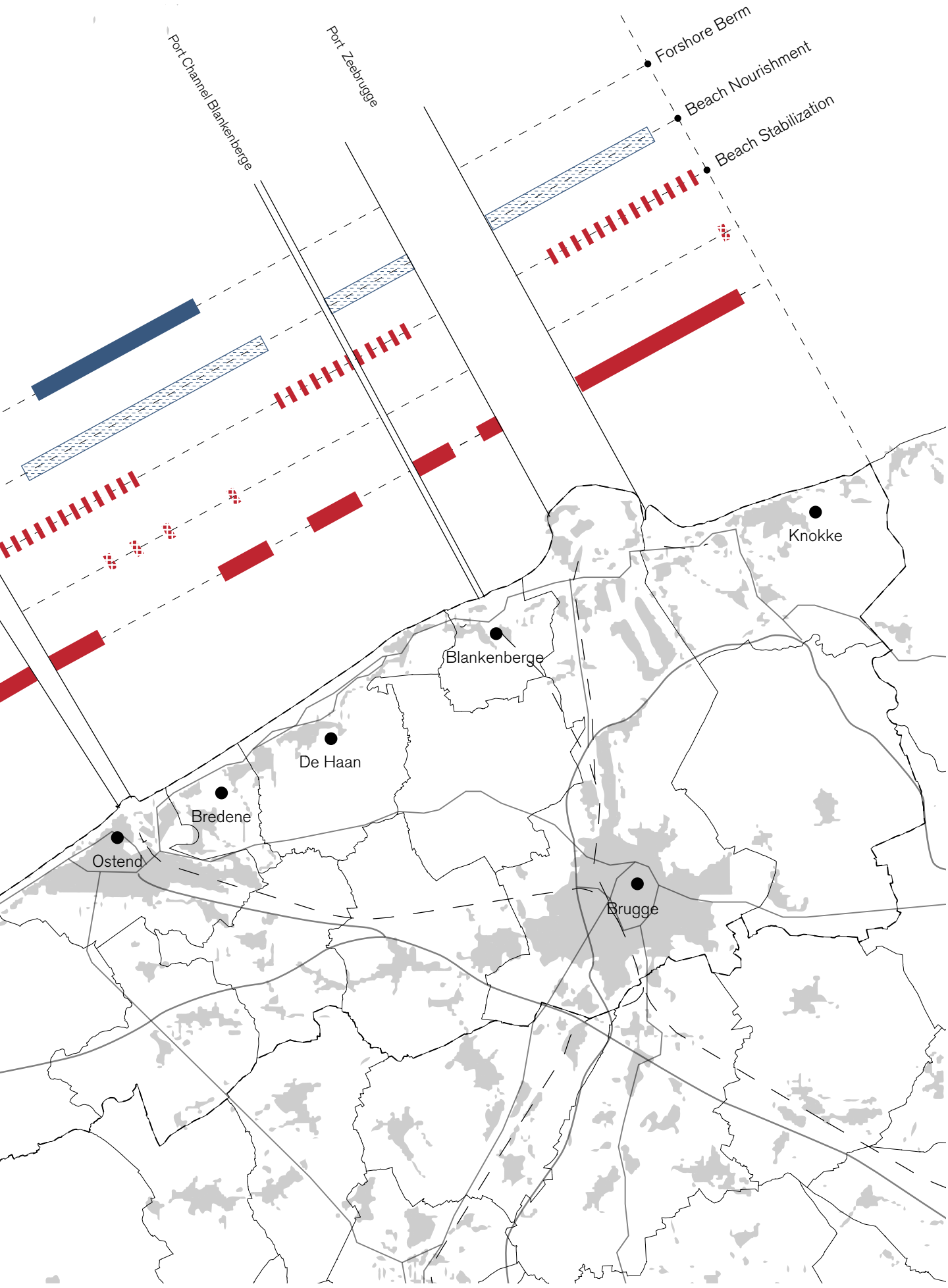


Fig.6-5 Overview of the Current Defence in BCP

Source: Made by the author


Port Channel Blankenberge
Port Zeebrugge
Forshore Berm
Beach Nourishment
Beach Stabilization
Knokke
Blankenberge
De Haan
Bredene
Ostend
Brugge

6.2 Coastal Defence in City of Ostend

Dike (Seawall + promenades + slope)

The current conventional coastal engineering in city of Ostend is a dike which consists 3 parts, the sea wall, the promenades and the slope.

The seewall in Ostend reaches the level of +9.6m TAW, and down to near -3 TAW. Built around 130 years ago, the sea wall nowadays doesn't meet the present safety standards and has become the weak link in the whole Belgian coastline.

On the top of the seawall there are promenades with the width of 25 meters and partly covered by high residential buildings. Because of the height difference, there is a slope between dike and city centre. With the grade of around 10%, the slope is also covered by residential buildings.

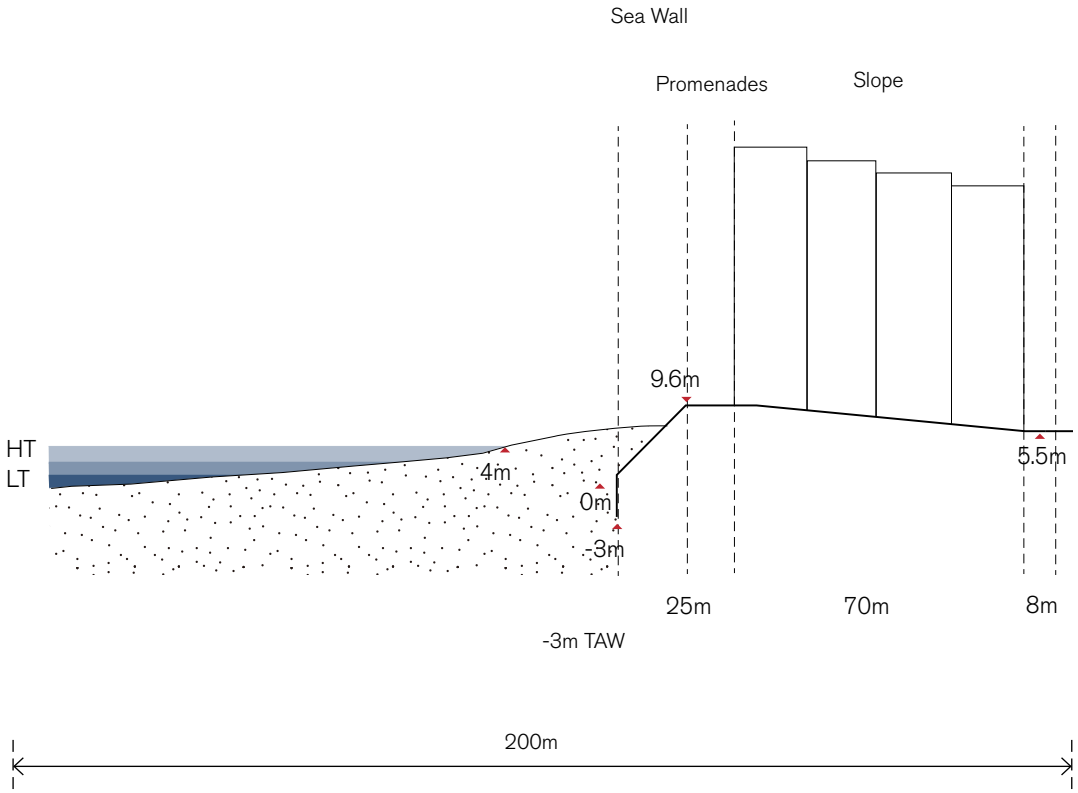


Fig.6-6 Schematic profile of the dike in Ostend

Source: Made by the author

Beach nourishment

Because of the weakness of the seawall, the beach nourishment has been implemented as a supplementary approach.

In 2004, the safety of the Ostend Centre was already increased by the construction of an emergency beach to a protection level of a 100-year storm. For this 800,000 m³ of sand was supplied.

In the 'Master Plan for Coastal Safety', Ostend is one of the most important area for sand supply. Thus, this emergency beach has been strengthened and regularly maintained, pending the final protection measures that will provide protection against at least a 1,000-year storm.

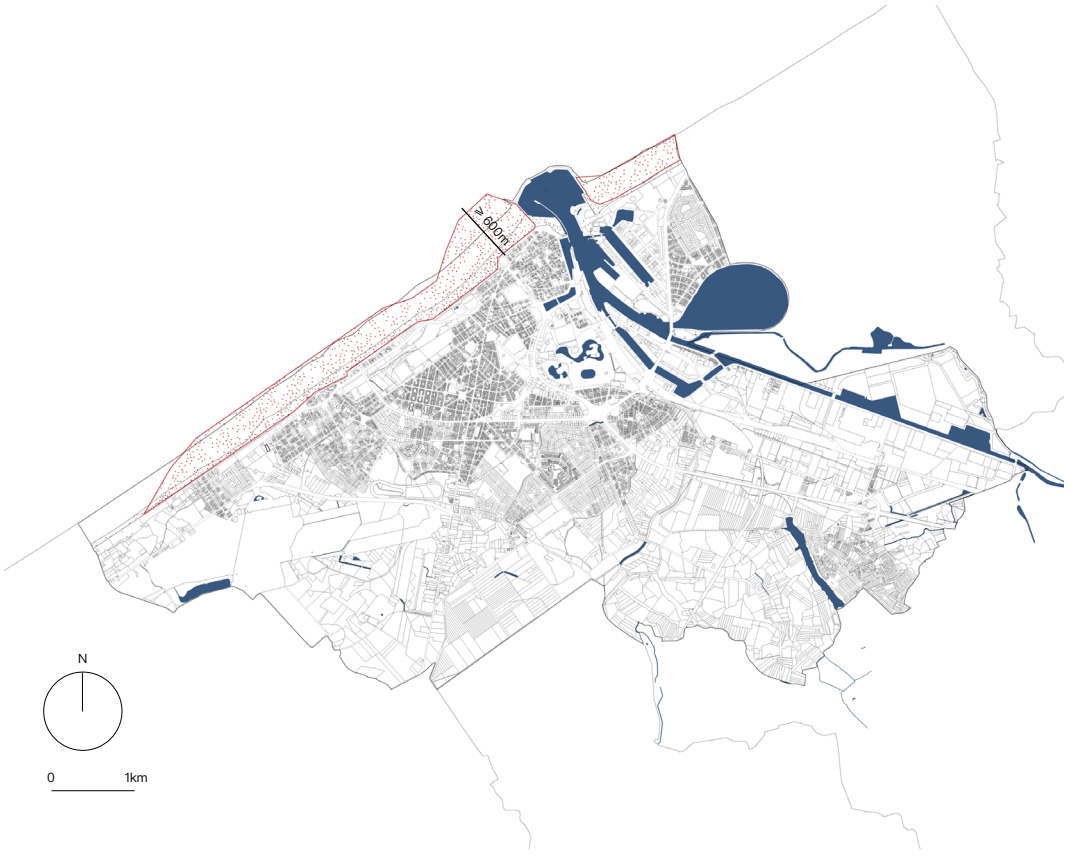


Fig.6-7 Beach nourishment in Ostend

Source: Made by the author based on afdelingkust.be

6.3 The Challenge of Beach Nourishment

Current situation

In Belgium, sand and gravel are mined in the Belgian part of the North Sea. This part of the North Sea is home to many human activities (such as shipping, fishery, military use, energy production, etc.), that are more or less limited for the space of sand extraction.

Nowadays, the amount of extracted sand fluctuates between 3 and 6 million tons annually (FPS Economy, service Continental Shelf, 2018; Zeegra association). More than 80 % of which is used in the construction sector. And another significant part of this is used for beach build-up as a function of coastal protection.

Indeed, beach nourishment (filling) is currently the main measure for maintaining beaches at their optimum level along the coast. It is necessary to keep beaches wide and high enough to prevent the coast from being flooded during spring tide.

However, sand extraction and beach nourishment has both direct and indirect influences for the existing biological communities and habitats in subaerial zones of beaches and in the borrow sites where dredging occurs.

Thus, some parts of the existing extraction sites have also been established where sand and gravel extraction is prohibited for the environmental considerations.

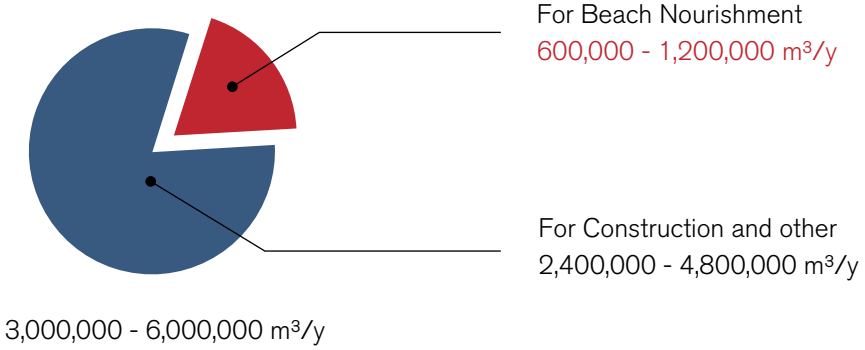


Fig.6-8 Production and consumption of sand in Belgium

Source: Made by the author

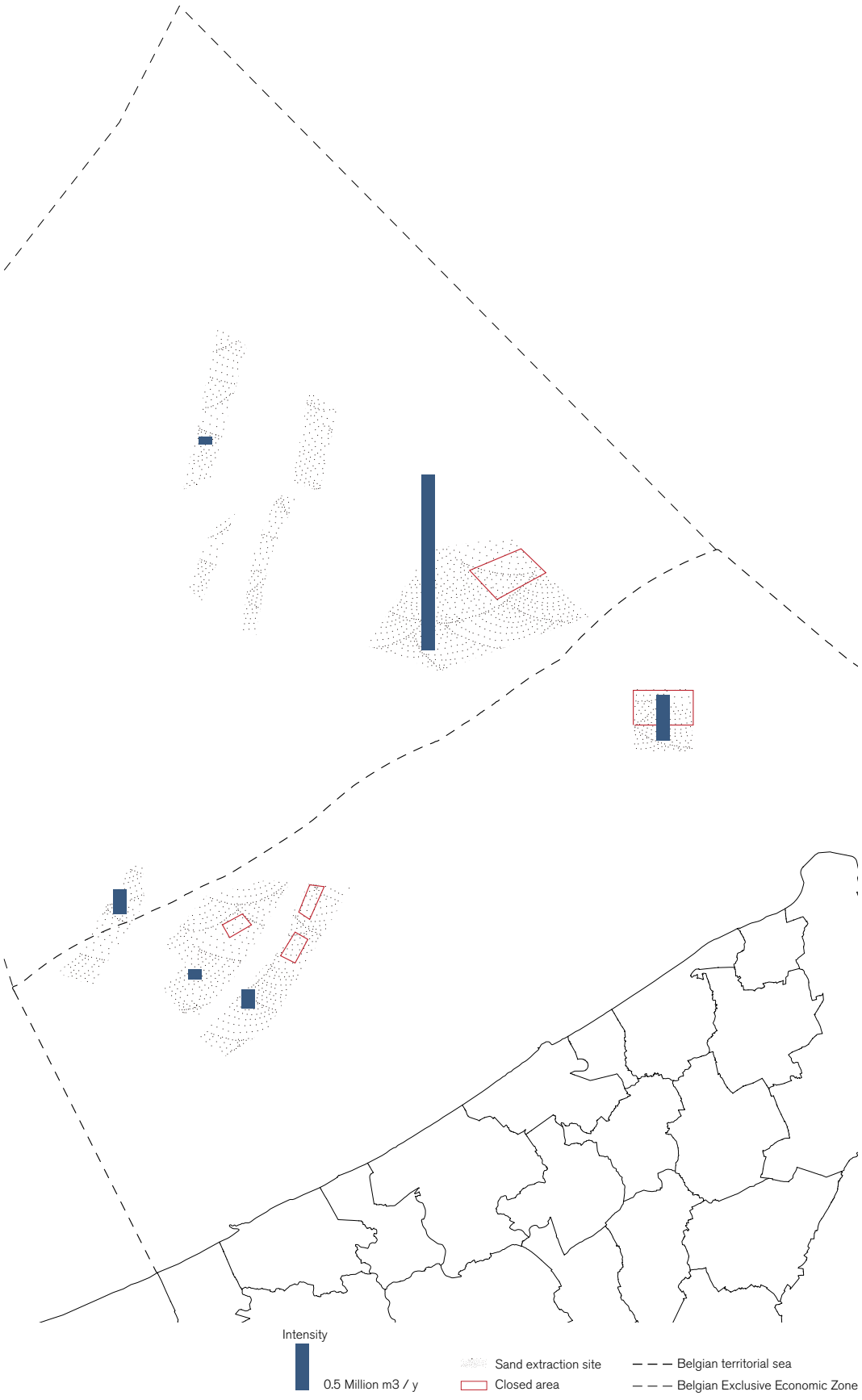


Fig.6-9 Sites of sand extraction in Belgian part of North Sea

Source: Made by the author based on kustportaal.be

Future challenges

Essentially, in Belgium, the base of the beach nourishment is determined by the balance between the 'supply' of sand from rivers and the sea, and the 'demand' for (or salvage space for) sand that is determined by the water depth. The sand cycle thus represents the most important supporting ecosystem service off the coast.

Facing the current climate change, this balance is weakened when the gradual increase in sea level is not compensated by a proportional supply of sediment from the rivers or the deeper sea. A study in the Netherlands shows that because of the climate change, the current sediment deficit in the diked lowlands of the Netherlands is estimated at 136 ± 67 million m^3/y. This causes coastal decline and threatens the longer term, maintaining safety and functions in the coastal area.

In the Belgium, the situation will become more serious. Because of the lack of large river estuaries in Belgium, most of the sediment comes from the sand extraction in the sea.

In order to understand how climate change (in this case, SLR) affects the sediment dificit, an estimation and simulation model is created by 'Metropolitan Coastal Landscape 2100', a research project launched jointly by the partners Space Flanders, the Flemish Government Architect and the Department of Mobility and Public Works.

According to this research, the coastal infill width in Belgian coastal plain varies between 1 and 5 km. Under the assumption that this coastal foundation is devoid of sediment supply, an indication can be derived for the growing sediment deficit as a result of sea level rise.

With an average width of this coastal foundation of 5 km, regarding the Flemish coast as a whole, the deficit is estimated at approximately 0.3 million m^3 per mm sea level rise per year. This means at the current rate of 2 mm / year, there is an increase of the deficit with the rate of 0.7 million m^3 per year. Assuming a gradual increase in the ascent rate to 9 mm / year in 2100, then the annual deficit grows to 1.1 million m^3 in 2030 and to 3 million m3 in 2100.

Based on this, we can initially calculate the current deficit is around 420,000 m^3/y, the deficit in 2030 will reach 660,000 m^3/y, and in 2100 will be 1,750,000 m^3/y. (Metropolitan Coastal Landscape 2100,

Therefore, more sustainable defence system is needed for the long-term protection and development.

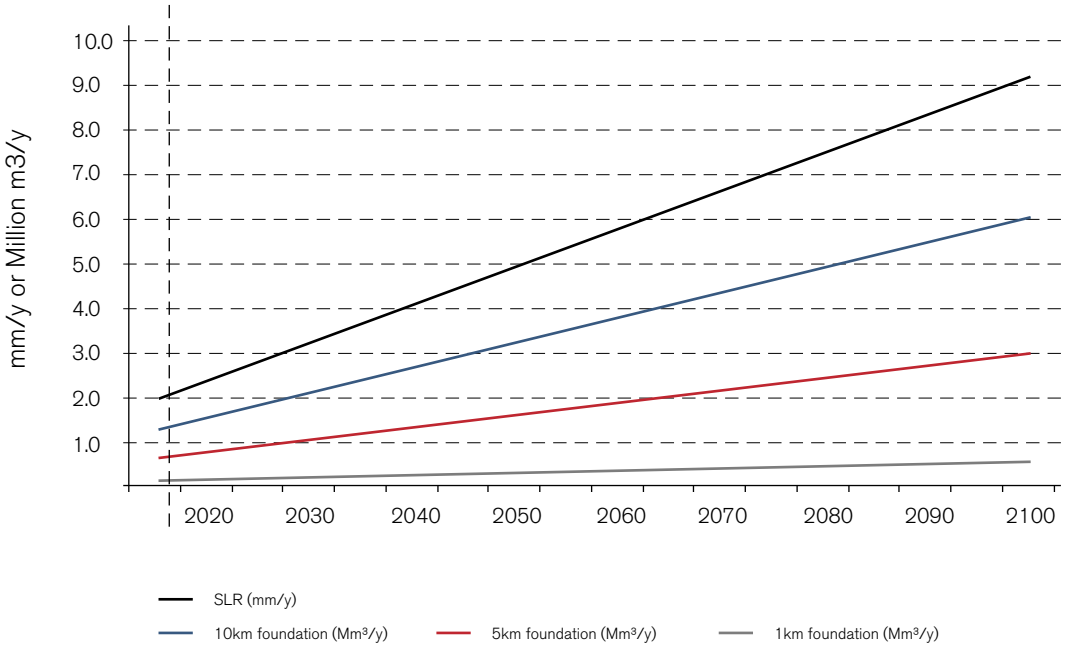


Fig.6-10 Prognosis for a linear increase in SLR and the parallel annual supplementation need to allow the Belgian coast to grow along with that increase

Source: Made by the author based on Metropolitan Coastal Landscape 2100

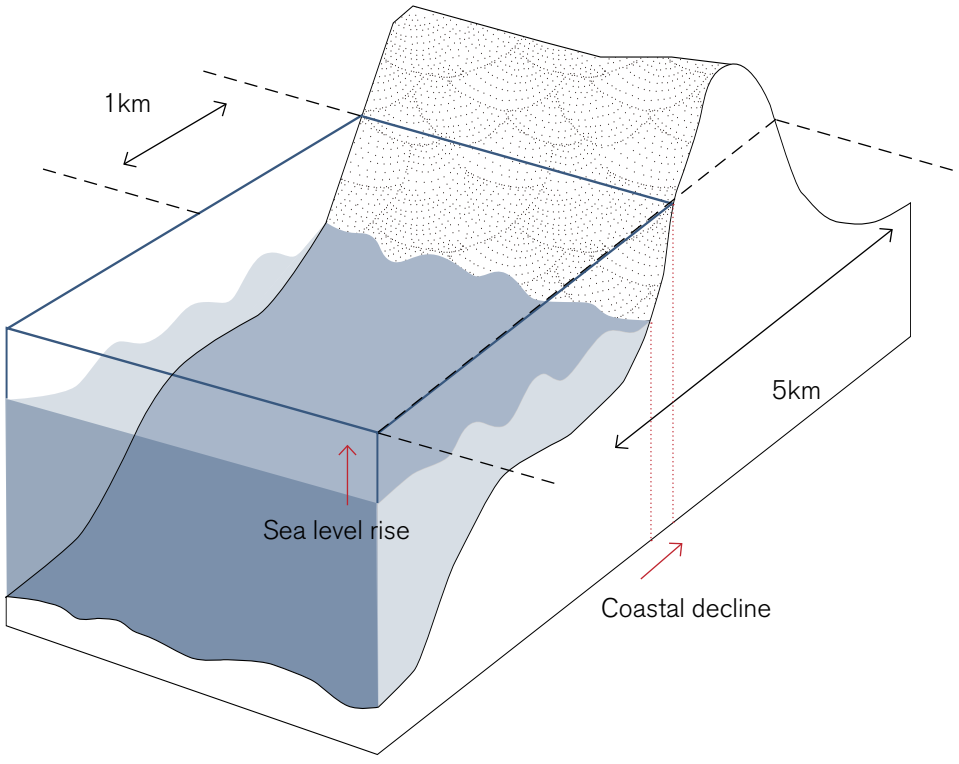


Fig. 6-11 Representation of the effect of sea level rise on the coastal location

Source: Made by the author based on Metropolitan Coastal Landscape 2100



Fig.7-1 Sea wall construction in Ostend

Source: https://www.mckeonstone.ie/services/ostend-seawall-defense-belgium/

07 Shifting the Thinking of Coastal Defence System

7.1 Conclusion of the Current Research
7.2 Definition and Assessment of Coastal Risks
7.3 Release the Stress

7.1 Conclusion of the Current Research

Risks

To conclude, areas with high chances of coastal flooding and coastal erosion, areas that are low-lying with low permeability, and areas where the current seawalls are weak are mapped. These areas are most vulneral regard to the future climate change.

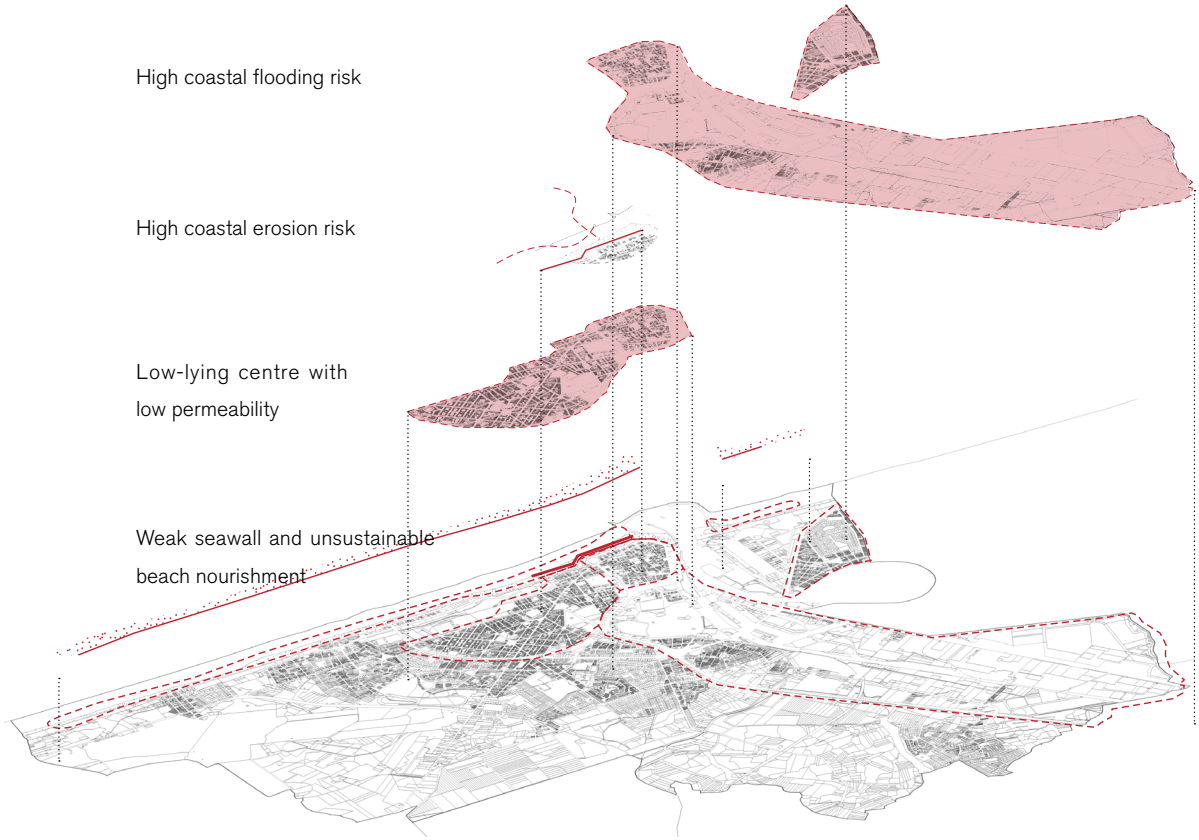


Fig.7-2 Map of risks

Source: Made by the author

Potentiality

On the other hand, there are also some areas in the city of Ostend with some positive characters, such as natural accumulation areas, high ecological marine areas and areas that has good base of green & blue networks. These areas can be considered as supportive elements for the later strategies and interventions.

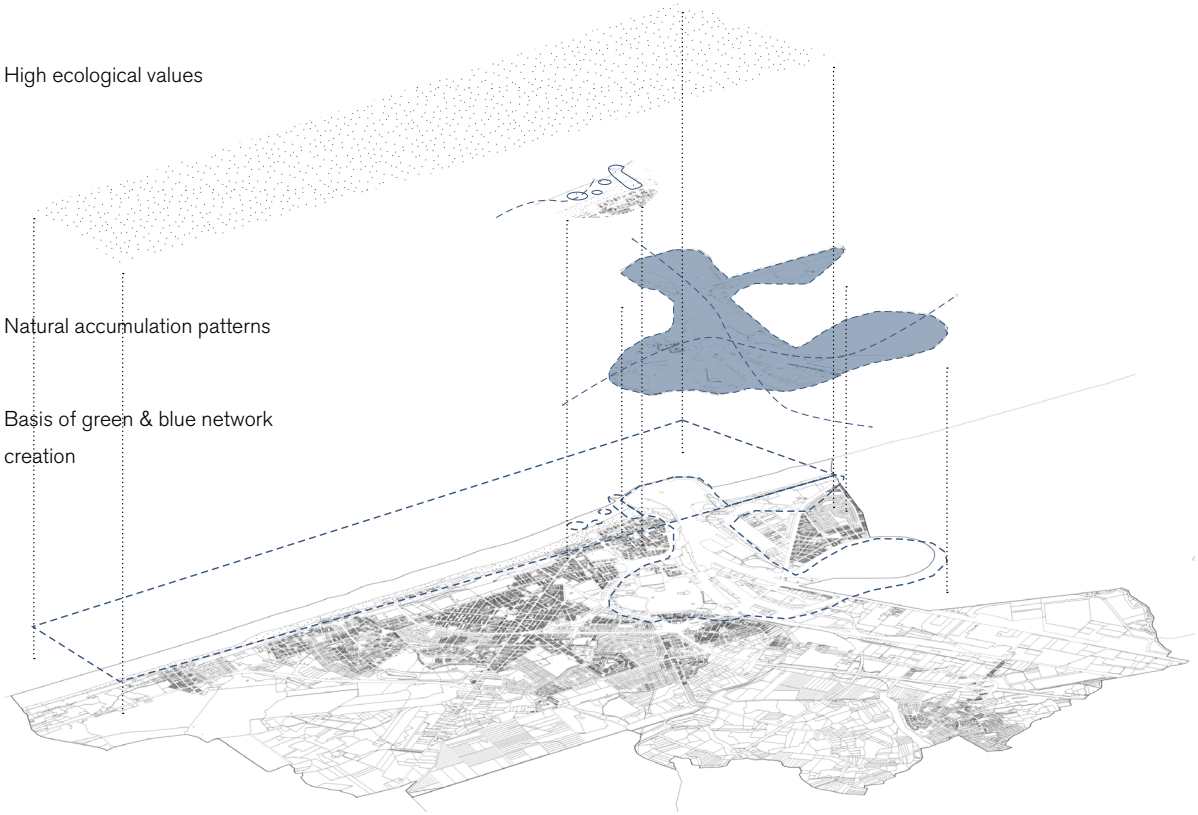


Fig.7-3 Map of potentiality

Source: Made by the author

7.2 Definition and Assessment of Coastal Risks

In order to show the abstract concept of coastal risks more specifically, the risks qualititive assessment method is introduced.

The 'Probability and Impact Matrix' is one of the most widely used risk assessment methods. It is based on the two components, namely, the probability of the risks occurrence and the impact on the research areas when they happends . The matrix is a two-dimensional grid that shows the likelihood of the risks occurrence and their effects the objectives very straightforword (Thorhallsdóttir, 2018).

Risk = Probability x Impact

More specifically, the probability is the possibility of a risky event occurring. The probability can be expressed in both qualitative and quantitative ways. When discussing probability in a qualitative manner, notions such as possibility, frequency etc. are used. It is also possible to describe the probability in a quantitive manner. This can be done by using scores assignment, percentages and frequencies (Curtis, P. & Carey, M., 2012). In this project, specifically, the probability is defined as the frequency and quantities of the overtopping water during the storm surge events.

Impacts are often defined as the consequences, or effects of a risk event on the project objectives. These impacts can be both beneficial or harmful to the objectives (Curtis, P. & Carey, M., 2012). The impact of risk events on different project objectives can be defined in both a qualitative and quantitative manner. These project objectives are cost, schedule, quality, scope, health, safety, etc.

Typically, the impacts are described relatively; as very low, low, moderate, high and very high, but often also defined using numerical scales. Dependent on the objective, the scales are given a description of what the impact entails (Project Management Institute, Inc., 2013). One risk event can affect more than one objective, so the impact of all the possible objectives effected must be considered. In this project, the impacts means the economic and life losses caused by the flooding events to urban systems and residents.

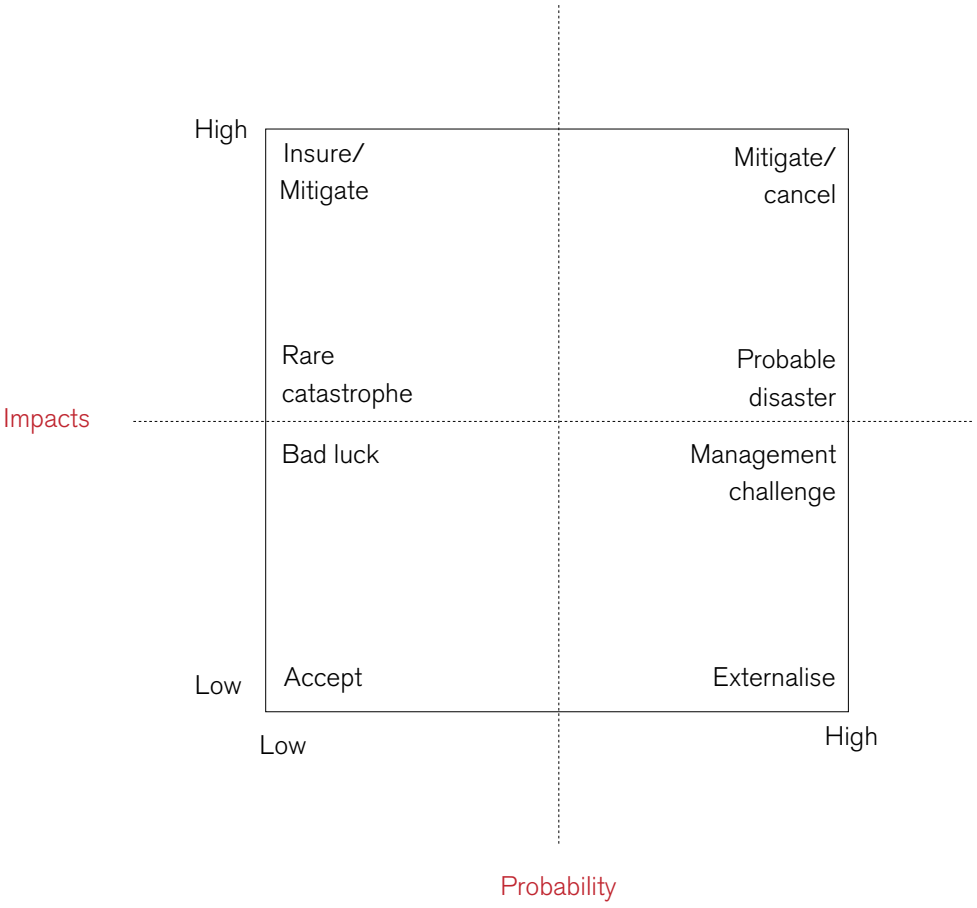


Fig.7-4 Risk Impacts and Probability Matrix

Source: Winch, G.M. 2010

7.3 Release the stress

Hold the line

The Flemish government has a Coastline Safety Masterplan to protect the Belgian coast, in the first phase on the short term. The Masterplan is designed "to combat a 1000-year storm." It maps the weak points and searches for a solution to ensure the safety for the entire coast until 2050. Another project of the Flemish government, Flemish bays, looks further ahead, with a time-frame until 2100. Its main goal is to approach climate change and sea level rises in an integral way using five pillars: Safety, Nature Quality, Attractiveness, Sustainability and Economic development. Here, the government is working closely with private dredging companies.

Effective measures included in the Coastline Safety Masterplan for 2050 are dune supplementations, beach elevations, storm surge barriers, the construction of storm walls, the reinforcement of existing dikes, the adaptation of dike slopes, etc. The entire Masterplan will cost 300 million euros, with 8 million to be added annually to the total cost in order to maintain the beaches.

The government decided to defend these zones by the "hold the line" principle, which means reinforce the defence line by strengthen and heighten the sea wall and maintain the beach nourishment.

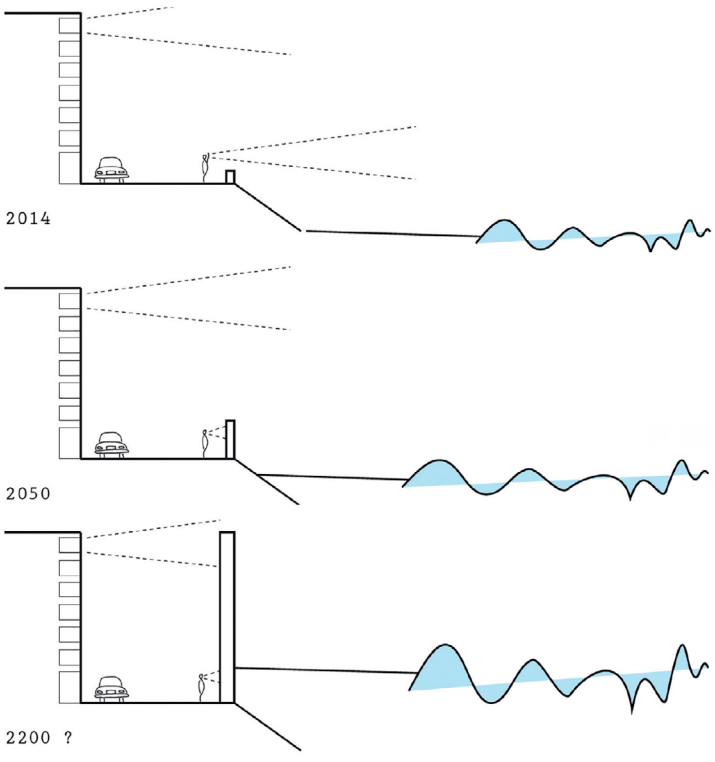


Fig.7-5 Holding the line

Source: Pillen, S., Scheerlinck, K., & Van Daele, E. (2018).

Unfold the line

The principle of 'holding the line' is actually trying to reduce the risks by reducing the probability. As a consequence, the total responsibility of coastal defence is all on the coastal lina and the current coastal defence system has became more and more engineering-based in order to block the risks away from urban and people.

However, as the matix shows, instead of only making efforts on probability reduction, the risks can also be reduced by reducing the impacts. Due to the difficulties of applying nature-based solutions in high-density urban areas only relying on reducing the probability, dealing with the impact at the same time offers a possibility.

As a conclusion, in stead of 'holding the line', we can actually 'unfold the line', which means the coastal defence could no longer be regarded as a line, but a zone that also includes sea and urban.

On the sea side, actions can be taken to mitigate the influences come from waves, currents, etc. On the urban side, better water management system can be introduced to reduce the losses and recovery time during the flooding. Therefore, the existing seawall and sandy beaches can no longer bear all the pressure from the coastal defence, and they can become more flexible.

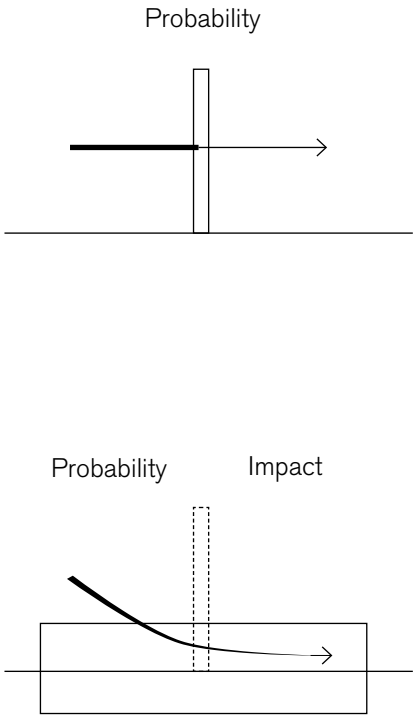


Fig.7-6 Diagram of 'unfold the line'

Source: Made by the author



Fig.8-1 Flooded city of Ostend

Source: Digital artwork by MiikeDV

08 Local Impacts & Identities

8.1 Local Flooding Senarios
8.2 Spacial Character
8.3 Social Character
8.4 Local Identities

8.1 Local Flooding Senarios

Design testing area

In order to have a more specific understanding of the impacts from the risks and also get base for the design, small-scale flooding simulation and research is necessary.

Here, based on the preliminary conclusions of the above studies, the city centre of Ostend has been selected as a small-scale influence and in-depth study area. In addition, due to the existence of the seawalls and harbors around the area, the direction of coastal flooding can be seen mainly from the northwest in this region, which could also help us to control and limit the variables while doing the small-scale simulations and calculations.

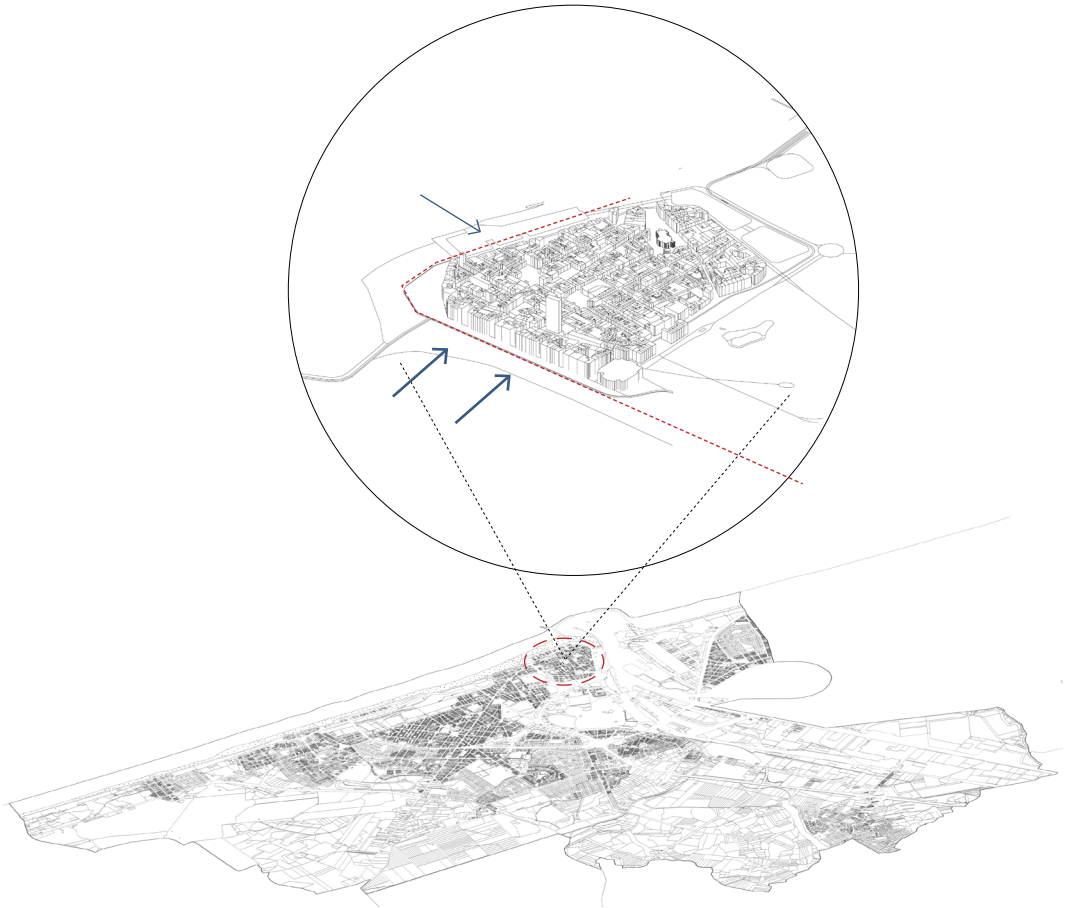


Fig.8-2 Design focusing area

Source: Made by the author

Methods

Here, the risks of coastal flooding can be regarded and quantified as the amount of the overtopping water at the time of the flooding events under the current conditions (sea wall as the main defence measure).

In a sequence of overtopping waves the maximum individual overtopping volume per meter run of the seawall, Vmax, can be calculated by the following equations (according to Wave Overtopping of Seawalls Design and Assessment Manual), and the outcome has been showed in the following pages.

$$N_{ow} / N_w = \exp(-C\,(R_* / r)^2) \quad \text{.....}$$

N_{ow}
The number of overtopping waves
N_w
The number of waves in the sequence
C
Empirical coefficient.
For the sea wall slope 1:4, C=110.5
R_*
Dimensionless crest freeboard
r
Roughness coefficient
For smooth concrete, r=1

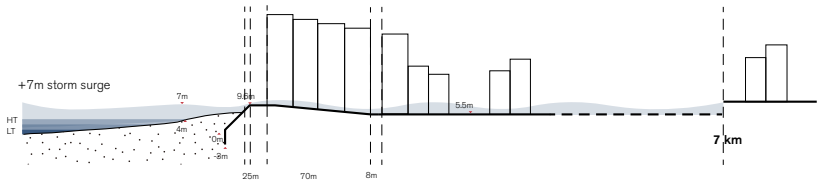
$$V_{bar} = Q T_m N_w / N_{ow} \quad \text{.....}$$

V_{bar}
Mean individual overtopping volume (m^3)
Q
Mean overtopping discharge rate per metre run of seawall
T_m
Mean period of the waves at the toe of the structure (s)

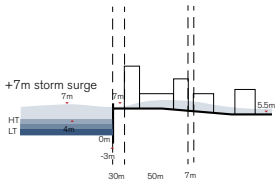
$$V_{max} = a\,(\ln(N_{ow}))^{1/b} \quad \text{.....}$$

V_{max}
Maximum individual overtopping volume
For Sop =0.04
a=0.96 **V**bar
b=0.92

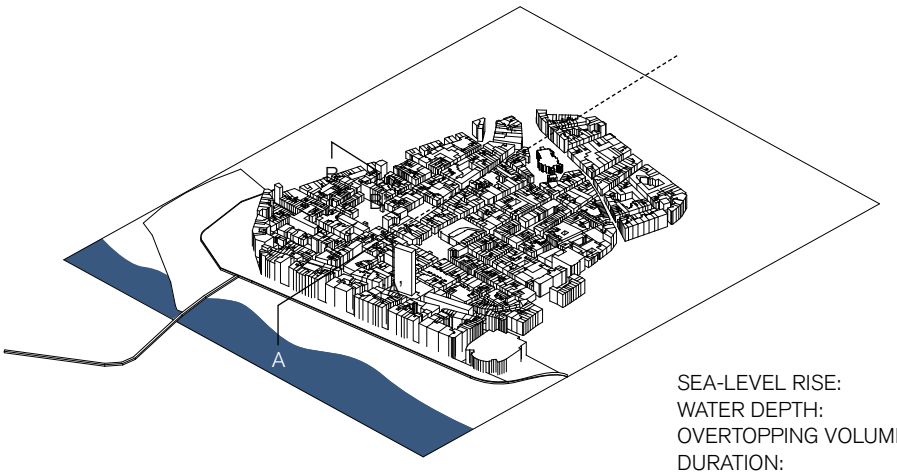
Current sea level & +7m TAW storm surge



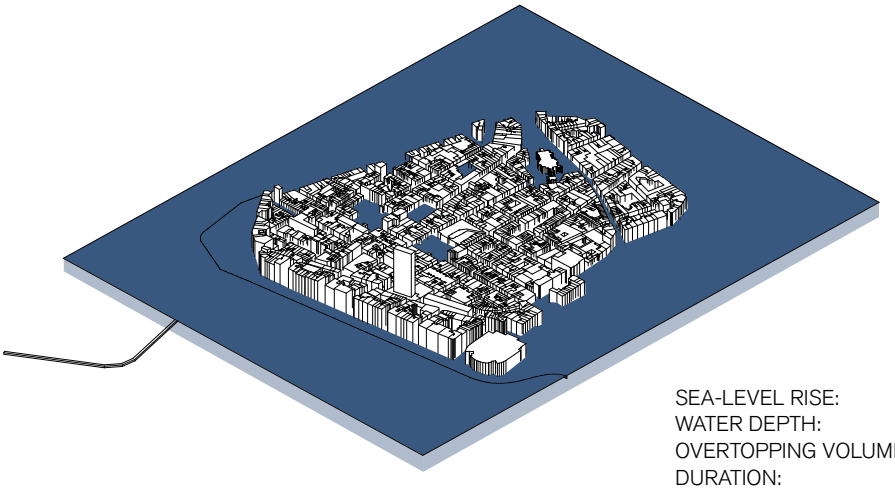
Schematic section A-A'



Schematic section B-B'



SEA-LEVEL RISE: 0m
WATER DEPTH: /
OVERTOPPING VOLUME: /
DURATION: permanent



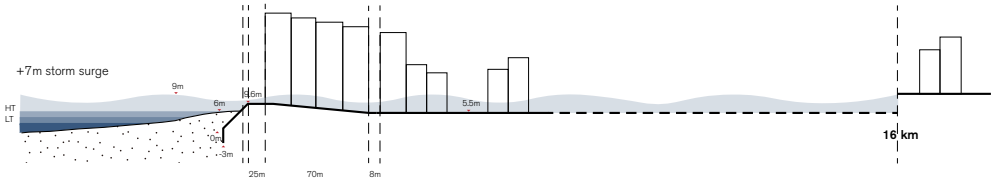
SEA-LEVEL RISE: 0m, 7 TAW STORM
WATER DEPTH: 2m
OVERTOPPING VOLUME: 30,000 m3
DURATION: temporary （48 hours)

Fig.8-3 Storm surge simulation under current situation

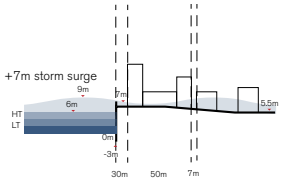
Source: Made by the author

0m-2m sea level rise & +7m TAW storm surge (2m SLR as an extreme)

In this situation, the average sea level has reached the height of current sandy beaches.



Schematic section A-A'



Schematic section B-B'

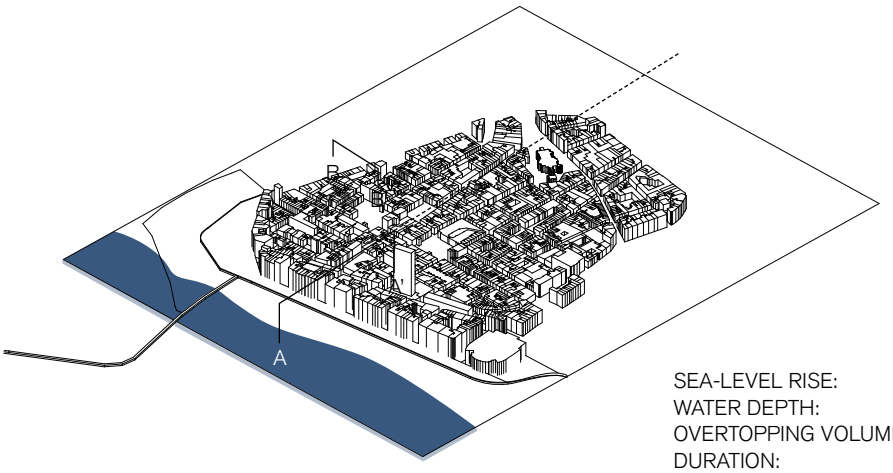
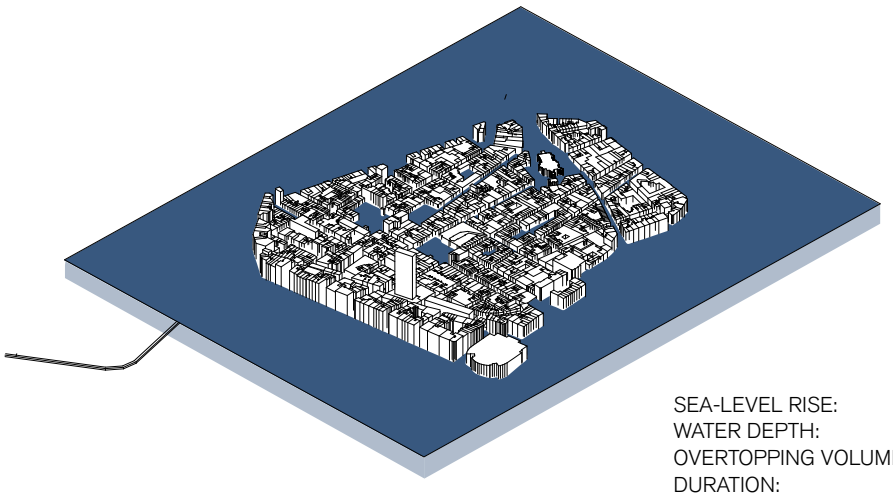


Fig.8-4 Storm surge simulation under 2m SLR

Source: Made by the author

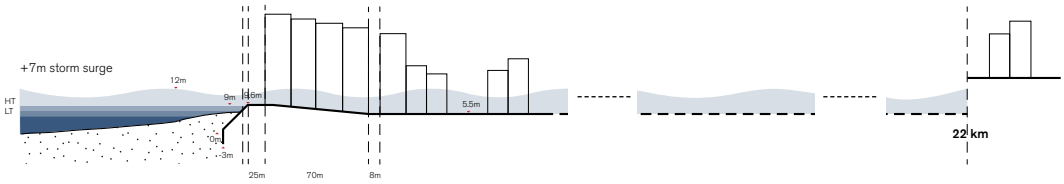
SEA-LEVEL RISE: 2m
WATER DEPTH: /
OVERTOPPING VOLUME: /
DURATION: permanent



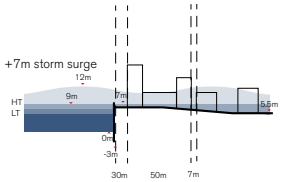
SEA-LEVEL RISE: 2m, 7 TAW STORM
WATER DEPTH: 4m
OVERTOPPING VOLUME: 143,364 m3
DURATION: temporary （48 hours)

2m-5m sea level rise & +7m TAW storm surge (5m SLR as an extreme)

In this situation, the average sea level almost reaches the height of current sea walls.



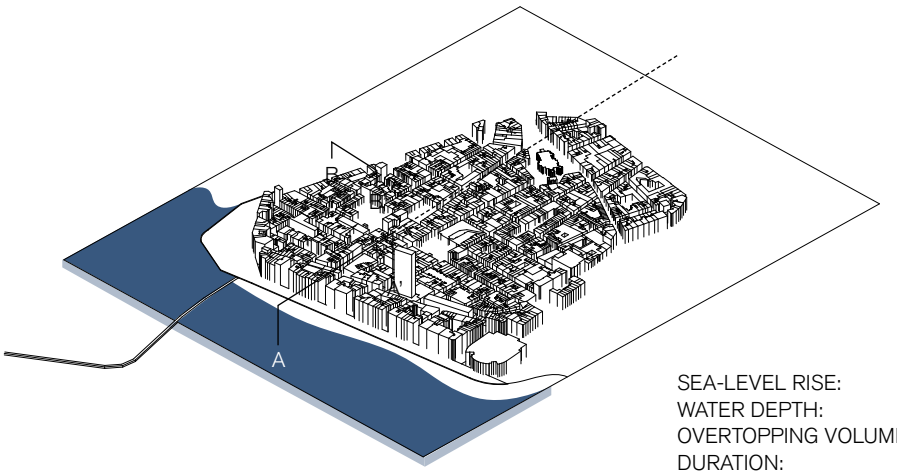
Schematic section A-A'



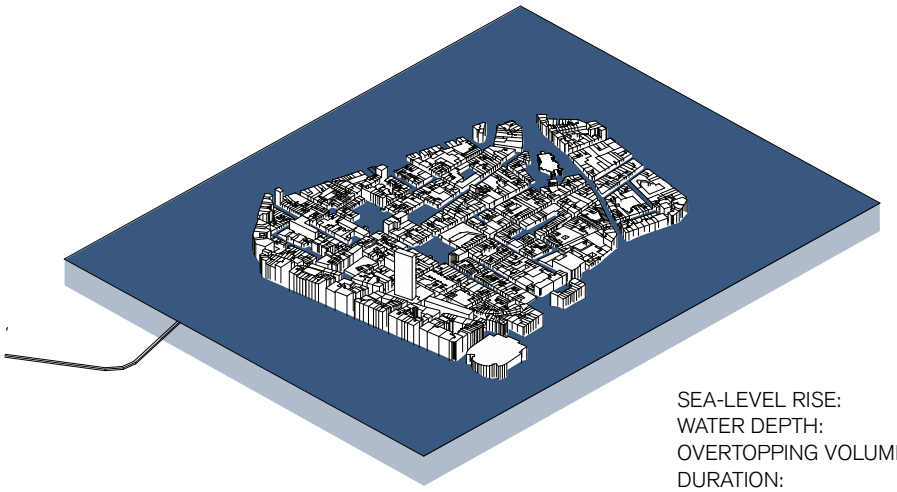
Schematic section B-B'

Fig.8-3 Storm surge simulation under 5m SLR

Source: Made by the author

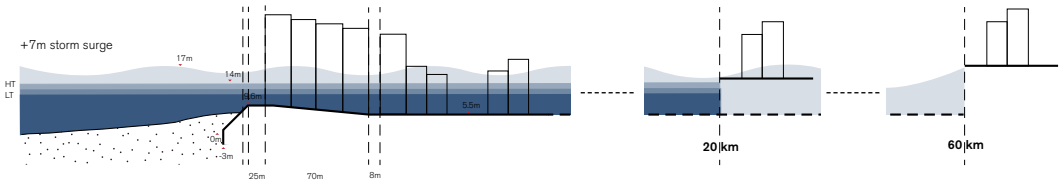


SEA-LEVEL RISE: 5m
WATER DEPTH: /
OVERTOPPING VOLUME: /
DURATION: permanent

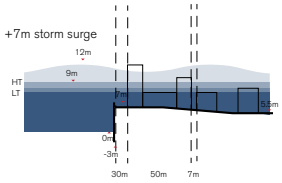


SEA-LEVEL RISE: 5m, 7 TAW STORM
WATER DEPTH: 7m
OVERTOPPING VOLUME: 672,900 m3
DURATION: temporary （48 hours)

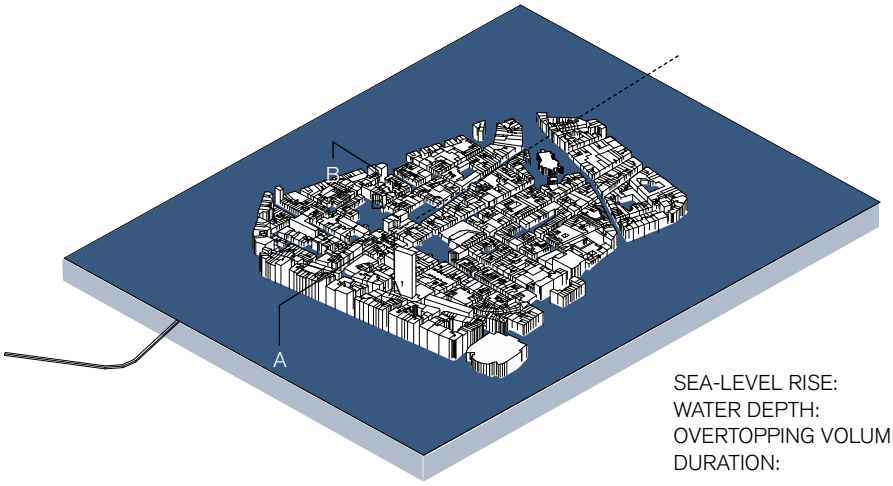
5m-10m sea level rise & +7m TAW storm surge (10m SLR as an extreme)



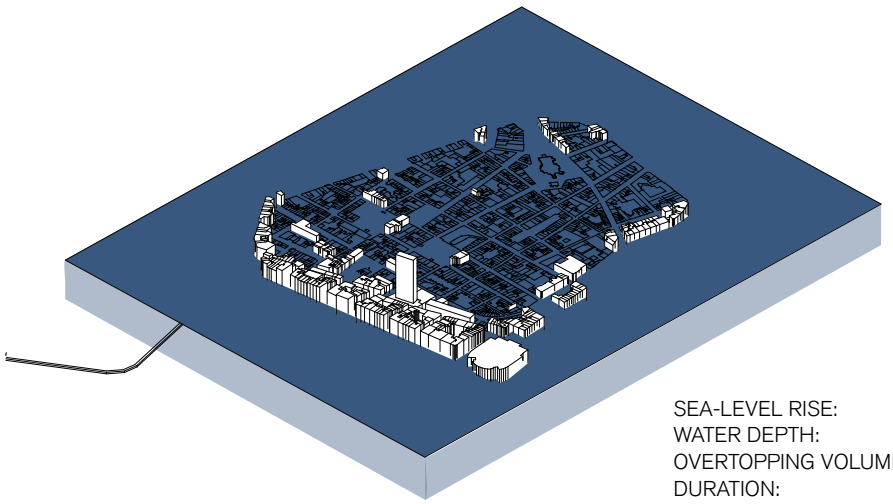
Schematic section A-A'



Schematic section B-B'



SEA-LEVEL RISE: 10m
WATER DEPTH: 7m
OVERTOPPING VOLUME: 3,920,000 m3
DURATION: permanent



SEA-LEVEL RISE: 10m, 7 TAW STORM
WATER DEPTH: 10m
OVERTOPPING VOLUME: 5,600,000 m3
DURATION: temporary （48 hours)

Fig.8-4 Storm surge simulation under 10m SLR

Source: Made by the author

Impacts conclusions and periods scheme

After the quantification of the coastal flooding risks, the impacts of how high and how far the overtopping water can reach has been showed much more clear. This also helps us to determine the time period of the project.

Transitional period is from now to 2040, and the main goal is to cope with the +7 TAW strom surge at the current sea level. In this period, short-term intervention and long-term strategies should be made for the future.

Strengthening period and Risky period represent for 0m-2m SLR when the sea level reaches the height of current sandy beaches (2040-2070) and 2m-5m SLR when the sea level reaches the height of current sea walls (2070-2100). In these periods, the main goal is dealing with the super storm surge under the influence of rising sea levels and uncertainties.

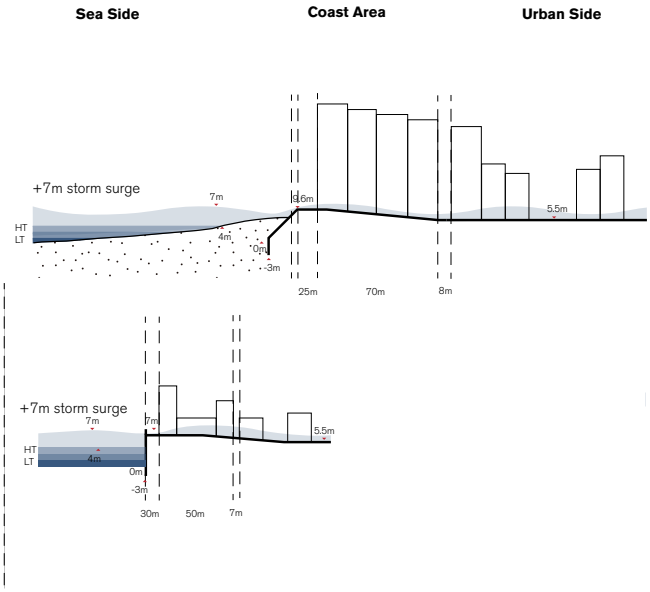
Limited period represents the 5m-10m sea level rise (after 2100), in this worst situation, there is huge uncertainty that it becomes too vague and might be not possible really design for it. Thus, it is the limitation set for this project and only some imaginary possibilities will be showed.

Transitional Period

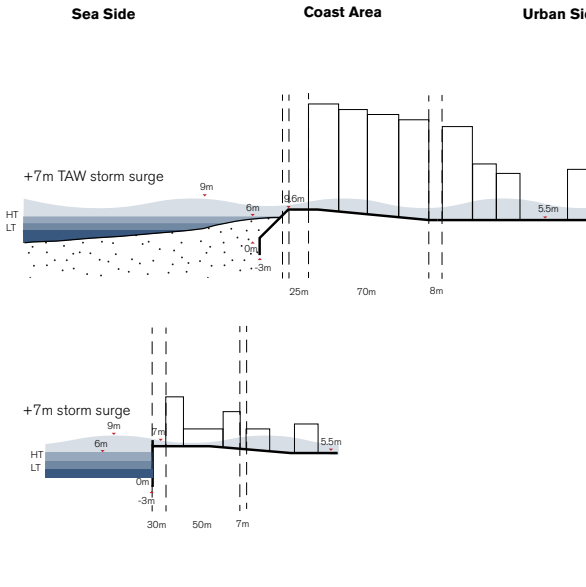
Strengthening Period

Impacts

0m SLR
+7 TAW



0m-2m SLR
(2m as an extreme)
+7 TAW



Risky Period

Limited Period

2m-5m SLR
(5m as an extreme)
+7 TAW

5m-10m SLR
(10m as an extreme)
+7 TAW

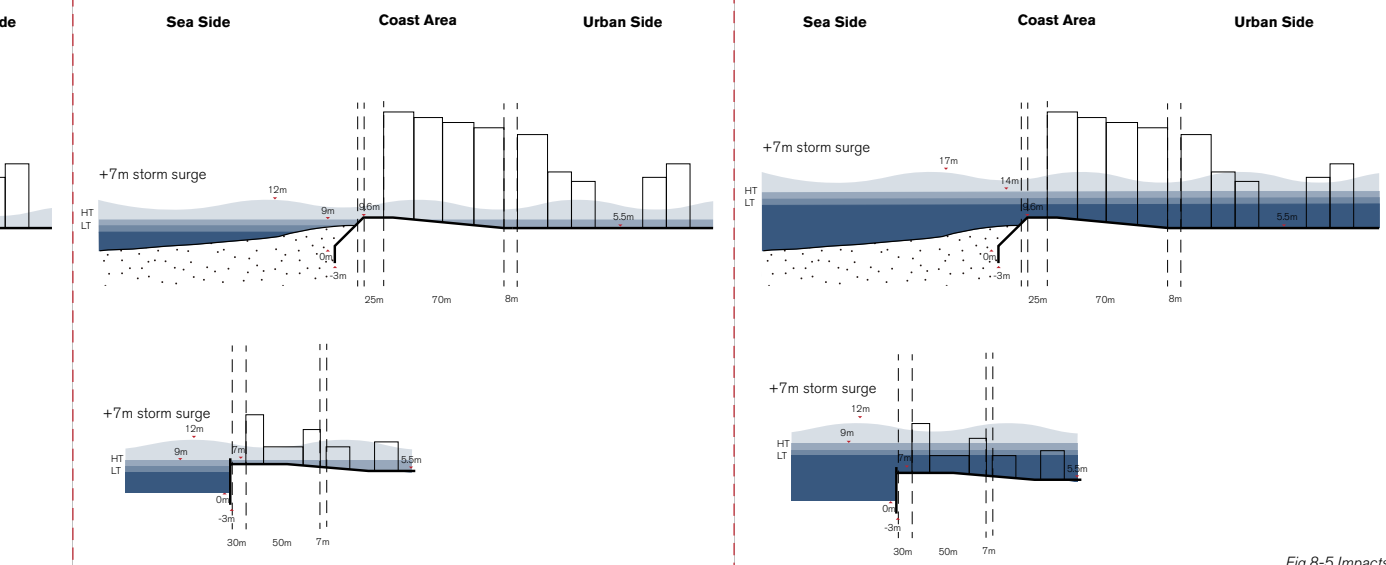


Fig.8-5 Impacts chart

Source: Made by the author

8.2 Spacial Character

Infrastructure network

In the city centre of Ostend, the dike and the centre are currently separated by the heavy transportation infrastructure with private cars and trucks(the main road of the city), the main purpose of this traffic line is provide connection between railway station and other west areas of the city. This road mainly has two negative effects, the impermeable pavement and the influence on the accessibility of the dike and the beaches.

The public transportation (buses and trams) are mainly going through more inland areas.

Parking

The city centre has a lot of parking areas, including both surface parking lot, side parking along the streets and some underground parking lots.

The surface parking accounts for more than one third of the total area of open space in city centre.

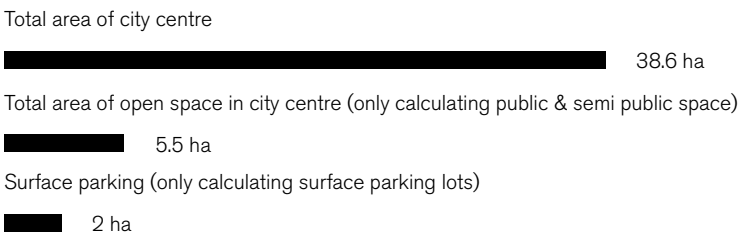




Fig.8-6 Transportation network in city centre of Ostend

Source: Made by the author



Fig.8-7 Walk and bike environment in city centre of Ostend

Source: Made by the author



Fig. 8-8 Van Iseghemlaan

Source: Google earth



Fig.8-9 Visserskaai

Source: Google earth



Fig.8-10 Vindictivelaan

Source: Google earth



Fig.8-11 Ostende Parking

Source: Google earth



Fig.8-12 Indigo Park - Parking Mijnplein in city centre

Source: Google earth



Fig.8-13 Side parking on Kapucijnenstraat

Source: Google earth

Facilities

The main commercial facilities in the city centre include commercial streets (Kapellestraat, Adolf Buylstraat in the inland centre and some part of Visserskaai on the east dike). Besides, a large shopping mall locates next to the old square. During weekend, there will be a open market at the square. The commercial facilities serve both tourists and local people.

The Casino Oostende, Cultuurcentrum and Catholic church are the main cultural centres where lots of public activites happend (mainly used by local residents).

Heritage

The heritage sites in Ostend is more than monuments and historic architecture, the open spaces close to the coastline have the potential to represent the historical struggle between the sea and the shore in a compelling way.



Fig.8-14 Map of facilities in city centre of Ostend

Source: Made by the author



Fig.8-15 Map of heritage in city centre of Ostend

Source: Made by the author



Fig.8-16 Shopping mall

Source: Google earth



Fig.8-17 Museum Zeilschip Mercator

Source: Photo by author



Fig.8-18 Cultuurcentrum De Grote Post

Source: Google earth



Fig.8-19 Zee excursies

Source: Google earth



Fig.8-20 Casino - Kursaal

Source: Google earth



Fig.8-21 Sint-Petrus-en-Pauluskerk

Source: Google earth

Open space & accessibility

The main public open space consists of sea dike, sea square and squares in the city centre, they are all hard paved and the green space in the city centre is very few.

Semi-public space means the space is accessible for the public, but the main function of the space is for the neibourhood, such as neibourhood garden and open space in school or other piblic buildings.

Private courtyard consists of the areas inside the block that are used for parking or storage, and the family housing's courtyards.

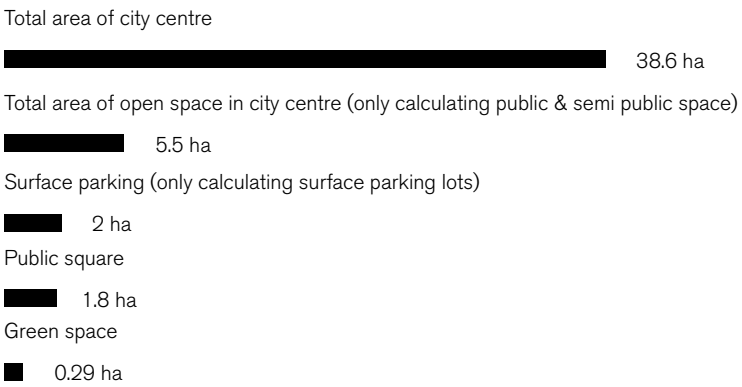
Public network

To conclude the previous analysis, we can clearly see that there are two part of the public activities concentration in city centre of Ostend.

The first concentration is near the sea where the dike and the beach offer a lot of open space. However because of the occupation of high-rise apartment buildings, some other public facilities (such as commercial and recreational functions) are lacking.

Another is more inland which consists of commercial street and some culture centres.

The current public network of these two part is quite seperated due to the main road surrounding and the functionality.





Public open space
Semi-public open space
Private courtyard
Green space
Courtyard parking

Fig.8-22 Map of open space system city centre of Ostend

Source: Made by the author



Main road
Main walking paths
Main public space
Important public building

Fig.8-23 Map of public network in city centre of Ostend

Source: Made by the author



Fig.8-24 Residential buildings on the dike

Source: Photo by the author



Fig.8-25 Vacant ground floor on the dike

Source: Photo by the author



Fig.8-26 East beach occupied by industrial facilities

Source: Photo by the author



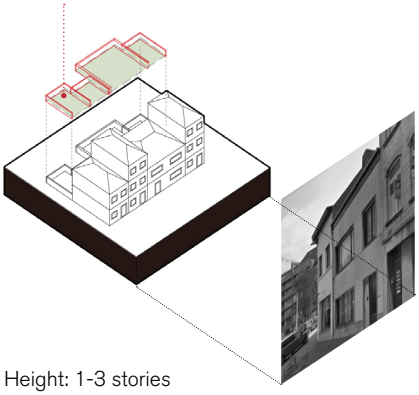
Fig.8-27 Bare beach after the windy weather

Source: Photo by the author

Building typologies classification

There are mainly 4 types of buildings, the main classification criteria are FSI (building Intensity) and the openness of its external space. At the same time, the relation between type of residents and the type of buildings can also be found.

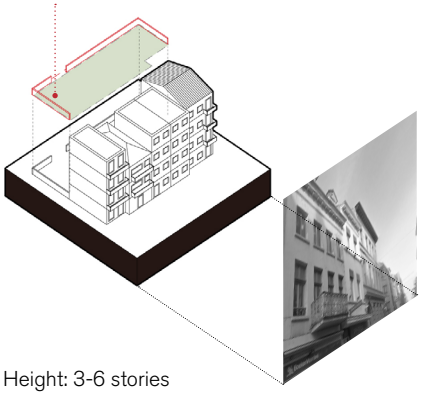
Closed courtyard



Height: 1-3 stories
Width: 3m-10m
Residents: Local family / Tenant

Terraced family house

Closed / semi-open courtyard

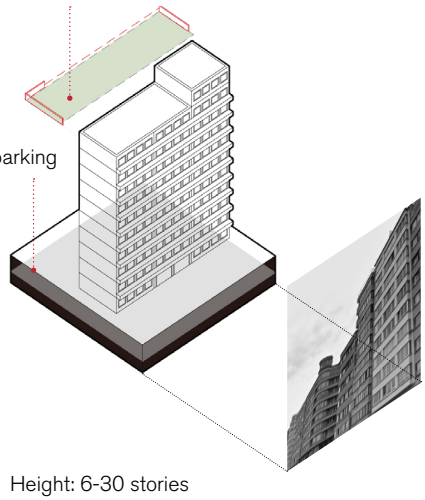


Height: 3-6 stories
Width: 3m-15m
Residents: Local family / Tenant / Tourists

Multi-family house

Semi-open / open courtyard

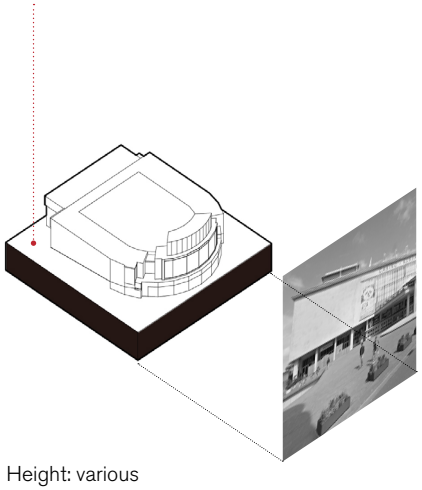
Underground parking



Height: 6-30 stories
Width: usually >15m / the whole block
Residents: Tourists / Tenant / Local family

High rise apartment

Open space



Height: various
Width: various

Public building

Fig.8-28 Building typology in city centre of Ostend

Source: Made by the author

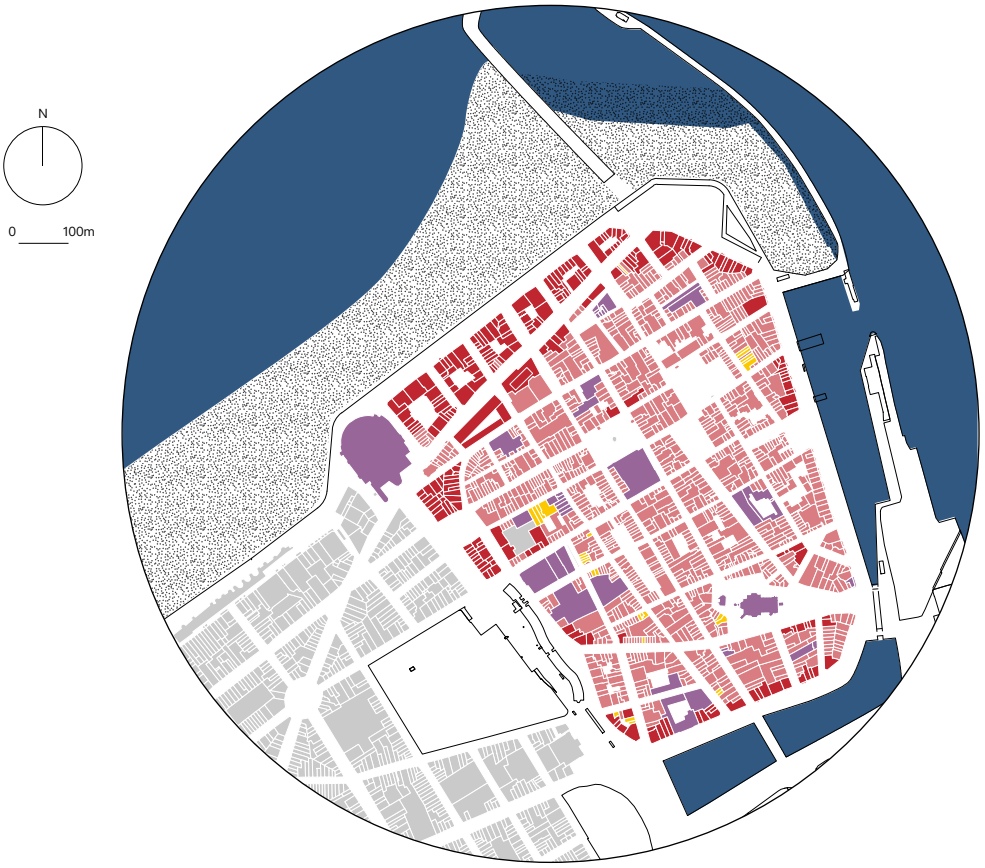
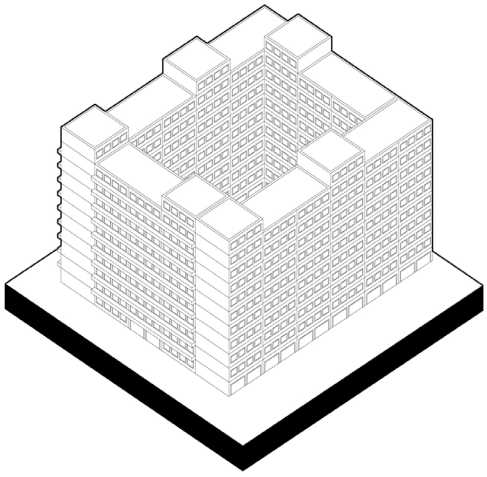


Fig.8-29 Building typology distribution

Source: Made by the author

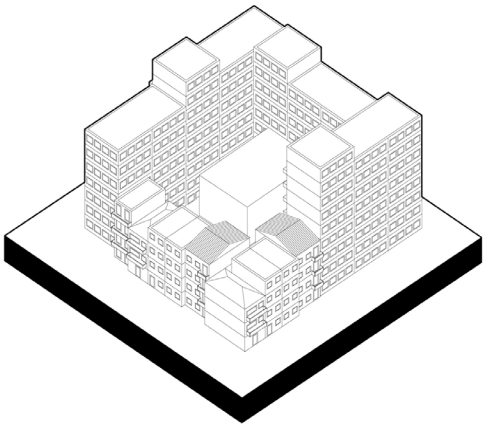
Block typologies classification

Based on the building typologies classification, the typologies of blocks can also be analysed by different buildings combination. Here four main typologies are summarized, each of them has different impacts on urban environment and difficulty of transformation.



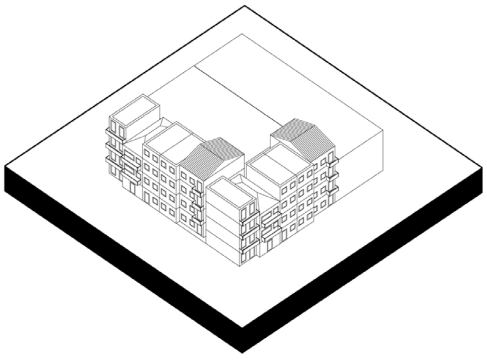
Holiday apartments
View blocking
Heat island effects

New 'Atlantic wall'



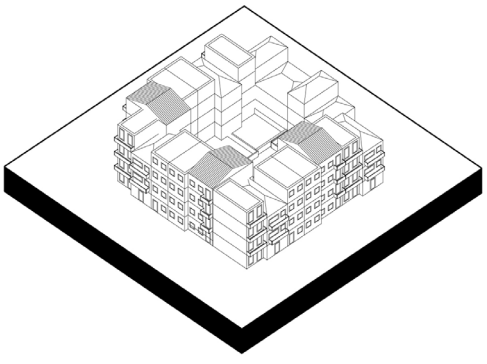
Holiday appartments with family houses
Private courtyard or storage building inside

Wrap and encroachment



Public building with family houses

Mixture of housing and functional building



Family housing block
Private courtyard
Complex ownership

Neighborhood living

Fig. 8-30 Block typology in city centre of Ostend

Source: Made by the author



Fig.8-31 Block typology distribution

Source: Made by the author

8.3 Social Character

Population density

Ostend has a little more than 71,000 inhabitants in 40,900 residential facilities (Land Registry, 2015). Population growth in Ostend has been limited in the last 10 years (103% compared to 110% in the comparable cities). The natural growth is negative. The dependency ratio is very high: 80% of the population is not economically active. The number of young people in the city is falling. The number of households is on the rise, but not as strong as the Flemish average (compared with reference year 2005: Ostend 104% Flanders and 109%).

Based on the demographic projection of the SVR, by 2024 the municipality can expect around 1500 new residents. This represents an additional need for 790 new homes. However, the housing policy plan aims at 3000 new homes by 2020. There will therefore be room for 2210 extra households or more than 4000 inhabitants. Ostend therefore opts for an increase in the number of inhabitants, aiming for a younger and active middle class.

From the current statistics (omgevingsanalyse Oostende 2015) and according to the municipality person, it can be seen that during the normal time, the city centre is actually not the most dense areas. However, during the weekends or holidays, the population in the city centre will be increasing to nealy twice than normal. This phenomenon tells us the housing sector in the city centre faces large chanllenge on balance between local residence and tourists. Besides, living facilities in the city centre should also be more flexible to meet the different requierment during different time.



Fig.8-32 Population density during normal time

Source: Made by the author based on omgevingsanalyse Oostende 2015



Fig.8-33 Population density during weekends and holidays

Source: Made by the author based on omgevingsanalyse Oostende 2015

Vulnerable community

There is a sharp rise in the underprivileged index in Ostend: 25% of the children of Ostend are born into a family with underprivilegedness. And the property prices show Ostend as an affordable municipality; all types of real estate are cheaper than the Flemish average.

Ostend is a city with many tenants: 45% of the patrimony is rented out, only 55% is occupied by the owner. 18% of the tenants have payment difficulties and 37% of those over 60 have a "seriously inappropriate home". Second housing that is usually bought by people from other cities for holiday living make up approximately 16% of the total assets; that is a lot lower than the other coastal municipalities. However, most of these holiday second houses are located in the city centre.

Ostend has a wide range of leisure activities (culture, youth and sport) compared to the rest of Flanders, with sufficient youth infrastructure and initiatives, but a low number of childcare places (38% compared to the Flemish average of 48%). Relatively few places are available in residential care for the elderly.

From the social statistics, it can be seen that except for the large quantities of holiday housing, the city centre also have large propotion of elderly people. Considering the lack of aged services, the city centre is one of the most vulnerable and unstable communities.

Low level of risks awearness

Beside, according to the interview and the questionaire, the level of the residents' awearness regarding to the storm surge flooding is very low. One of the reasons could be the current coastal defence strategies have worked, so the serious strom surge events that caused huge losses like one in 1953 has not happened for a long time. Another reason might be the lacking of the publicity and education of history events and future risks.

The current strategies are not sustainable in the long-term and also reduce people's risk awareness, causing greater uncertainty.

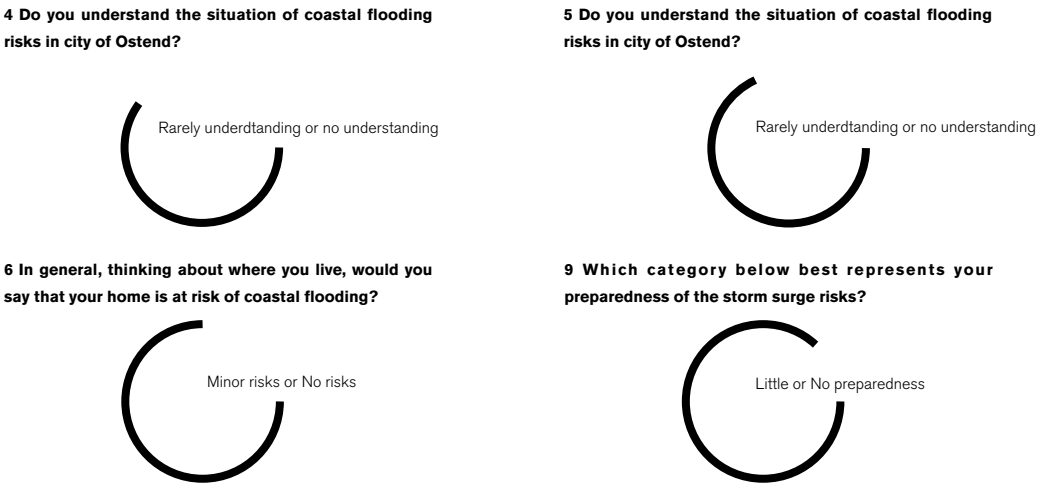
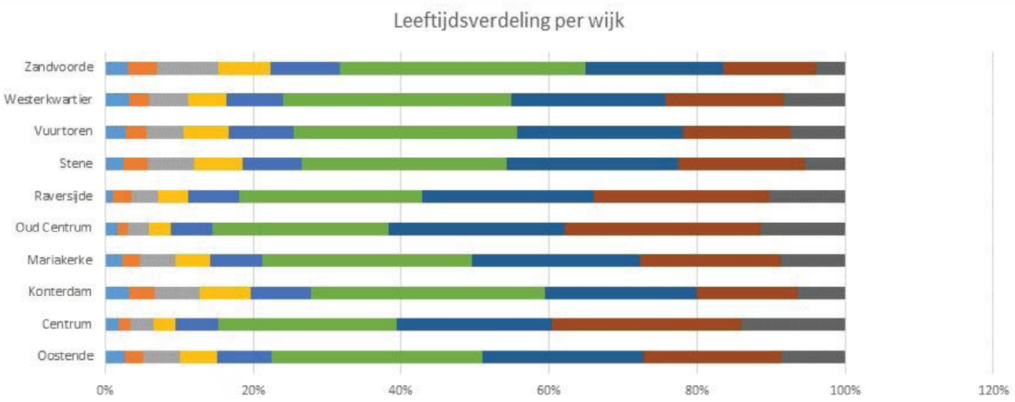


Fig.8-34 Selection of some questions and outcomes about risks awearness in the questionaire

Source: Summarized by the author



	Oostende	Centrum	Konterdam	Mariakerke	Oud Centrum	Raversijde	Stene	Vuurtoren	Westerkwartier	Zandvoorde
0-2 jaar	3%	2%	3%	2%	2%	1%	3%	3%	3%	3%
3-5 jaar	3%	2%	3%	2%	1%	2%	3%	3%	3%	4%
6-11 jaar	5%	3%	6%	5%	3%	4%	6%	5%	5%	8%
12-17 jaar	5%	3%	7%	5%	3%	4%	7%	6%	5%	7%
18-24 jaar	7%	6%	8%	7%	6%	7%	8%	9%	8%	9%
25-49 jaar	28%	24%	32%	28%	24%	25%	28%	30%	31%	33%
50-64 jaar	22%	21%	21%	23%	24%	23%	23%	22%	21%	19%
65 - 79 jaar	19%	26%	14%	19%	26%	24%	17%	15%	16%	12%
80+ jaar	9%	14%	6%	9%	12%	10%	5%	7%	8%	4%

Fig.8-35 Schematic elevation view of 'amphibious units'

Source: Omgevingsanalyse Oostende 2015



Fig.8-36 Distribution of vulnerable community in Ostend

Source: Made by the author based on "Kustlint Oostende" 2016-2017

8.4 Local Identity

Combine both spatial characters and social characters, the identity of the city centre can be concluded.

First of all, it is one of the areas most threatened by coastal flooding due to its location and relative height. Secondly, due to the particularity of its social structure, most of the high-rise apartments are used as holiday second housing, and the occupancy rate is usually higher during summer. However, due to the local climate, the flood events are more frequent in winter and spring, which mwans in the high-risky season, the high rise buildings are usually has high vacancy rate while the most affected people are residents living in lower houses.



Fig.8-37 Main square and traffic

Source: Google earth



Fig.8-38 Rock Strangers - art work by Arne Quinze in sea Square of Ostend

Source: Photo by the author

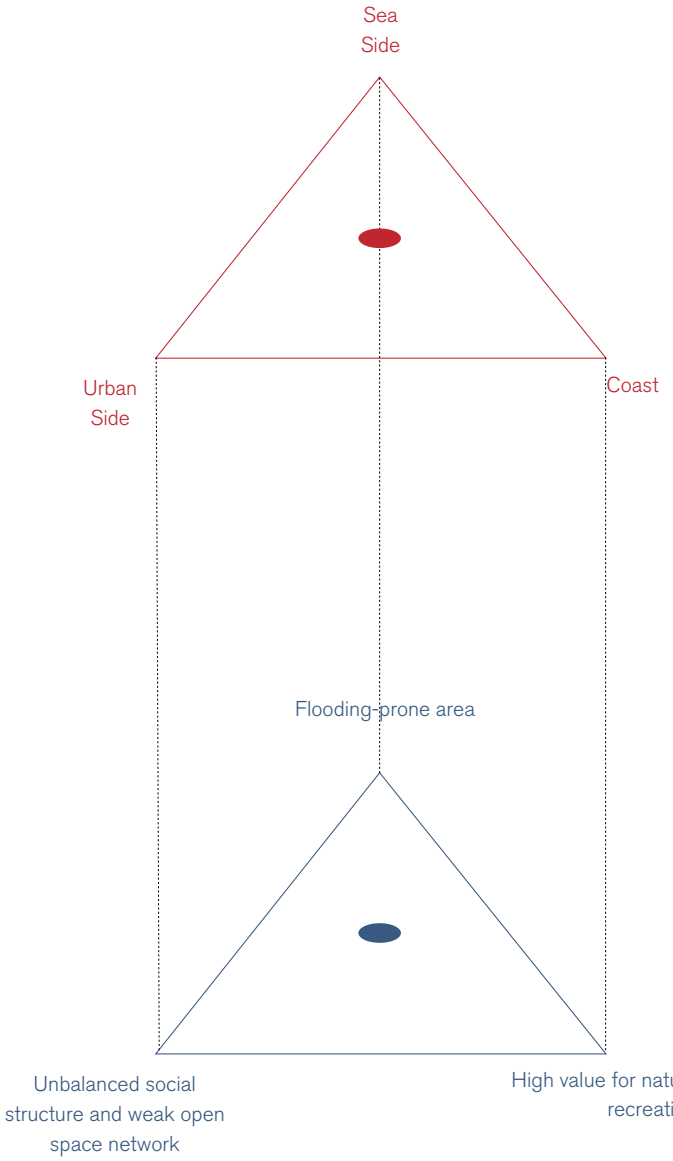


Fig.8-39 Diagram of local identity

Source: Made by the author



Fig.9-1 Ostend break water in harbour area

Source: Photo by the author

09 Local Design Testing

9.1 Design Objectives
9.2 Strategies
9.3 Intervention Scheme
9.4 Transitional Period
9.5 Strenghthening Period
9.6 Risky Period
9.7 Limited Period

9.1 Design Objectives

The overall analysis and the conclusion of local identity give us clear design direction. Same as the research objectives, the design objectives are also divided into sea side, coast and urbanside. The main goal of interventions in the focusing area is directly dealing with the vulnerability in coastal risks defence, social aspects and also the quality of life. At the same time, we must give full play to local advantages and make rational use of existing resources and values.

Thus, the design goals can be concluded as Safety, Nature Restoration, Living quality and urban development corresponding to the local identies.

Therefore, the integrated coastal defence system can actually serve as a medium for connecting the three design subjects. Taking the coastal defence system transformation as a trigger point, connecting three major parts (sea, urban and coast), achieving three goals and creating other added value.

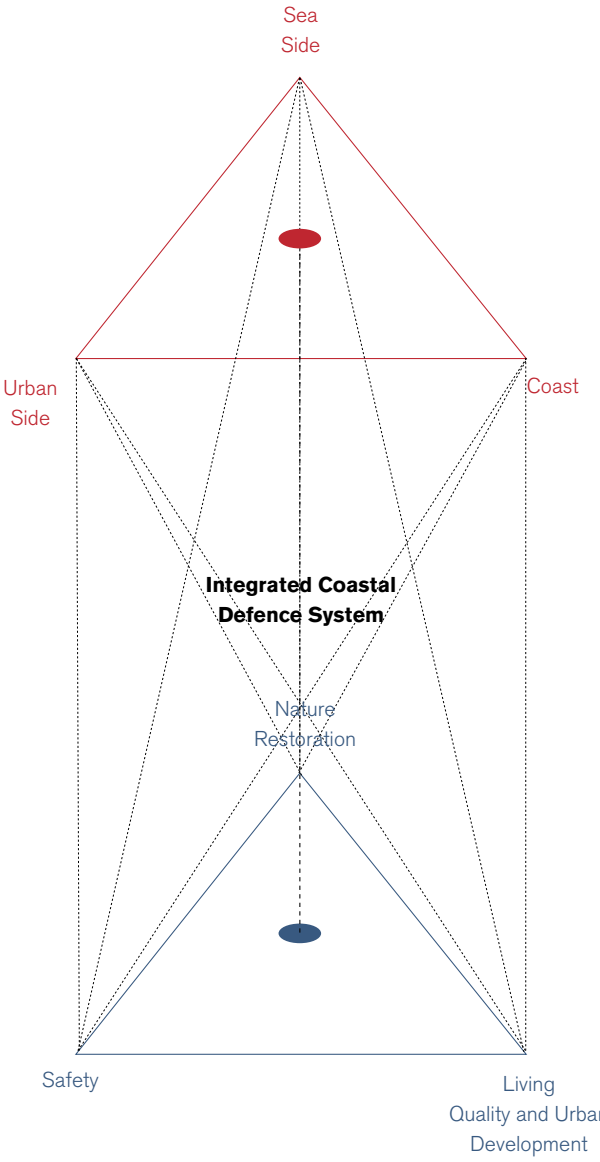


Fig.9-2 Diagram of design objectives

Source: Made by the author

9.2 Strategies

As it has indicated before and according to the Probability and Impact Matrix, the new coastal defence system shouldn't only focus on the probability reduction, but should also deal with improve the consequence even if the events happend. This concept can actually link the three parts together and improve the situation in which the three are separated from each other, eventually, the relation between urban and sea can change from resistance to coexstence.

This concept gives the base of design strategies. On the sea side and part of the coast, the main strategy is risks prevention. And on the urban side, the whole urban can be regarded as part of defence system that reduce the risks impact by improving the urban resiliency spatially and also socially.

To be more specific, the intervention on sea side is mainly for mitigation, nature force utilization and ecosystem restoration. Sea side intervention can help the implementation of the intervention on the coast, which is mainly for transformation of both land use and buildings. The urban itself as the third layer of protection and also as the part of impact reduction, the main focus is increasing the resiliency of infrastructure to make it more permeable and add its water capacity, which can not only serve as a buffer for flooding, but also reduce the dependence on drainage facilities for rain water, in order to alleviate the double hazards mentioned earlier.

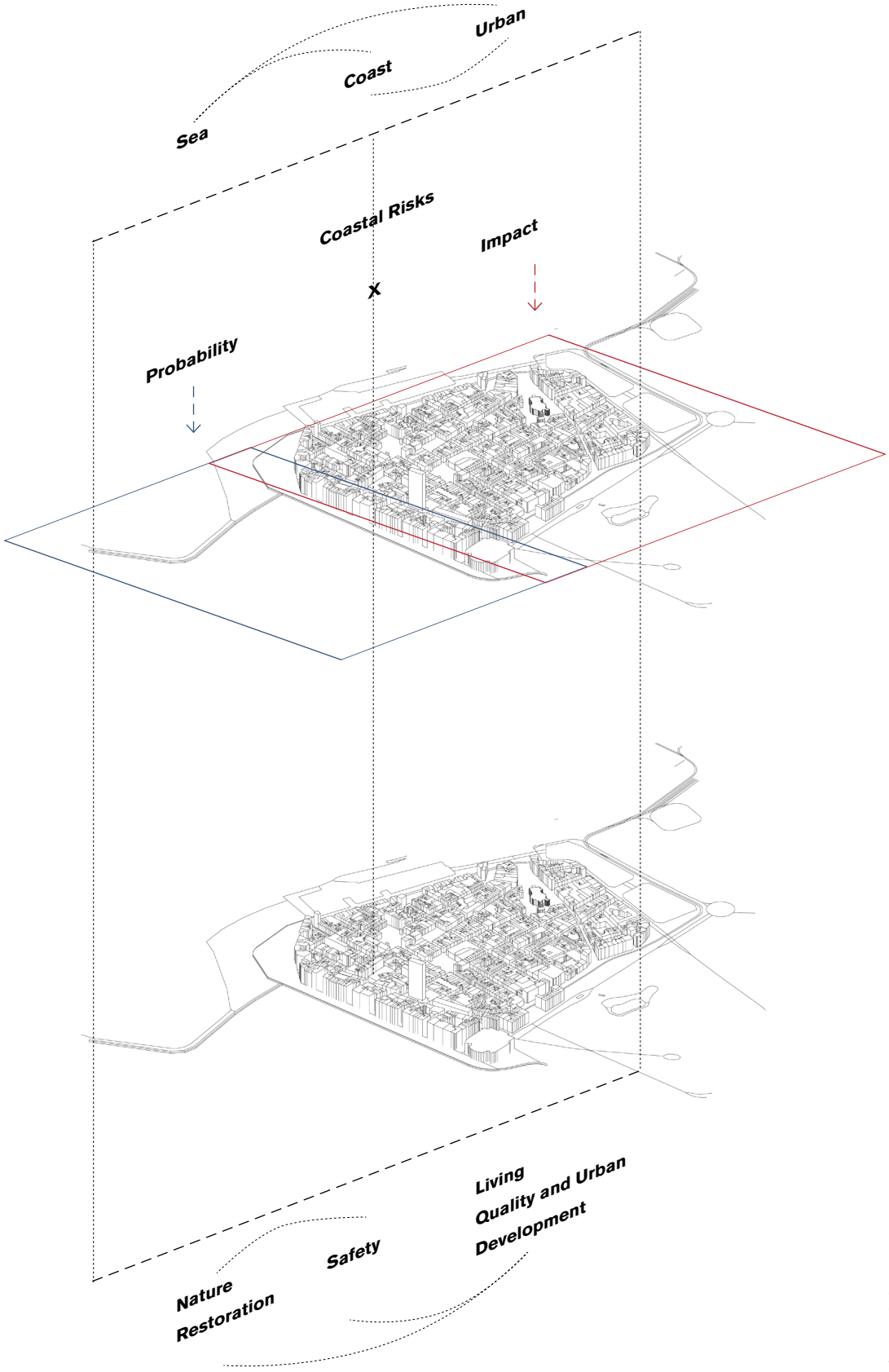


Fig.9-3 Design strategies

Source: made by the author

9.3 Intervention Scheme

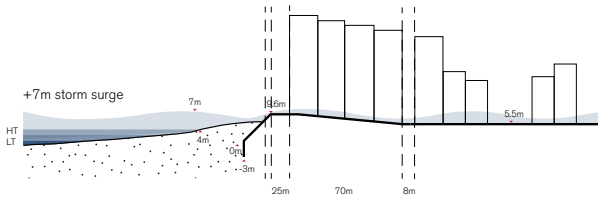
0m SLR
+7 TAW

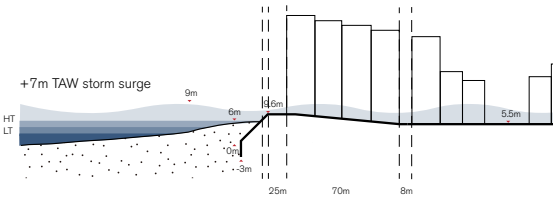
0m-2m SLR
(2m as an extreme)
+7 TAW

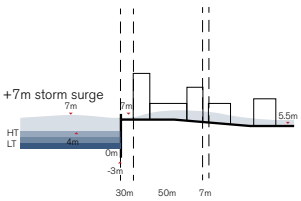
Sea Side **Coast Area** **Urban Side**

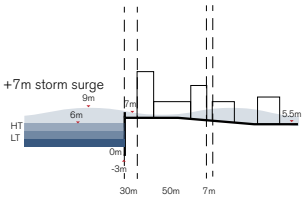
Sea Side **Coast Area** **Urban Sid**

Impacts





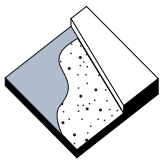




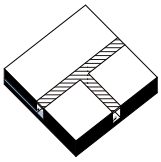
Structure Measures



Oyster reef restoration



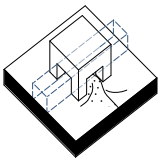
Natural accumulation beach



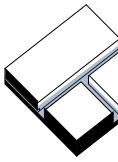
Infrastructure transformation



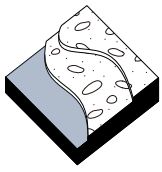
Oyster reef expansion



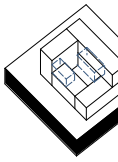
Building typology transformation



Infrastructur transformati

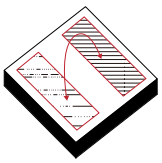


New high land

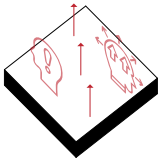


Block typolo transformati

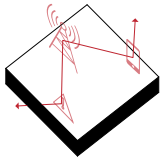
Non-Structure Measures



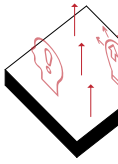
Landuse transformation



Public awareness & Education



Early warning system

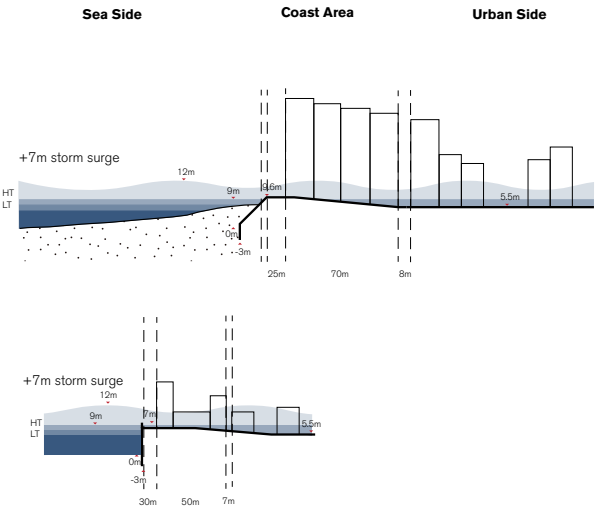


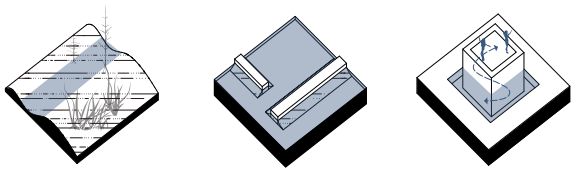
Public awaren & Educatio

Transitional Period

Strengthening Period

2m-5m SLR
(5m as an extreme)
+7 TAW

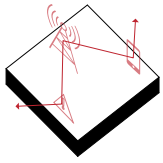




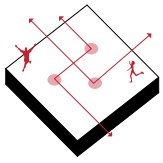
Ecological engineer

Ecological breakwater

Smart shelter



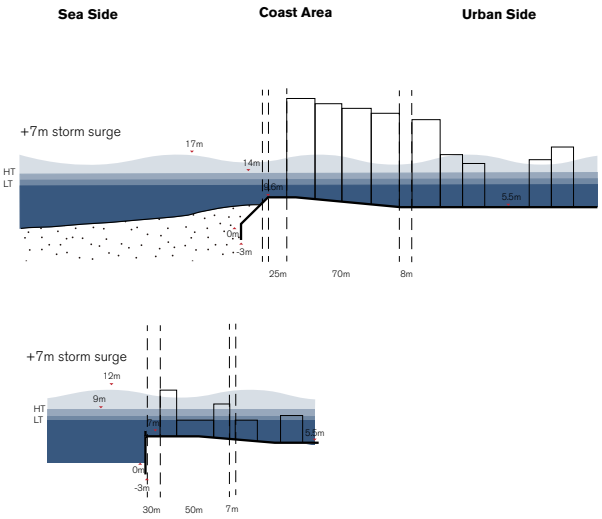
Early warning system

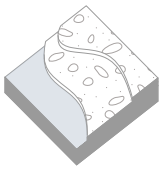


Evacuation

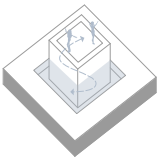
Risky Period

5m-10m SLR
(10m as an extreme)
+7 TAW

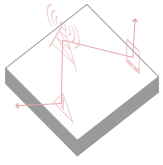




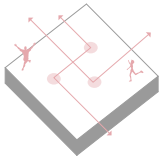
New high land



Smart shelter



Early warning system



Evacuation

Limited Period

Fig.9-4 Intervention scheme

Source: made by the author

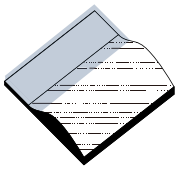
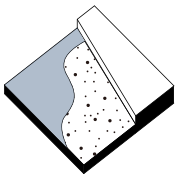
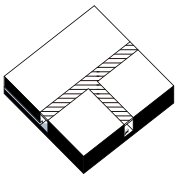
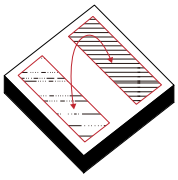
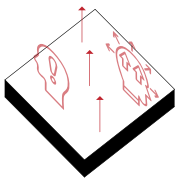
9.4 Transitional Period

Now - 2040

In this period, in stead of putting sand everywhere to keep the shoreline stable, oyster reef restoration can be applied on the near shore area, which will influence the movement of the shoreline.

On the coast, dune restoration can be implemented between sandy beach and the dike to keep the current beach more stable and also bring more ecoservices to the urban. Besides, the underground of the dike is transformed to the parking space to reduce the surface parking spaces. And the land use plan should also be transformed in the dike areas, bringing more public functions to the ground level.

On the urban side, the idea is creating multilayer buffering system. The urban main road between dike and urban area are transformed to the main buffer line, the boulevard, where the traffic will be largely reduced. In more inland areas, green network is created together with the surface space that is free from the parking.

	Sea Side	**Coast**	**Urban side**
Structure measures	 Oyster reef restoration	 Dune restoration	 Infrastructure transformation
Non-Structure measures		 Landuse transformation	 Public awareness & Education

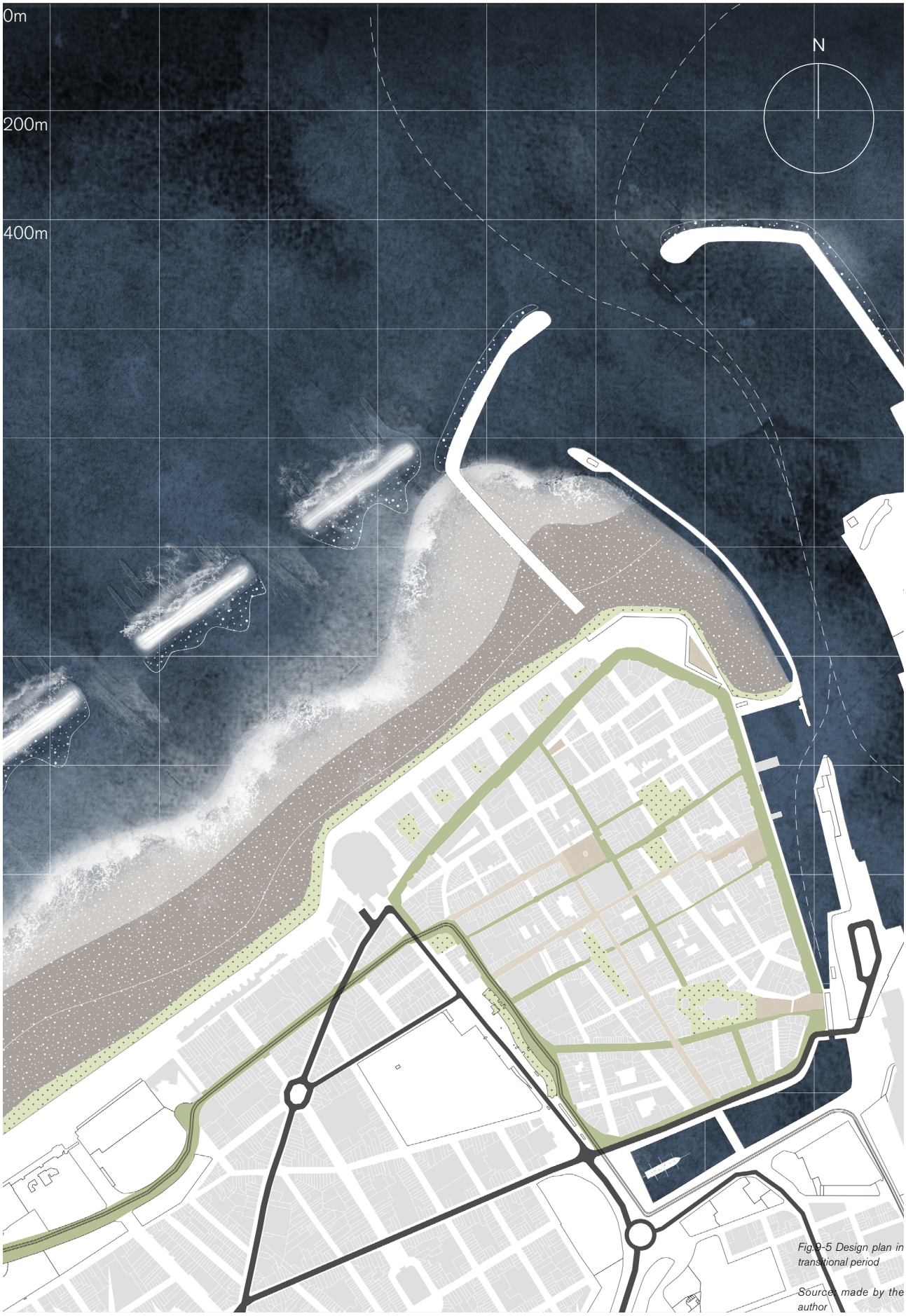


Fig.9-5 Design plan in transitional period

Source: made by the author

Project A - Oyster reef restoration

Because of the historical oyster habitats, the artificial oyster reefs are feasible measure to reduce the wave energy in the lee areas. The reefs can be designed to reduce or prevent the erosion of an existing beach or a beach nourishment, or to encourage natural sediment accumulation to form a new beach (Hawkins et al, 2010).

These structures reduce the incoming wave energy across the structure by triggering wave breaking, by partially reflecting the waves and by dissipation related to the wave induced porous flow in the structure (Hawkins et al, 2010). The ideal way is to design it partly intertidal and integrated with other habitats units to bring more ecological values to the marine ecosystem.

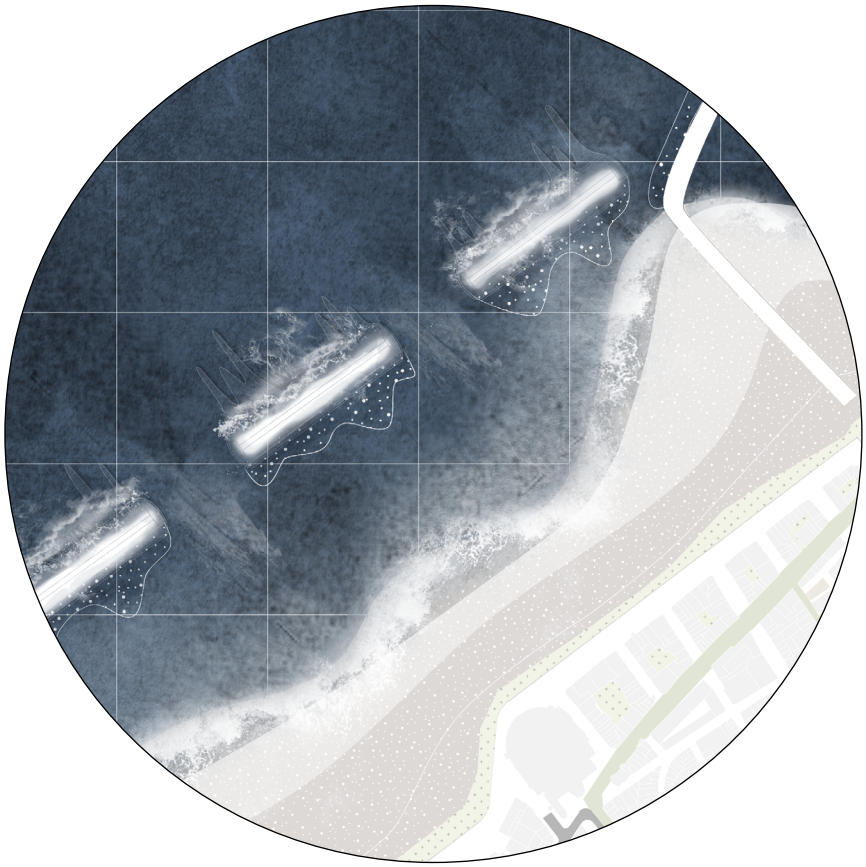
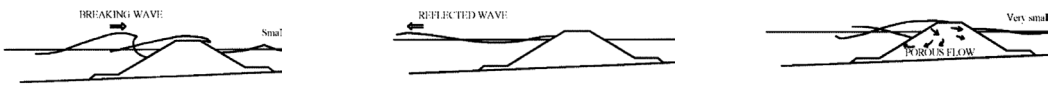
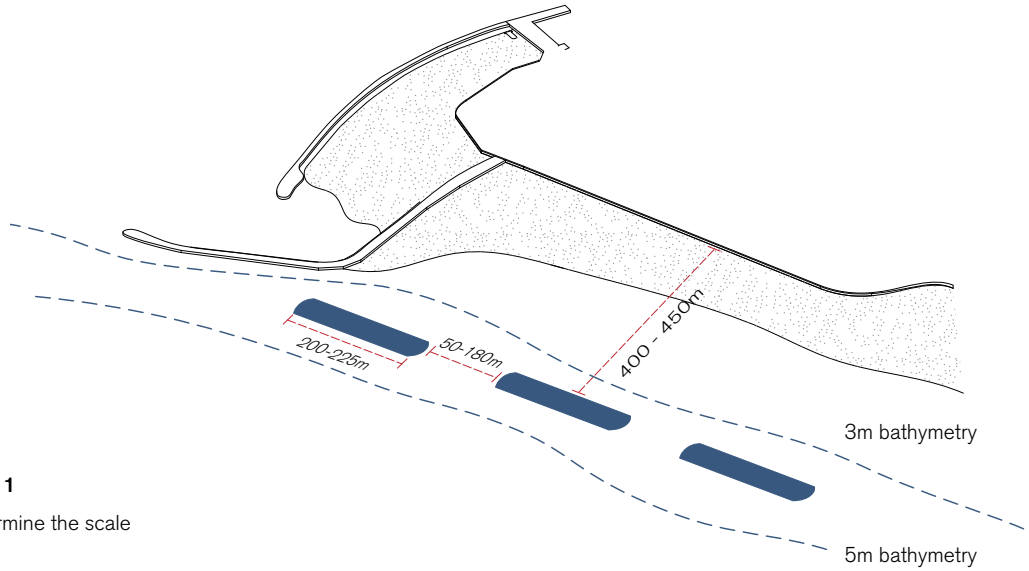


Fig.9-6 Illustration of the sheltering effect of an artifitial reef

Source: H F Burcharth, 2017

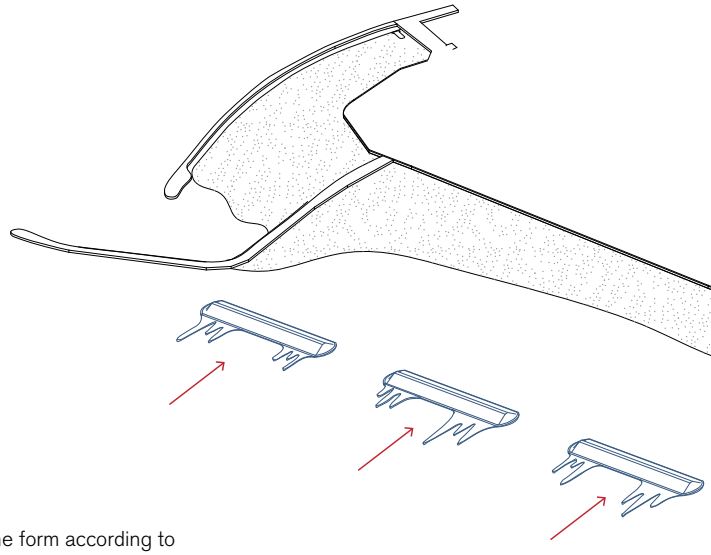


Implementation strategies



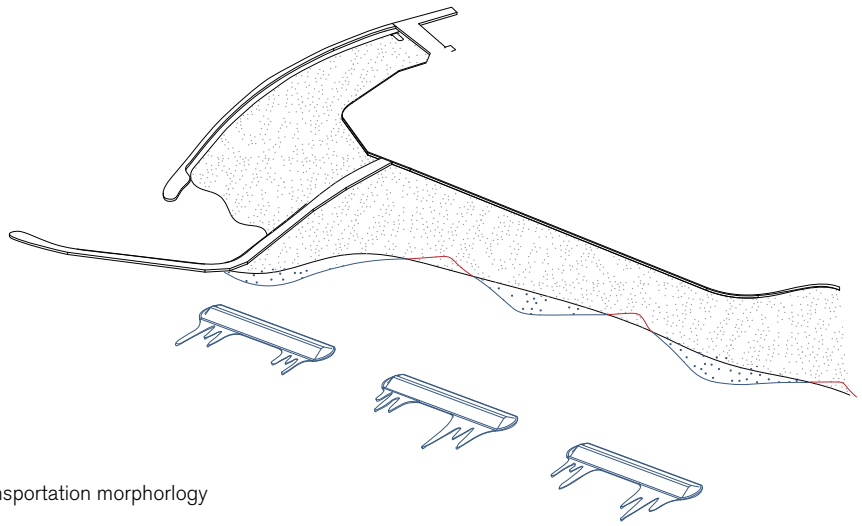
Step 1

Determine the scale



Step 2

Partly change the form according to wind and wave direction



Step 3

Sediment transportation morphorlogy

Fig.9-7 Implementation strategy of oyster reef

Source: made by the author

Oyster restoration techniques

Broadly speaking, the artificial reef construction is also a engineering project. So the main idea is integrate the reef with different type of created habitat that suitable for different kinds of marine creatures. In this way, the engineering can also have larger ecological benefits.



Cod

100cm



Mackerel

20-30cm
max 65cm



Plaice

50-60cm
max 100cm



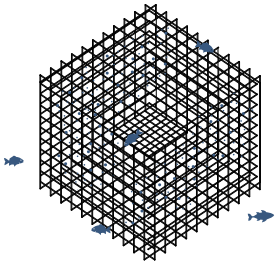
Sprat

10-18cm



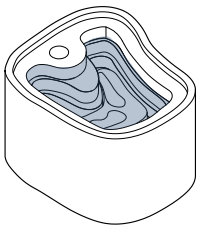
Sole

30-40cm
max 70cm



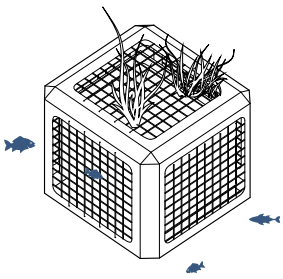
Spat gabion

Spat gabion is a good way to integrate oyster reef with spat habitats which can be used as aquaculture facilities.



Tide pool

Tide pool units can help compensate for the loss of natural intertidal habitats by increasing biodiversity and biological productivity along the structure (econcretetech.com).



Armoring units

Bio enhancing armoring unit ssupported double the species richness and biodiversity of invertebrates. They can also increase the fish diversity and reduce the dominance of nuisance and invasive species.

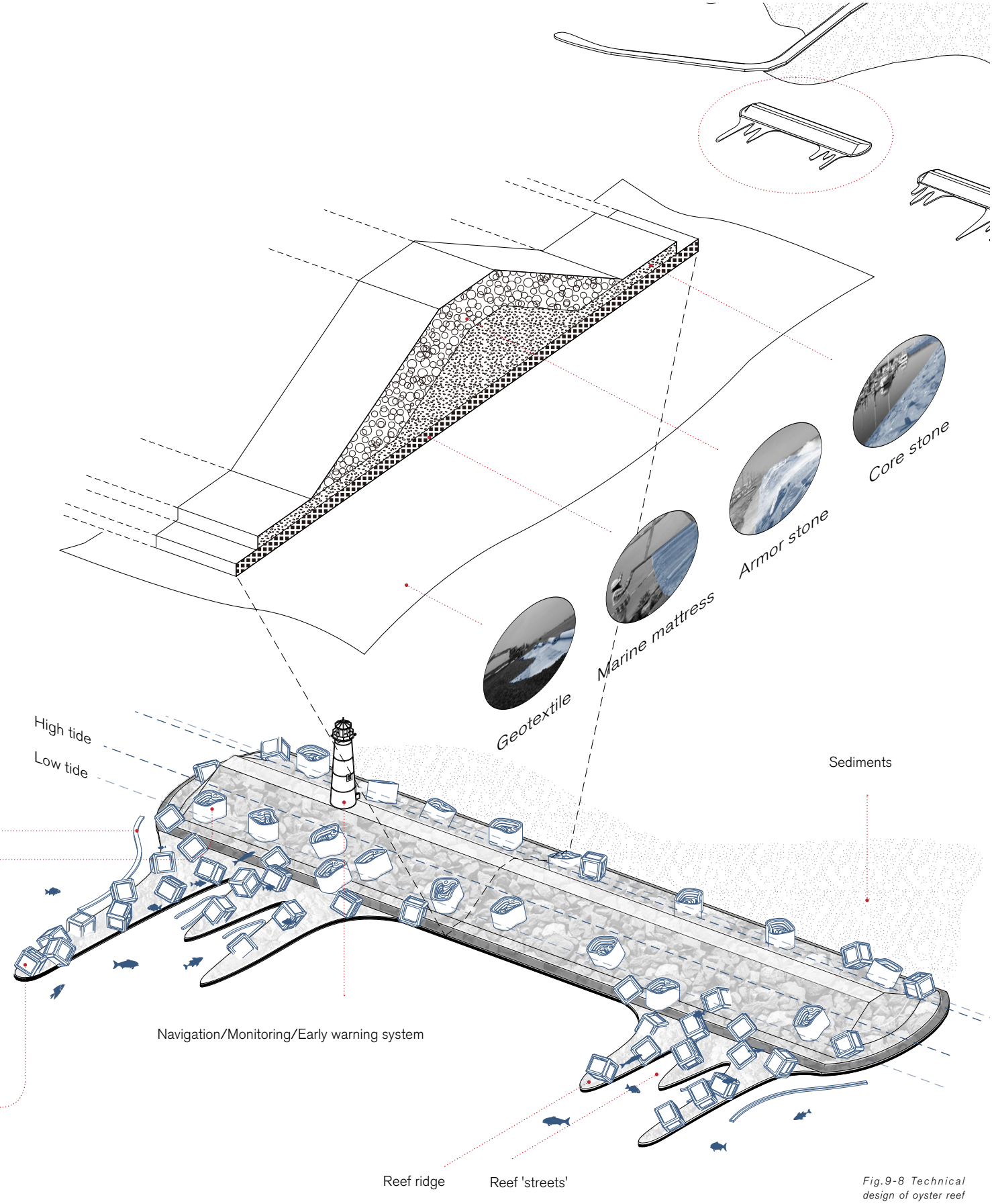


Fig.9-8 Technical design of oyster reef restoration

Source: made by the author

Project B - Dike transformation and dune restoration

On the coast, the project of dike transformation and dune restoration can be carried out. The underground parking can be created under the dike based on the current subsurface parking sites. Thus the surface parking inside the coastal block and city centre can be removed. Secondly, the land use of the coast area should be more mixed, and the ground floor of the buildings on the dike can be transformed to be more public. Moreover, the dune restoration can happen in front of the dike. On the one hand, it makes the nearshore part of the beach more stable, on the other hand hand, it also diversify the coast landscape.



Implementation strategies

Layer 1 Buildlings

Ground and first floors are transformed to public use

Layer 2 Dikes

Space inside the block is transformed to open space

Layer 3 Dunes

Dune restoration infront of the dike

Layer 4 Underground parking

Use underground space of the dike for parking and water storage

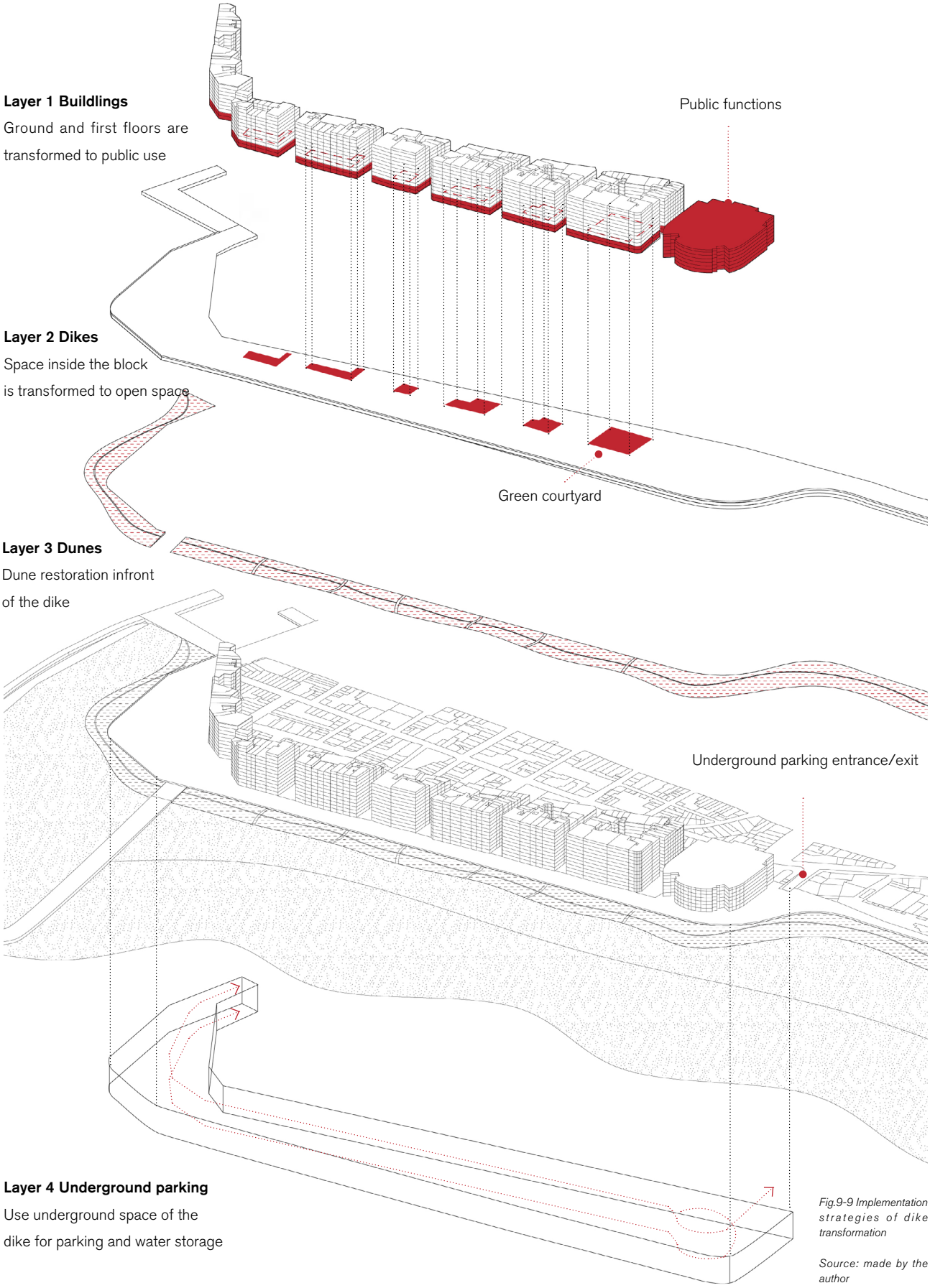


Fig.9-9 Implementation strategies of dike transformation

Source: made by the author

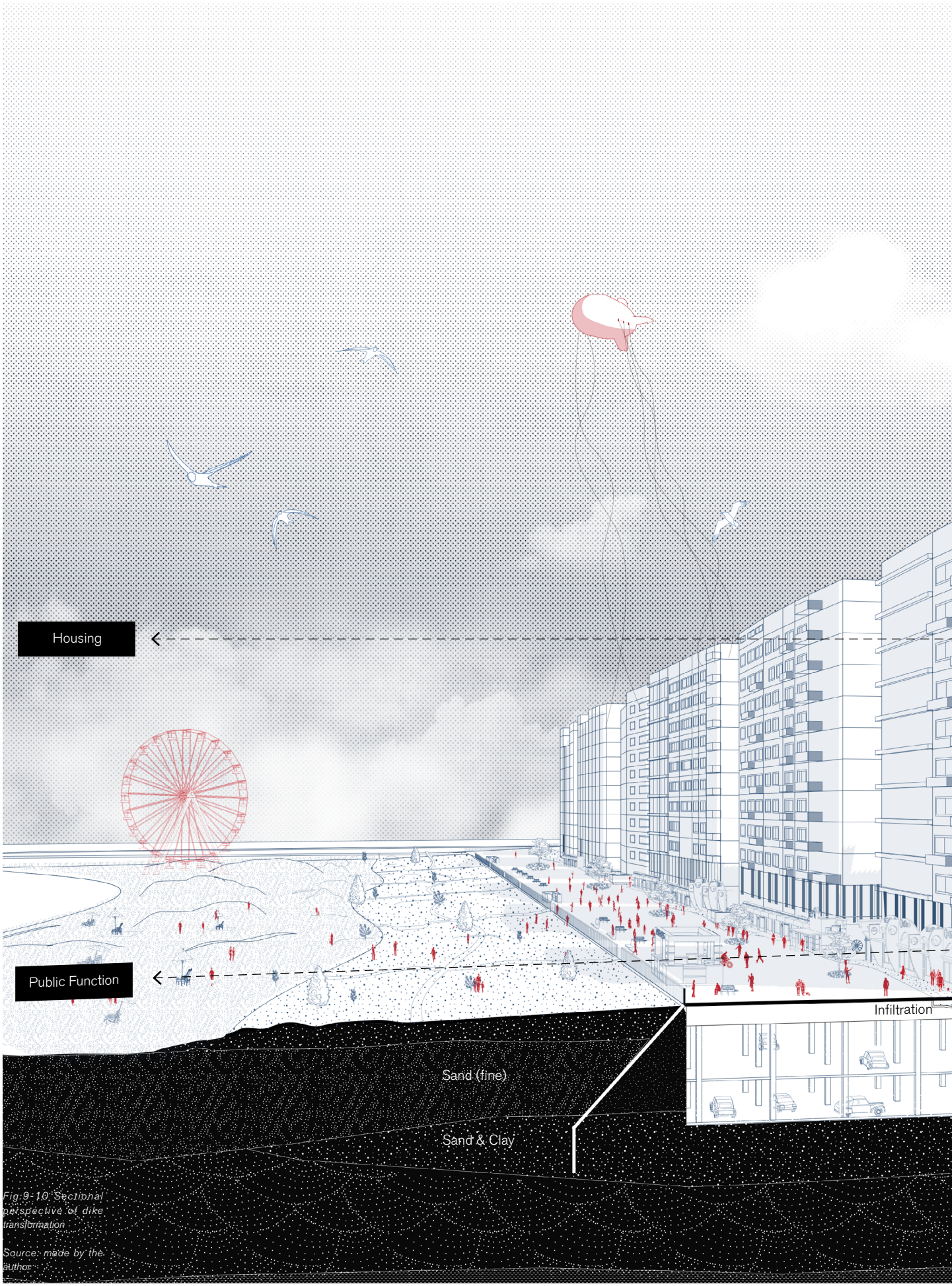
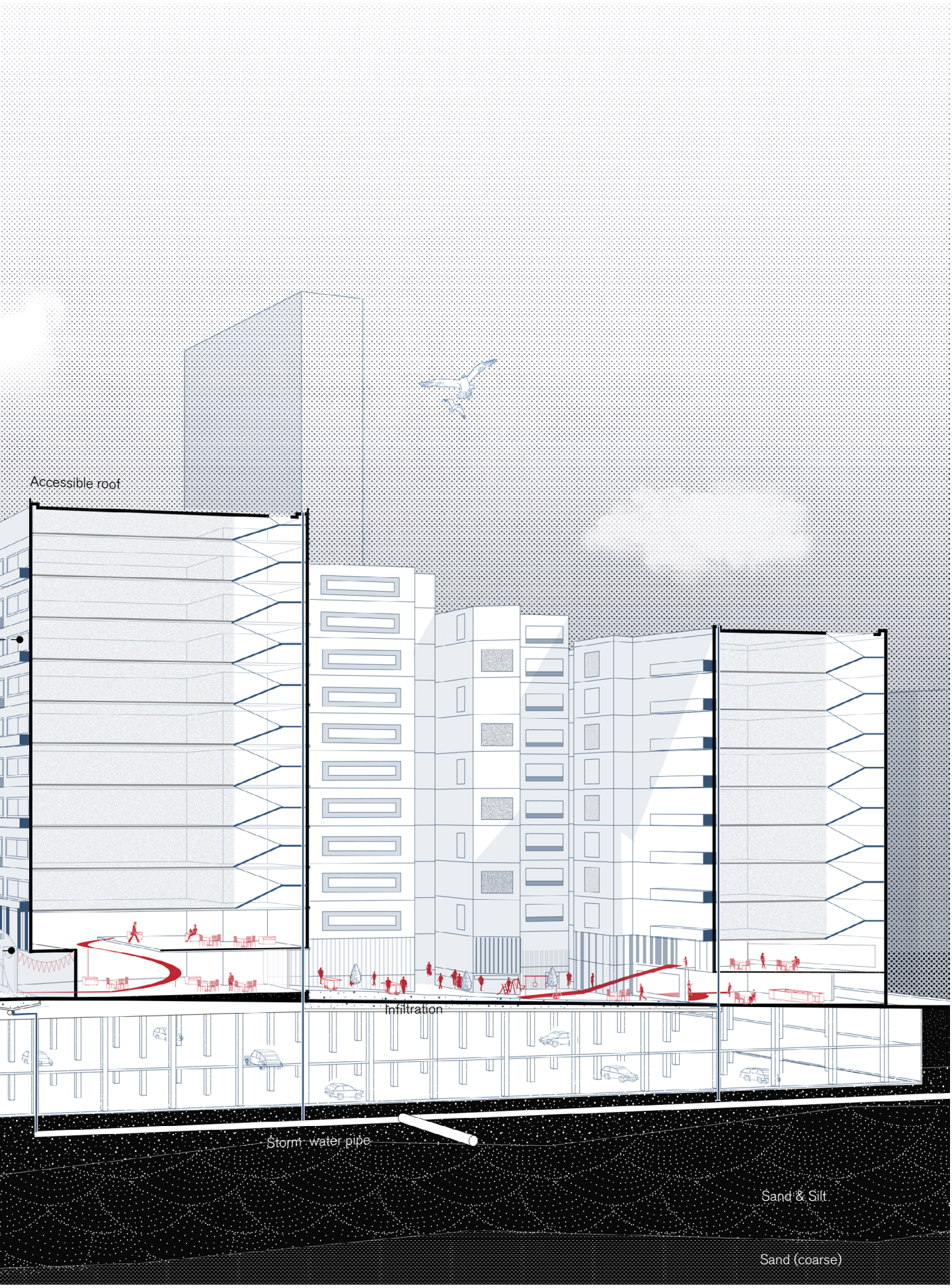


Fig.9-10 Sectional perspective of dike transformation

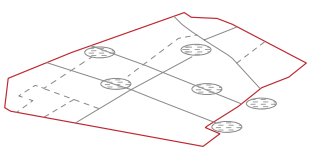
Source: made by the author

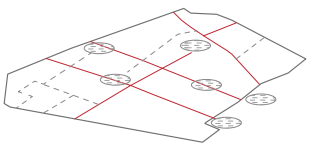

Accessible roof
Infiltration
Storm water pipe
Sand & Silt
Sand (coarse)

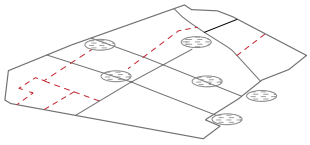
Project C - Multilayer buffering system I

On the urban side, the main idea is creating multilayer buffering system embeded into the current urban fabric. The principle of the intervention including reviewing of the historical landscape, the exisiting green space and surface parking that can be removed, the topography with water flow directions that points out the areas where overtopping water flows and with most risks. Together with the current urban functionalities, three layers of buffering system can be created.

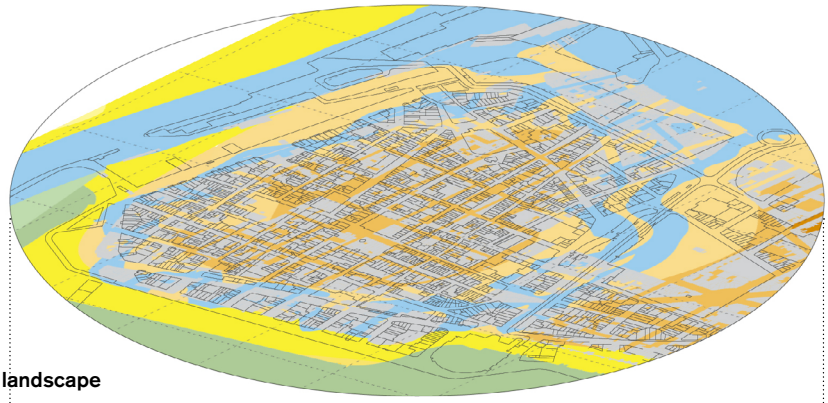








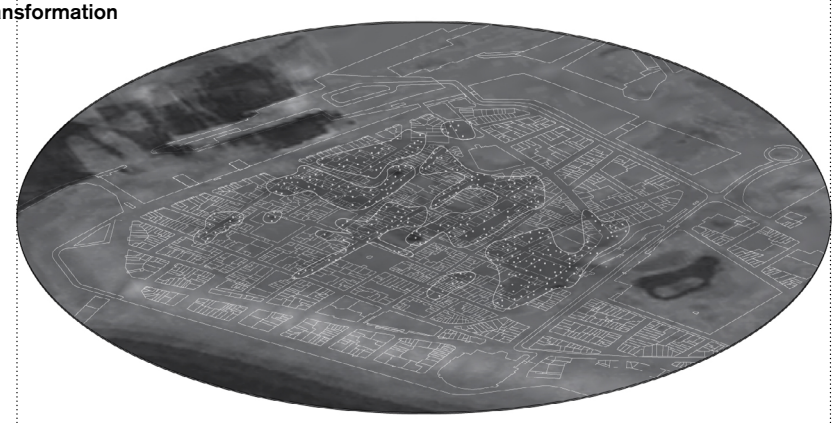
Implementation strategies



Layer 1 Historical canal landscape



Layer 2 Exsiting green space
and surface parking transformation



Layer 3 Water flows



Multilayer buffering system

Fig. 9-11 Implementation strategies of multilayer buffering system I

Source: made by the author

Techniques

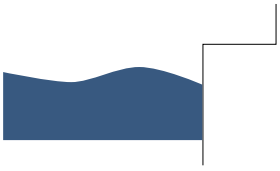
A study about the overtopping volume and it relation with the typology of the dike and architectural alternatives for better integration in the setting had been carried in Ghent University(Doorslaer et al, 2011).

In this study, the hydraulic model was created to test the overtopping reduction during the storm events in city of Ostend under different designed situation. There are two parts of the testing.

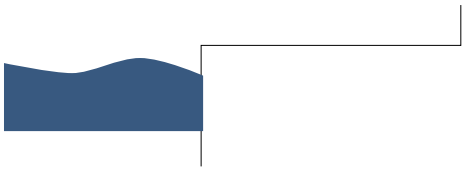
First is the relation between the overtopping volume and the wideness of the buffer zone. From the outcome we can see that the wider the buffer, the more overtopping water reduced.

Secondly, different type of interventions in the wide buffer zone are also tested, namely wide steps, short steps and steps with stilling water basin. As a conclusion, the most ideal measure is wide buffer zone with stilling water basin.

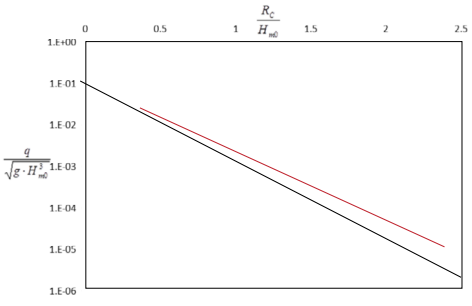
This model gives the technical base and guidance for boulevard intervention on or behind the current dike. Combining the specific context of the site, the design of the multi-layer buffering system can be carried out.



A: 2m wide



B: 15m wide



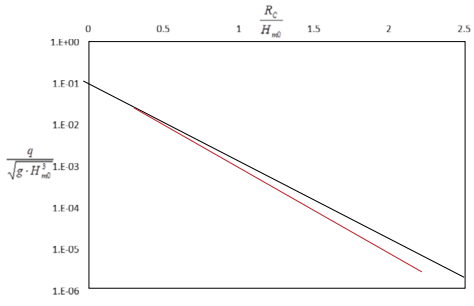
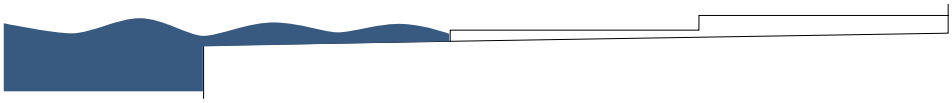
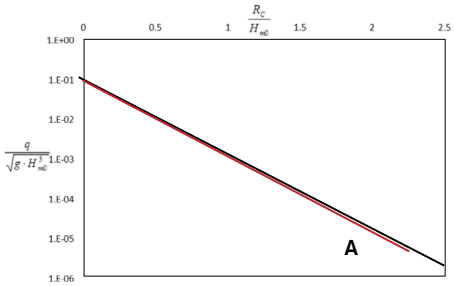


Fig. 9-12 Dimensionless graph on overtopping discharge over a vertical wall (semi-logarithmic).

Source: Van Doorslaer, 2015

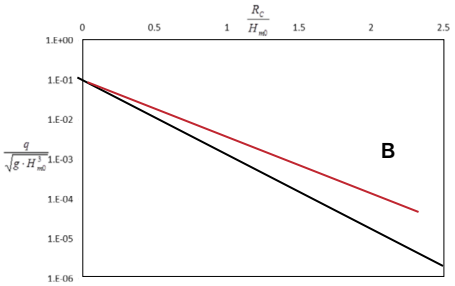


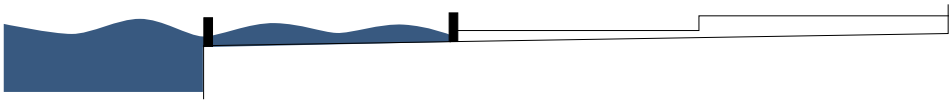
A: Wide steps





B: Short steps





C: Steps with stilling water basin

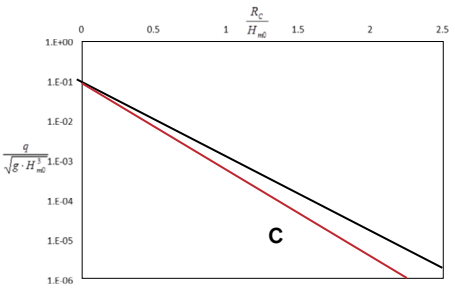
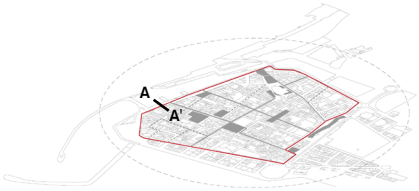


Fig. 9 - 13 dimensionless overtopping graph of all geometries related to the standard geometry (Reference Line 2).

Source: Van Doorslaer, 2015



Main buffe liner:

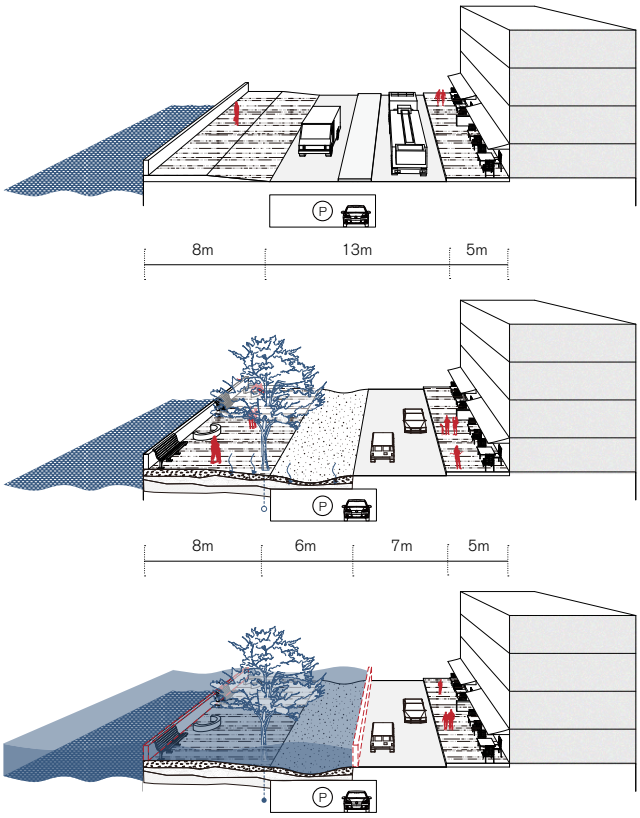
Boulevard on the dike

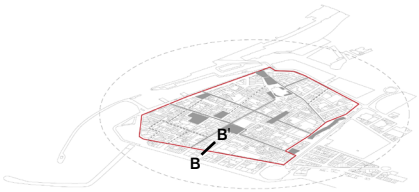
Reducing the traffic

Still water basin with removable storm

Fig.9-14 Design section of the boulevard on the dike

Source: made by the author





Main buffer line:

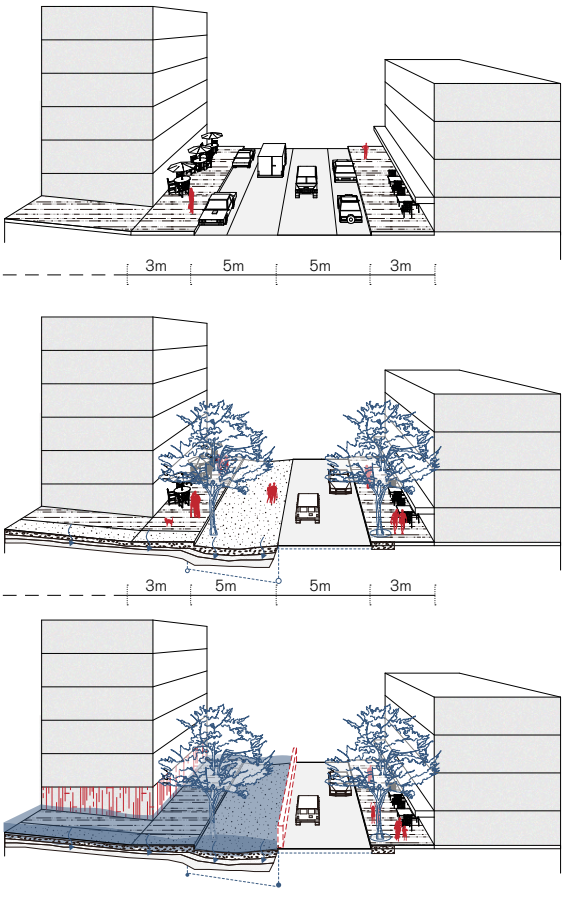
Boulevard behind the dike

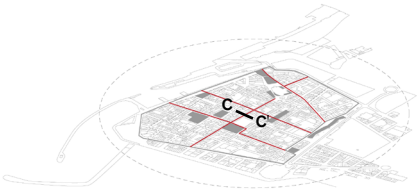
Reducing the traffic

Still water basin with removable storm

Fig.9-15 Design section of the boulevard behind the dike

Source: made by the author





Secondary buffer line:

Hollow pavement

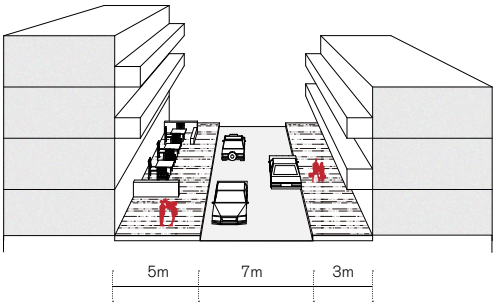
Removing the traffic

Green and walking streets

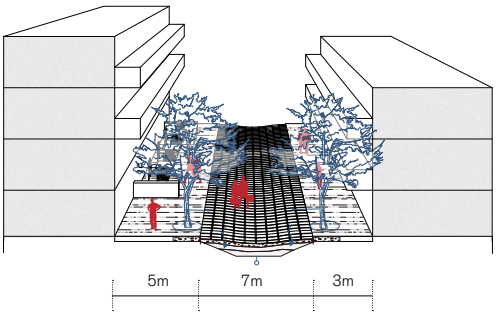
Fig.9-16 Design section of the hollow pavement

Source: made by the author

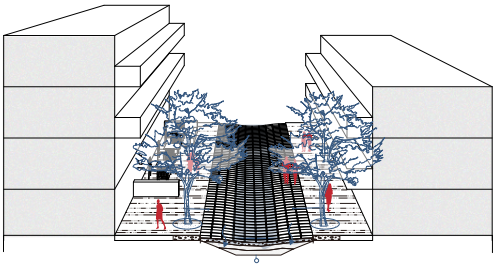
Current situation

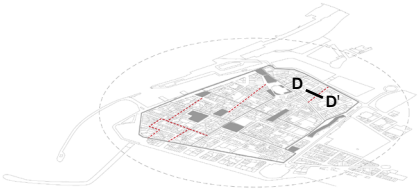


Proposed



During storm time





Third buffer line:

Greening street

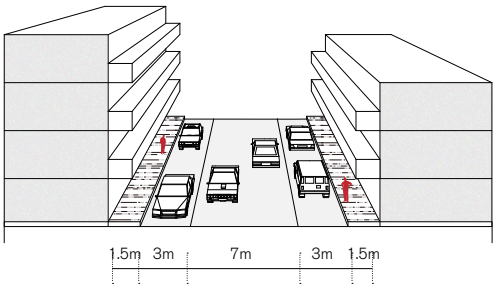
Removing the side parking

Green streets

Fig.9-17 Design section of the greening street

Source: made by the author

Current situation



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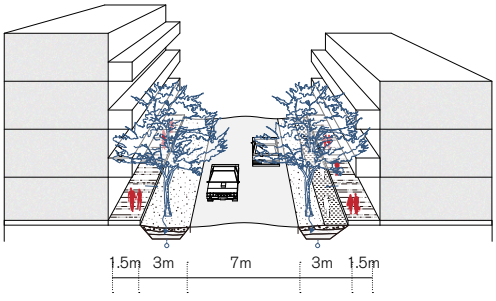
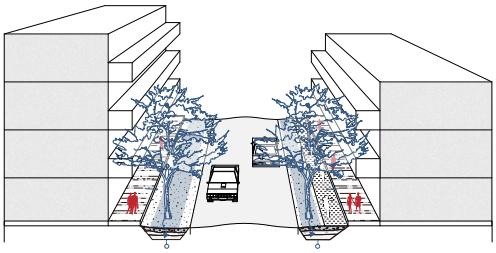


During storm time



Species

Because of the salty environment, different species with high salty environment tolerence are selected and recommended that can be planted on the boulevard and also the dune restoration areas on the beach.

The main species are grouped into trees and shrubs. The group of trees is more suitable on the urban side, while the group of shrubs is more suitable for the dune restoration on the sandy beach.



European ash



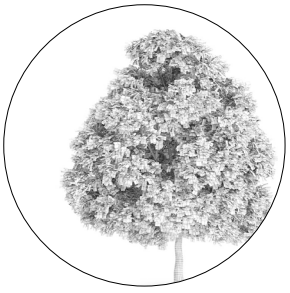
Scots pine



White Spruce



Holly oak



Swedish whitebeam



Field maple

Fig.9-18 Salty tolerant species recommendation

Source: made by the author



Sand oat



Orache



Salicornia



Blue sea thistle



Hippophae



Calendula

9.5 Strengthening Period

2040 - 2070

In this period, the main idea is strengthening the previous actions towards the direction of strategies.

On the sea side, the oyster reef system can be expanded to reach larger positive impacts.

On the coast, based on the land use transformation and public sense creation, the building typologies on the dike can be transformed and the dune can actually penetrate further inland. Besides, the area between two breakwater can be heighten for the future development. This area has more protection from the breakwater and also has the nature accumulation process which makes it more efficient and easier to heighten up.

On the urban side, the multilayer buffering system can be updated to deal with the more serious risks. Two blocks are also chosen as the pilot block transformation projects.

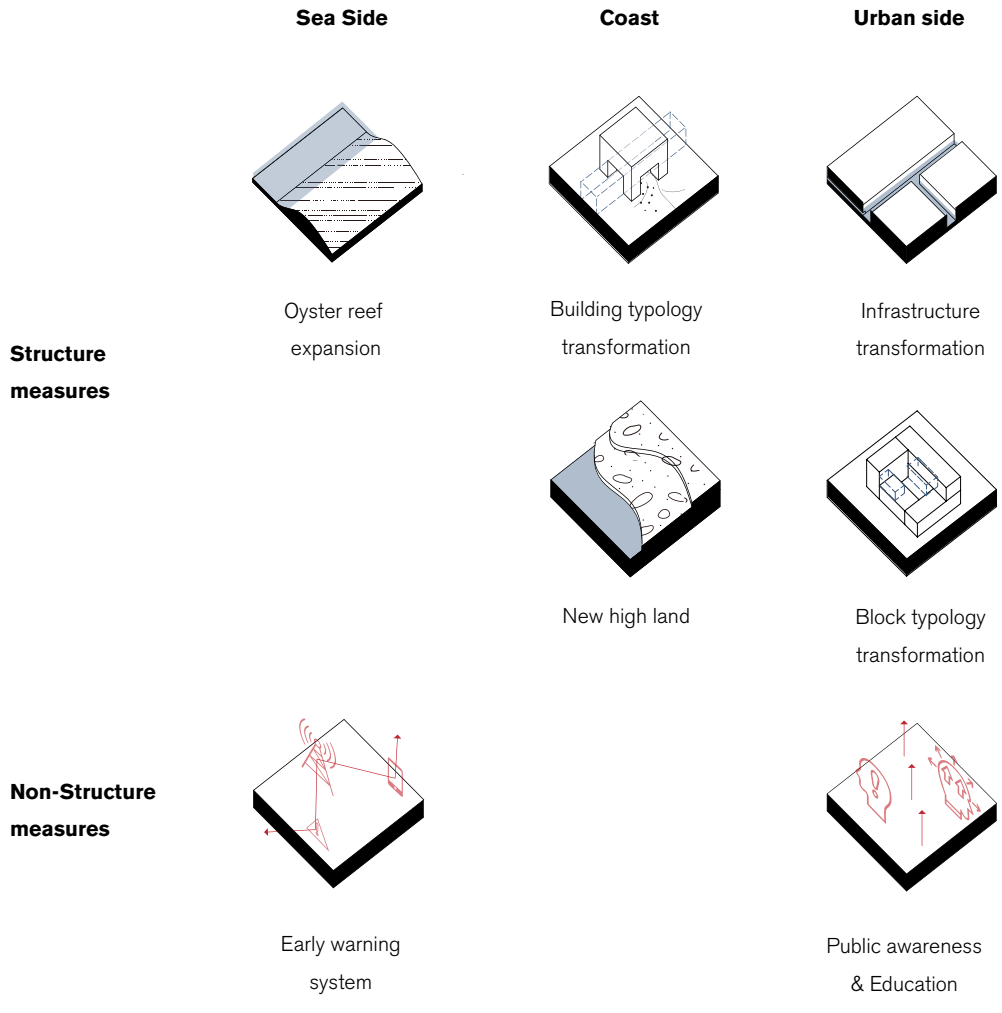


Fig.70 Schematic elevation view of 'amphibious units'

Source: made by the author

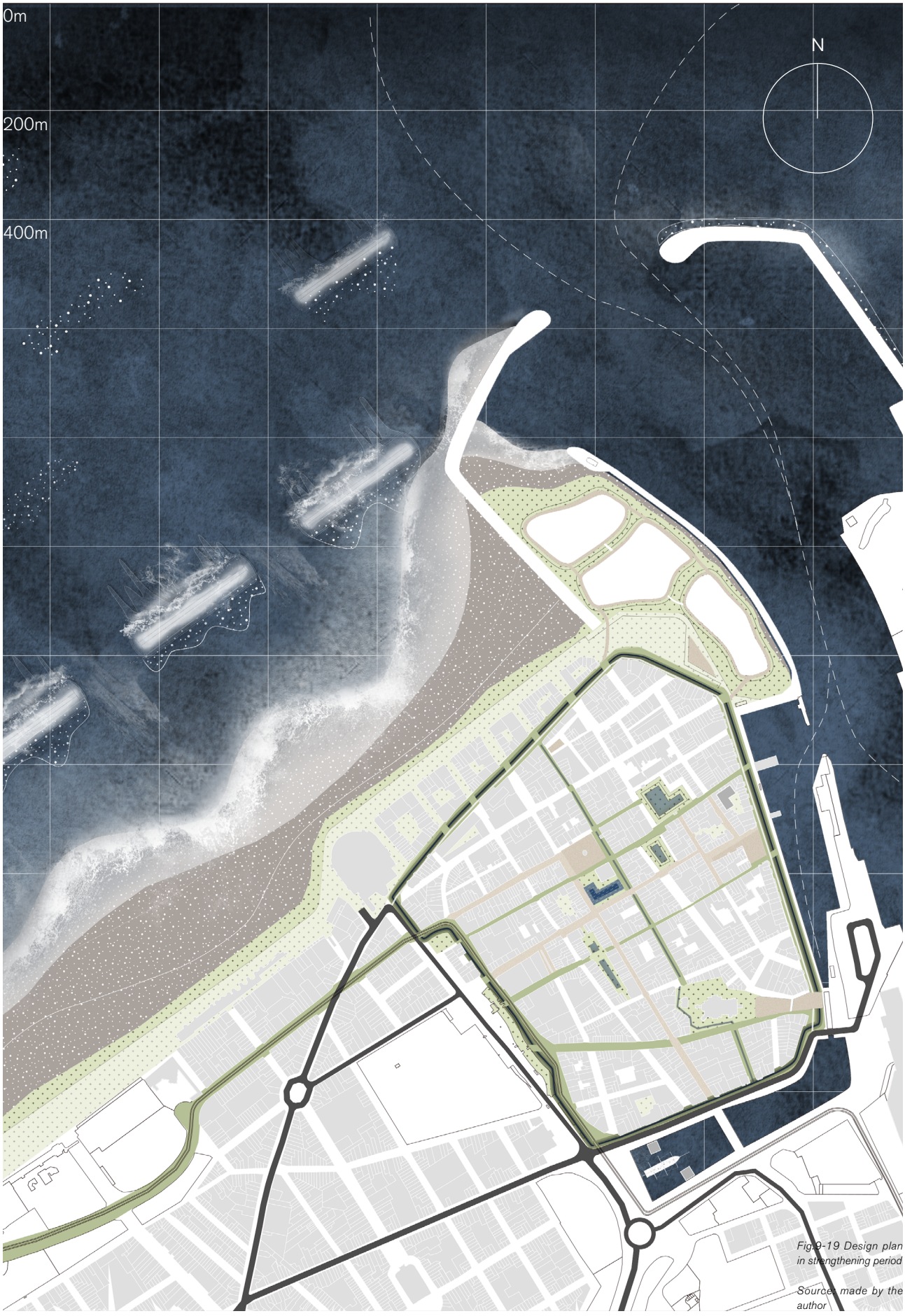


Fig.9-19 Design plan in strengthening period

Source: made by the author

Project A - Dike and dune integration

In the period, the lower floors of the building blocks on the dike can be more open so the dune restoration can also happen inside the dike, penetrating into the city, providing more protection from storm to the city as well as more green space. By doing this, more diverse and public coast can be expected.



Implementation strategies

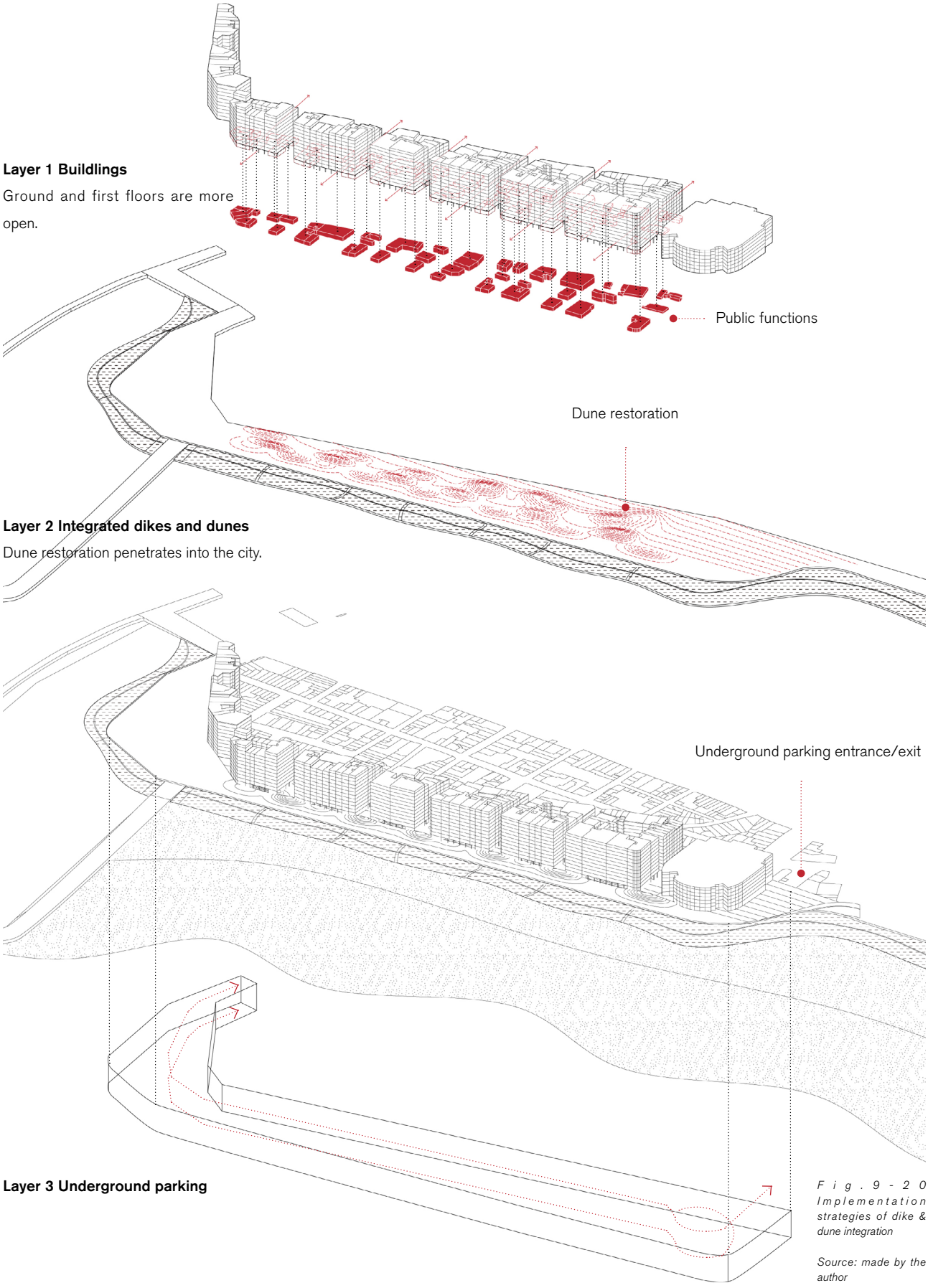


Fig. 9-20 Implementation strategies of dike & dune integration

Source: made by the author

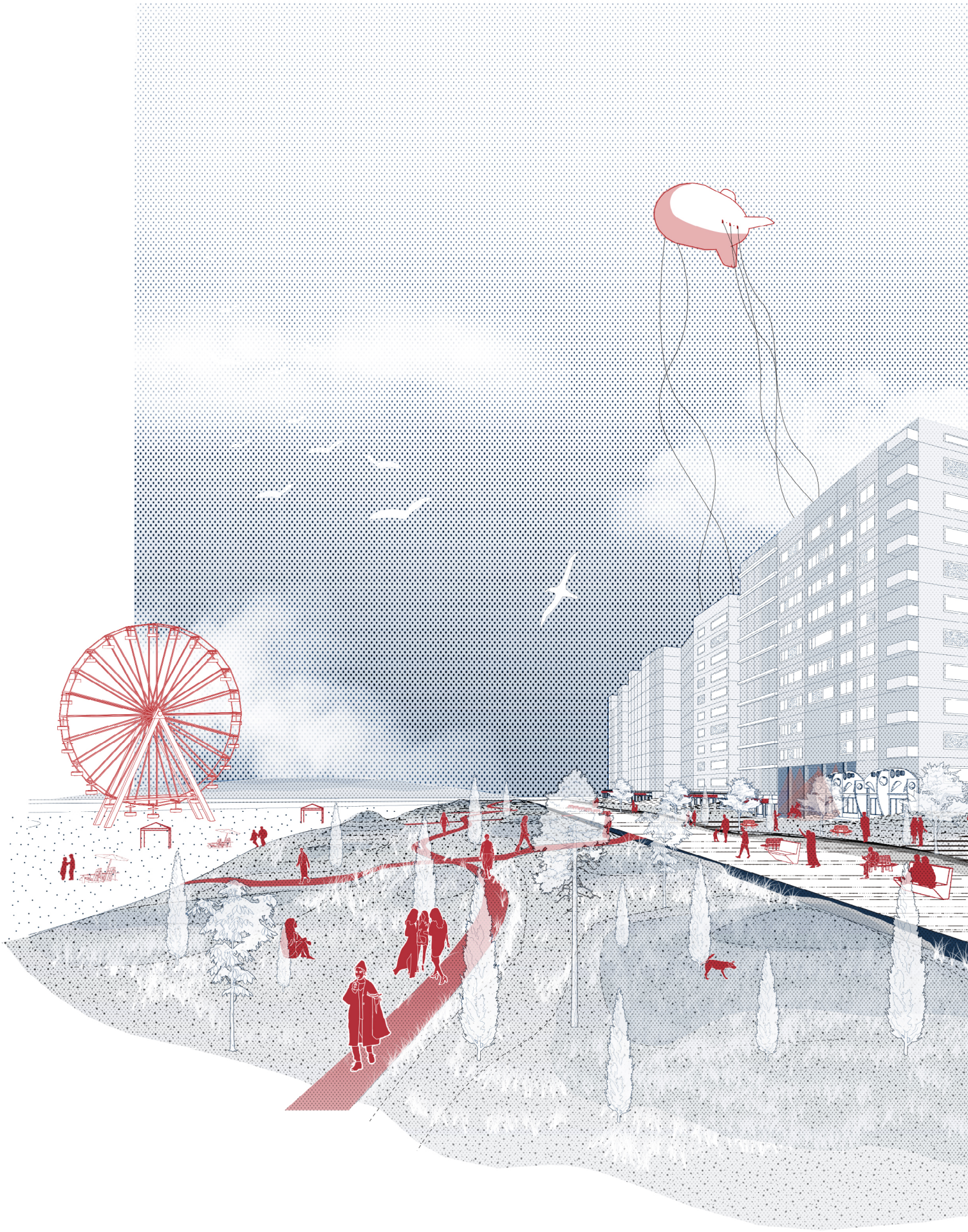




Fig.9-21 impression of dike & dune integration

Source: made by the author

Project B - Multilayer buffering system II

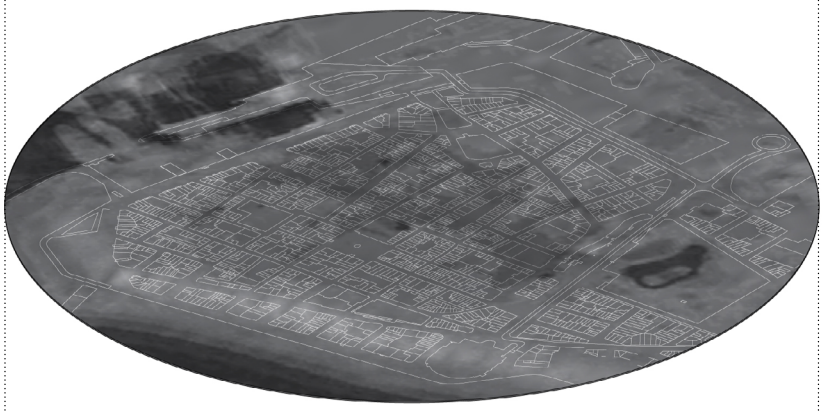
Based on the transitional period intervention, facing the increasing risks, the multilayer buffering system on urban side can be updated. The main projects show here as examples are the sunken garden ring and two block transformation (one public block and one residential block).



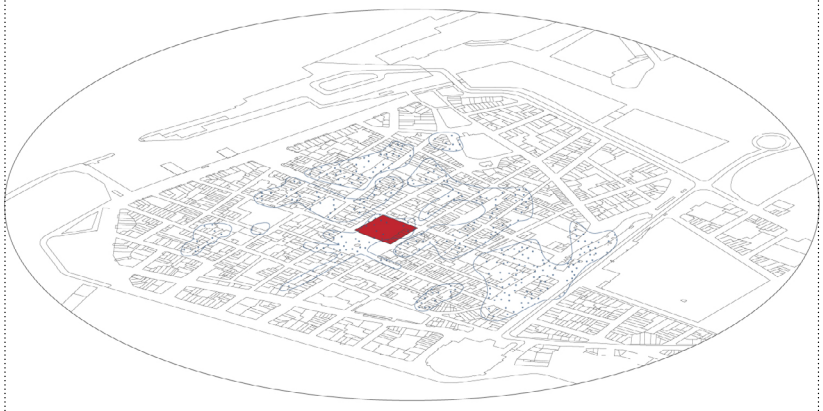
Implementation strategies



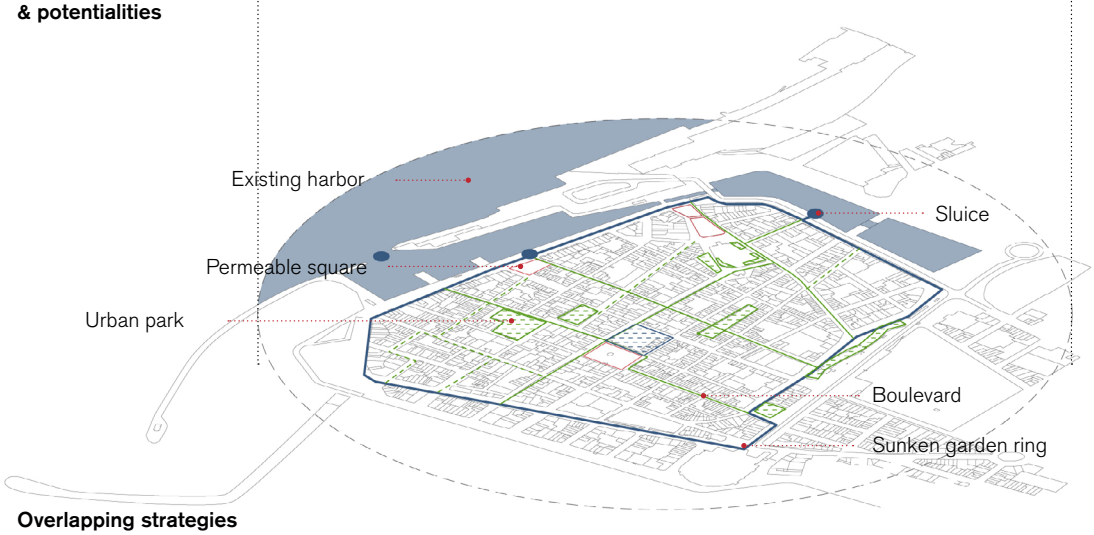
Layer 1
Open space networking



Layer 2
Topography



Layer 3
Constructions with risks
& potentialities



Overlapping strategies

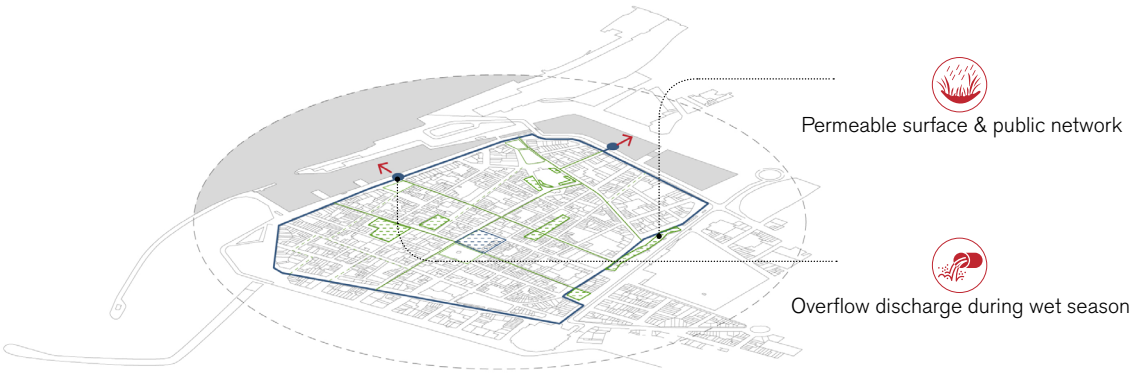
Fig. 9-22 Implementation strategies of multilayer buffering system II

Source: made by the author

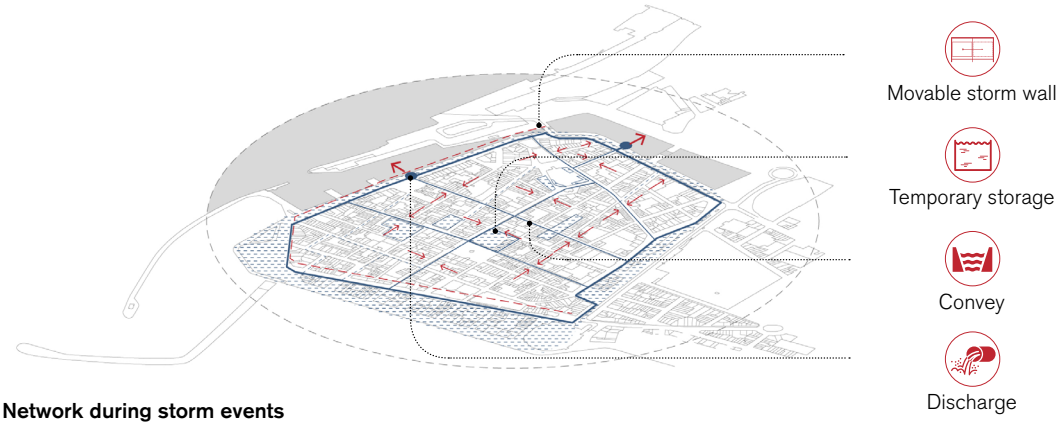
Infrastructure transformation - Sunden garden

One of the main ideas in this period is transforming the main boulevard into a sunken garden ring (for the part on the dike, the current underground parking space can be made use of), which will be deeper and wider compare to the previous situation.

During the normal time, together with other buffer line and transformed urban block, the public network can be created. And during the storm events, the network helps to transport the overtopping water and discharge the water much quicker afterwards.



Network during normal time



Network during storm events

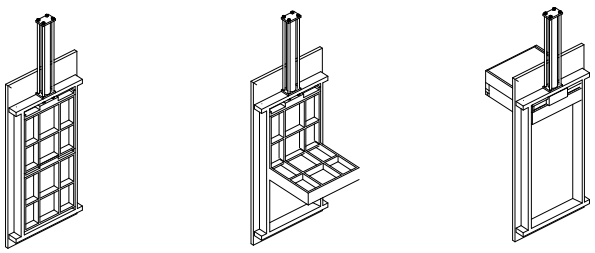
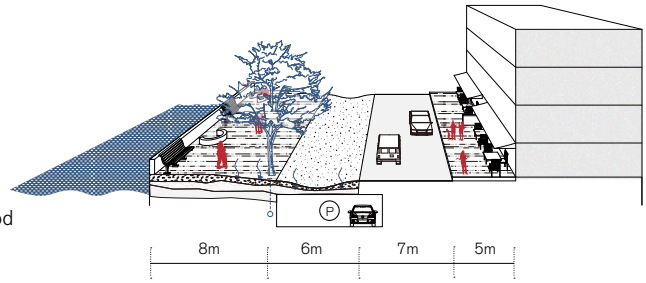
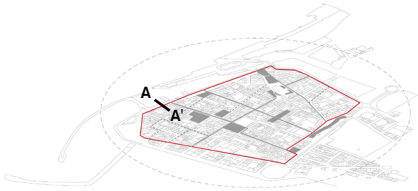
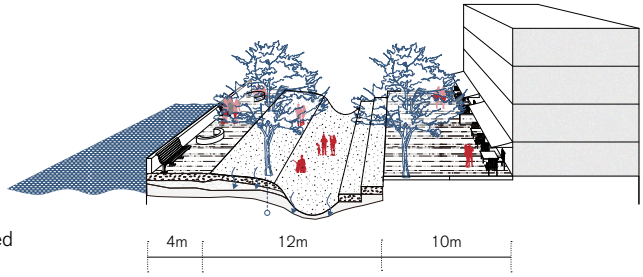


Fig.9-23 Buffering network under different situation

Source: made by the author







Main buffer line:

Sunken garden on the dike

Making use of the underground space

Removing the traffic

Public space during normal time

Still water basin with removable storm

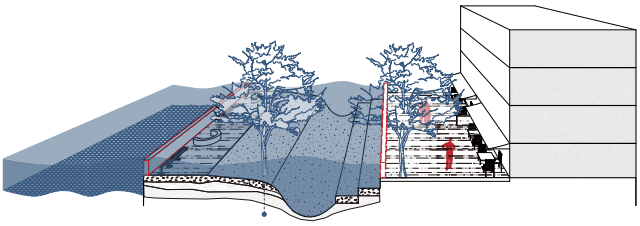
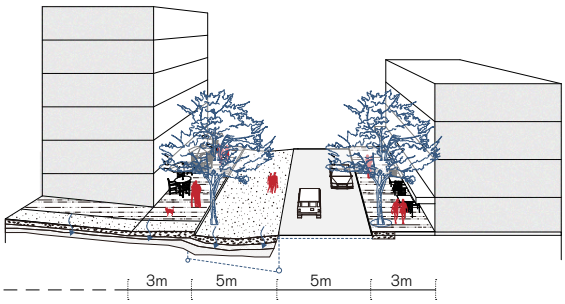
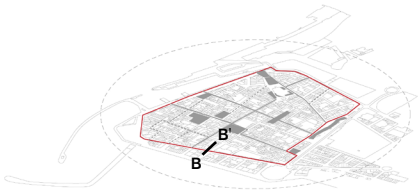
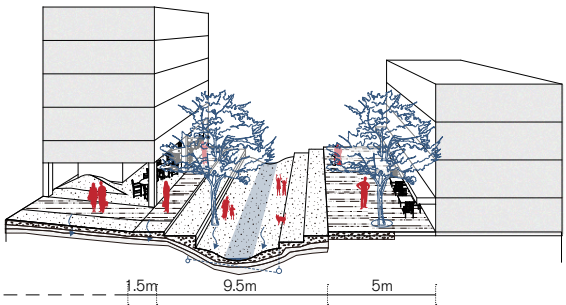


Fig.9-24 Design section of the sunken garden on the dike

Source: made by the author







Main buffer line:

Sunken garden behind the dike

Removing the traffic

Public space during normal time

Still water basin with removable storm

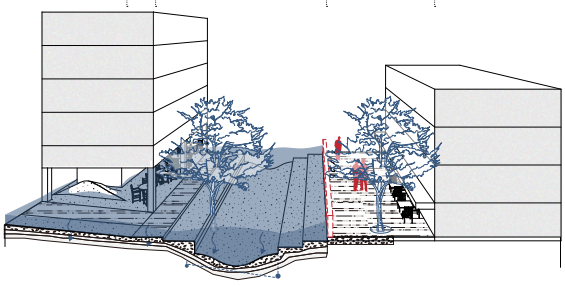


Fig.9-25 Design section of the sunken garden behind the dike

Source: made by the author

Block typology transformation - Water square

The first block typology transformation is the current shopping mall next to the old square.

According to the topography and water flow analysis, this area is the relatively low point in the city of Ostend, thus, facing larger risks.

The idea is transforming the whole block to a water square, linking to the secondary buffer line. The current tower building of the shopping mall is densified and the ground floor of some surrounding buildings are transformed to be commercial space to compensate some commercial functions.

The water square can have different functions during the different seasons.

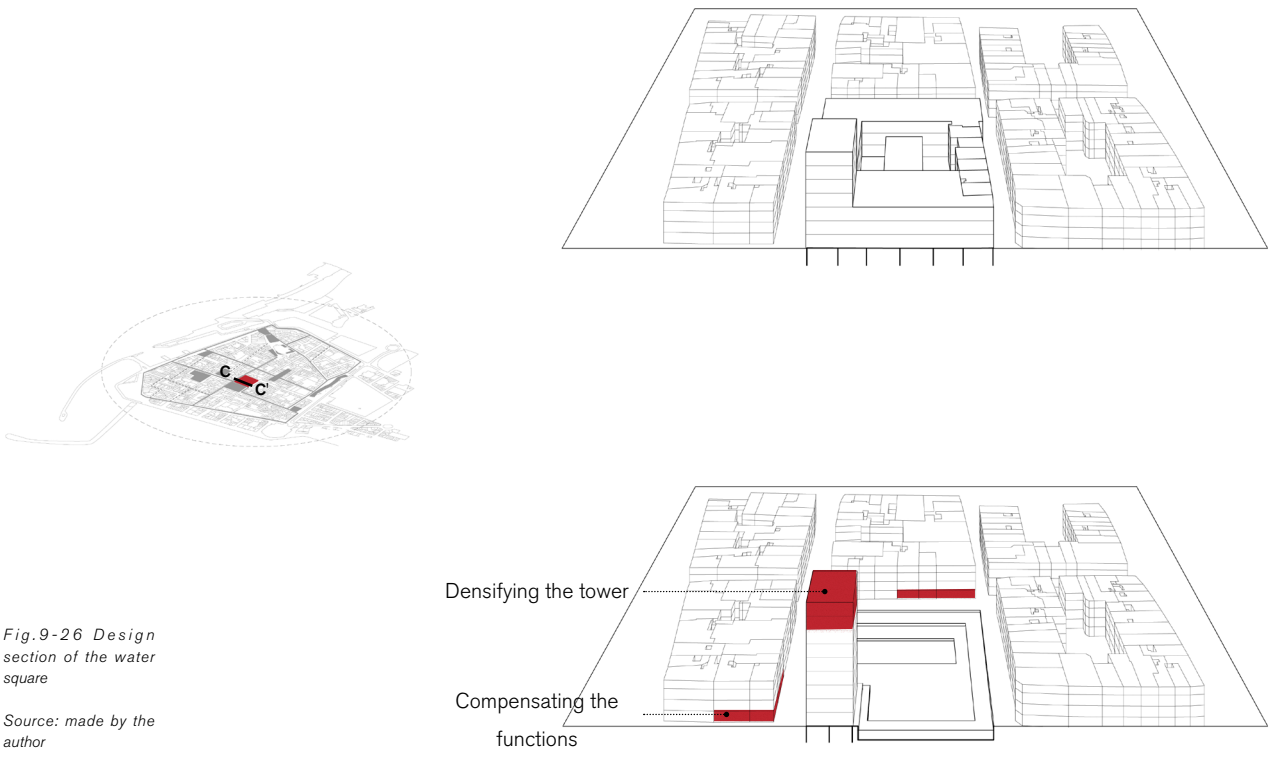
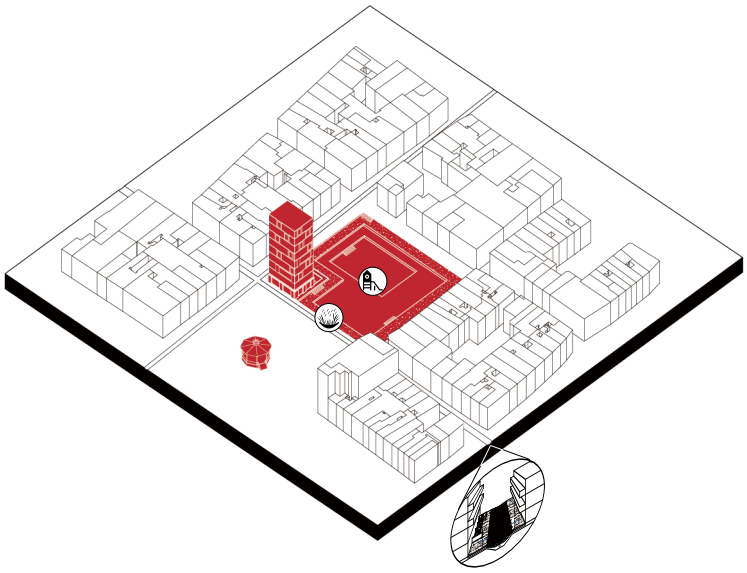


Fig.9-26 Design section of the water square

Source: made by the author

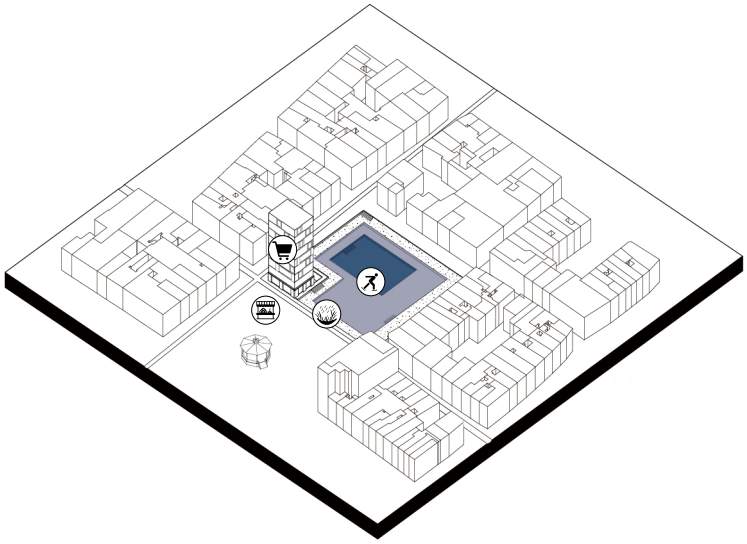
Dry season

During the dry season, the water square can become a extended public space of the current old square. Functions contain play ground, rest space and urban garden.



Wet season

During the wet season, the playground could be flooded. And because the wet season is during the winter, the water can be frozen and the playground can become a ice-skating ground.



Storm events

The water square links to the buffer lines, so during the storm events, the overtopping water can be transported here and the whole water square bacomes the temporary water retention area. After the events, the water can be transported back through the buffer and discharged quickly

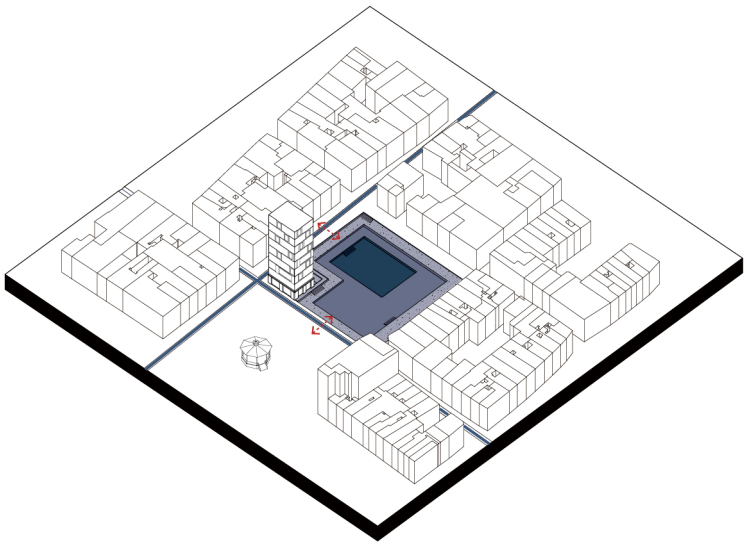


Fig.9-27 Water square under different situation

Source: made by the author


SHOPING FEEST-CULTUURPALEIS
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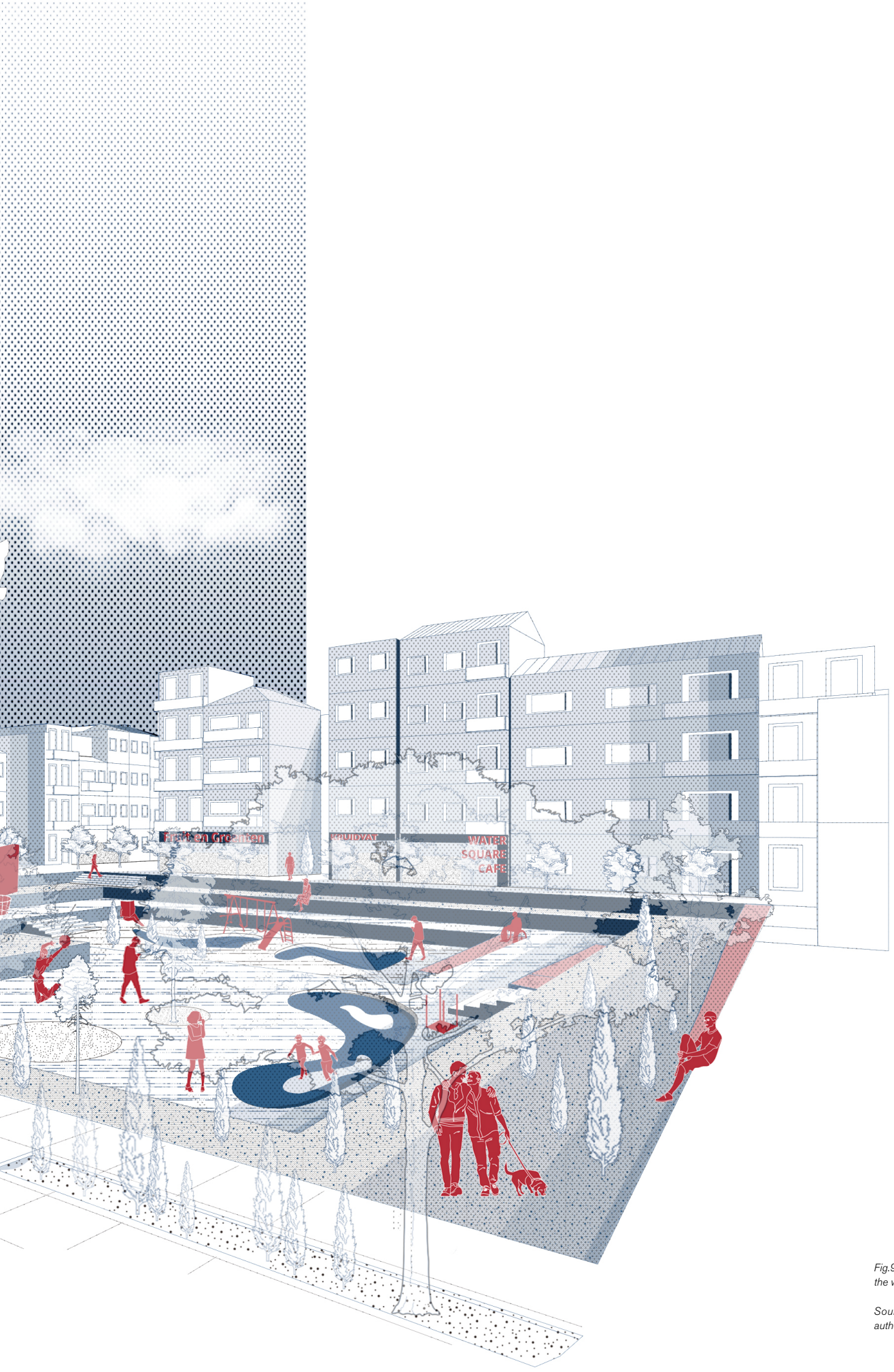


Fig.9-28 Impression of the water square

Source: made by the author

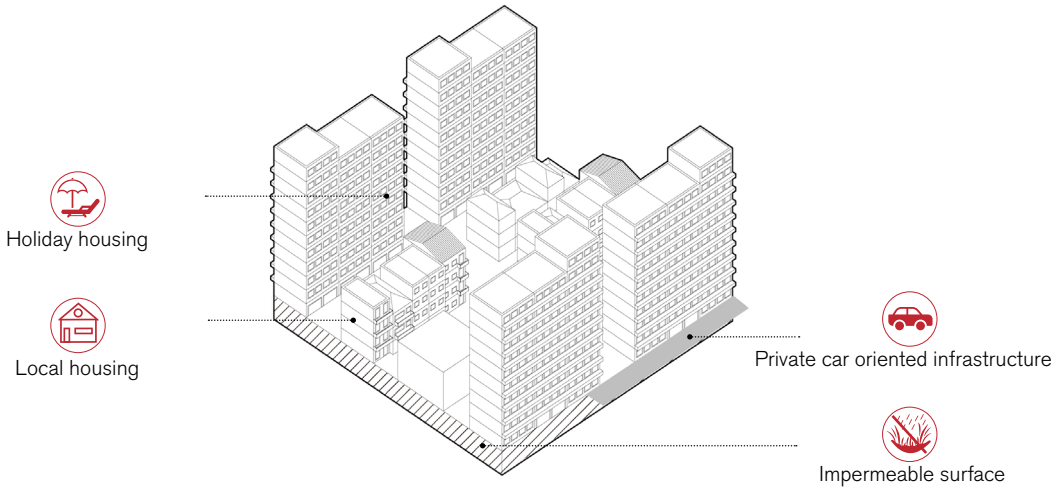
Block typology transformation - Concept of co-living urban block

Except for the public block transformation, in this period, the current living pattern should also be challenged due to the long-term adaptation. And because of the previous intervention, the transformation of living patteren is also possible.

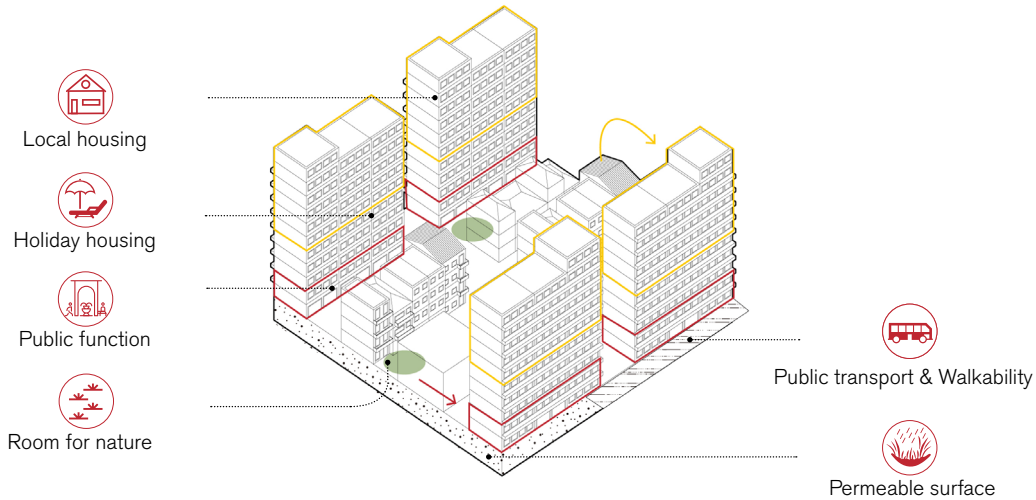
As it shows before, the current high-rise apartments are always occupied by the holiday housing, which is often empty during the risky season. While local people are settled in the low-rise and low-quality houses.

Thus, the co-living urban residential block has been proposed, in which local people are located more high-rise area while low rises are used for holiday housing, together with the improving surrounding environment. This proposal can be implemented together with the governance, regulation and housing management.

Here, one block is selected as a example to show the design.



Schematic model of current block



Schematic model of possible future block

Fig.9-29 Block typology transition proposal

Source: made by the author

Block typology transformation - Design case study

The selected residential block locates in the street on the dike next to the harbour.

The block consists of the high-rise holiday apartments and low-rise local family housing. Currently the inside area of the block is occupied by the storage room and the private courtyard that shared by the residents in family housing. The quality of the family housing is relatively low (The construction is old, the materials are worn, and the water resistance of ground floor is weak).

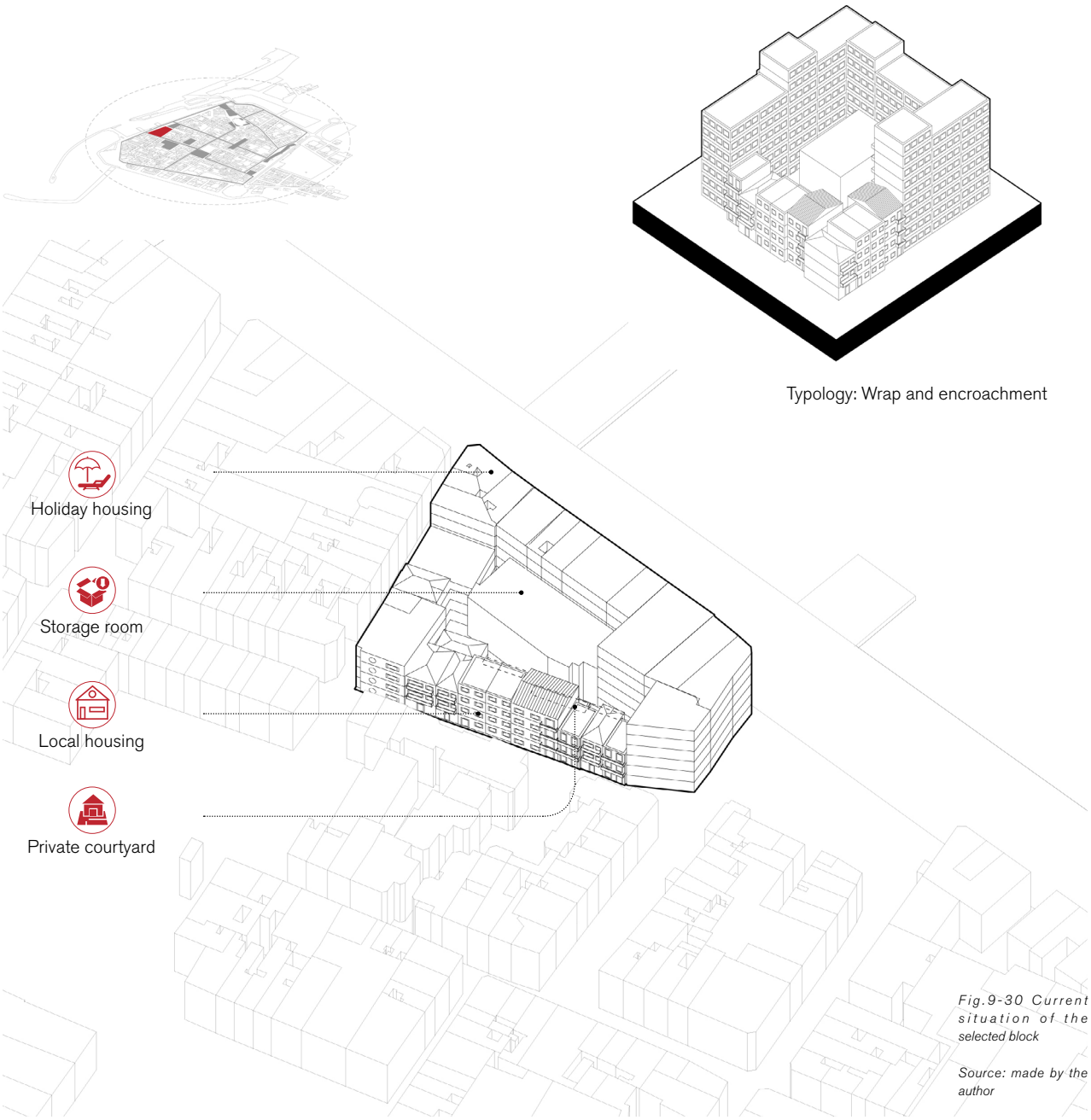


Fig.9-30 Current situation of the selected block

Source: made by the author

Block typology transformation - Design case study

The design proposal consists of four main parts. Firstly, the storage building is removed. The high-rise holiday apartments are transformed to be more open and connect to the city public network. The low-rise family housings are renovated and the block is partly densified.

By doing so, some improments can be achieved both at the aspect of personal living and at the aspect of neighborhood environment.

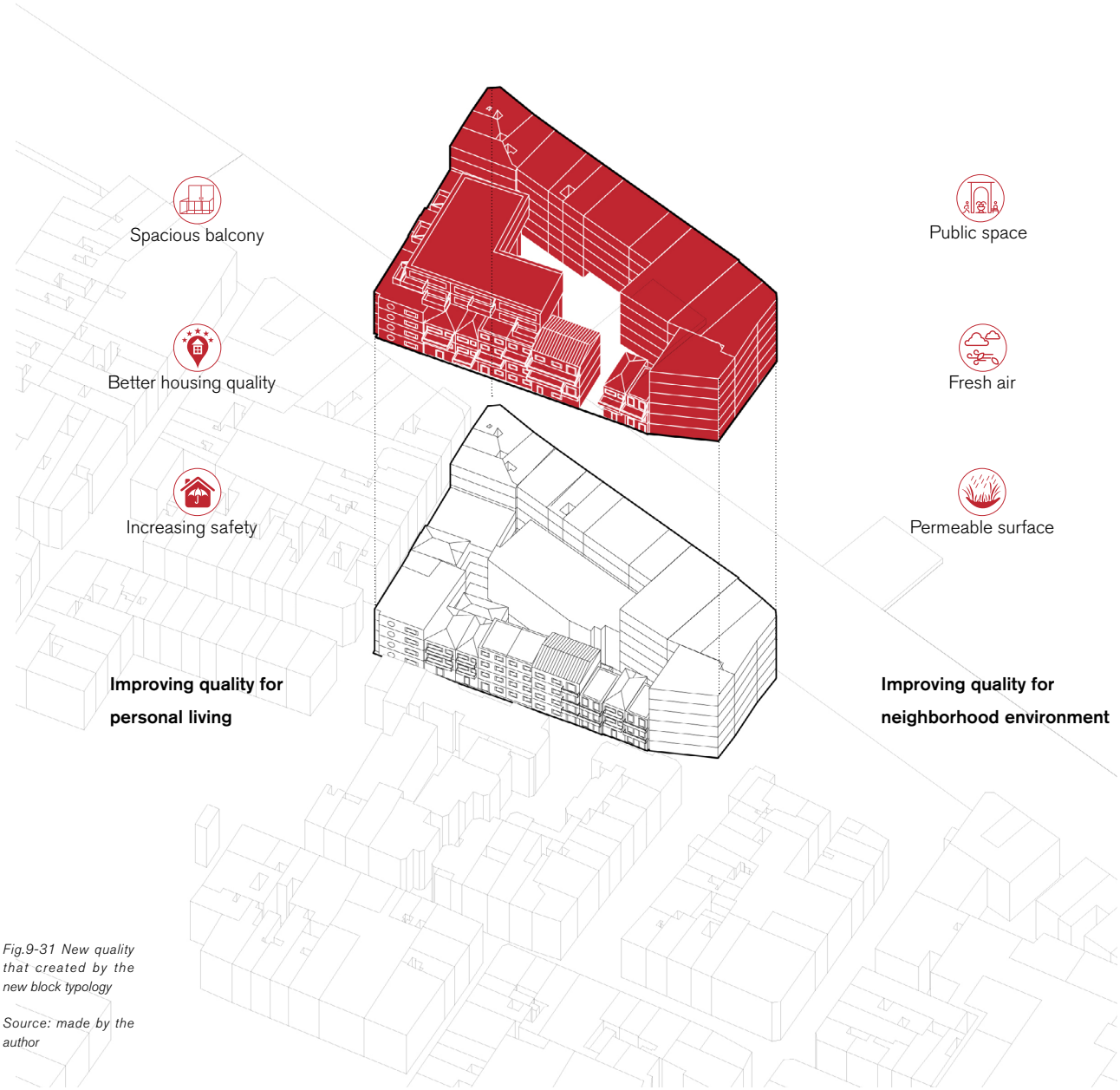
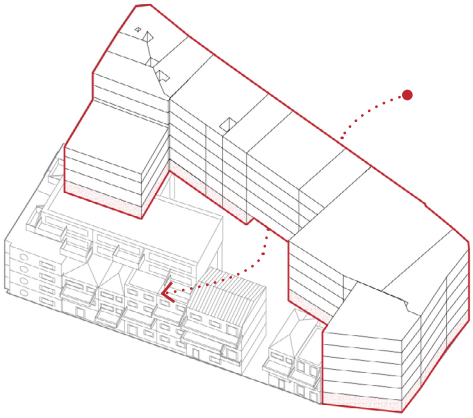


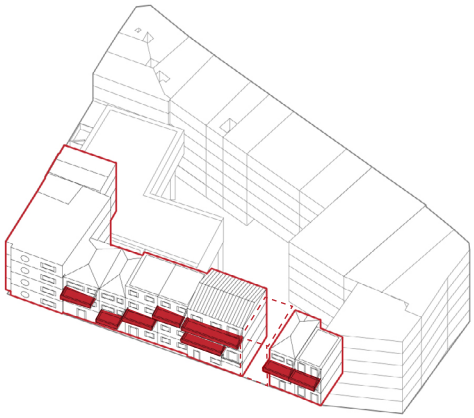
Fig.9-31 New quality that created by the new block typology

Source: made by the author



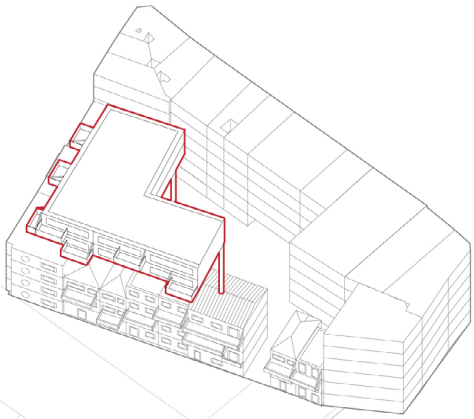
Apartment transformation

Removing some part of the ground floor, linking to the public network in the city centre



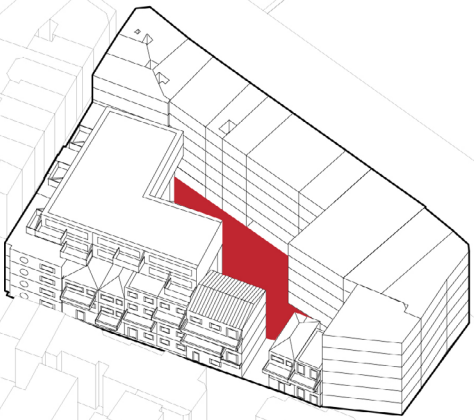
Family house renovation

Improving the housing quality
Removing the courtyard and adding the balcony



Partly densification

Adding new buildings above the low-rise housing for local residents



Removing the storage building

Fig.9-32 Axonometric drawing of different elements in new block

Source: made by the author

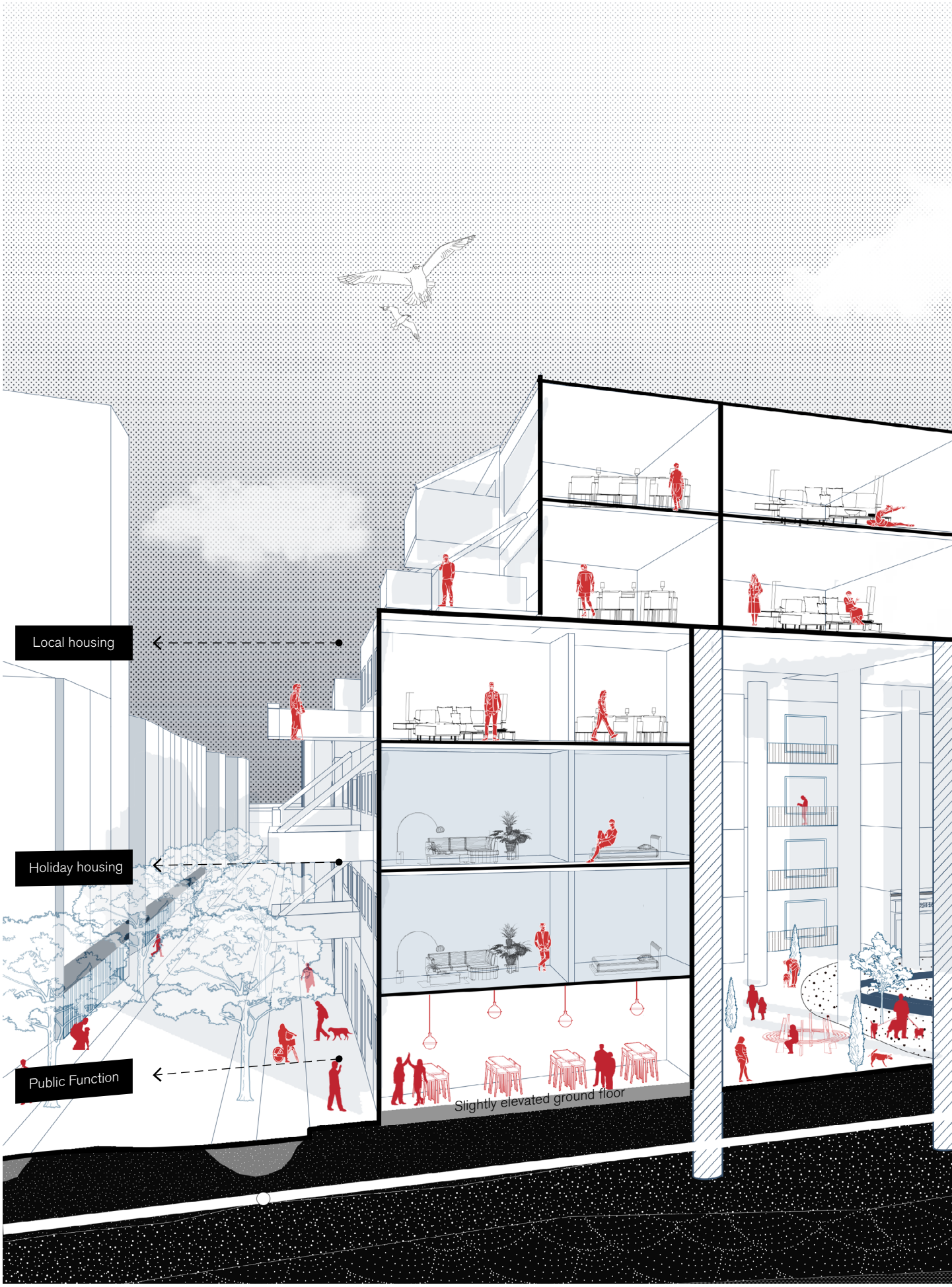

Local housing
Holiday housing
Public Function
Slightly elevated ground floor



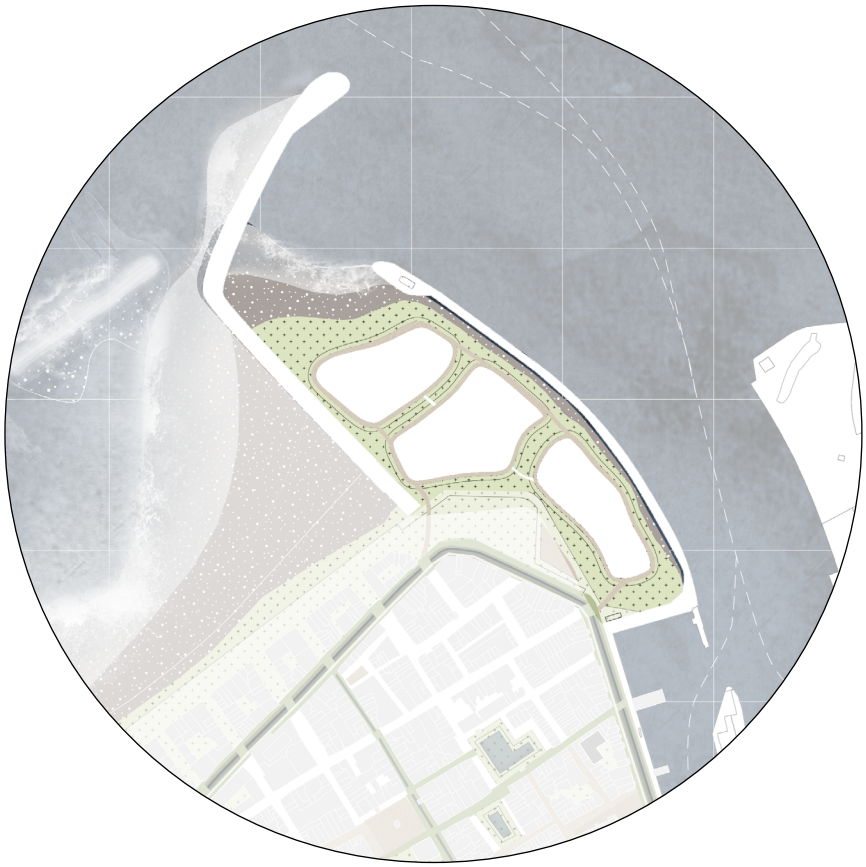
Fig.9-33 Sectional perspective of building block transformation

Source: made by the author

Project C - Urban new land

Based on the research, the area between two breakwater have the natrual accumulation process, thus we can work together with nature and create high lands here for the future development of the city. The principle of this intervention contains preserving the buffer zone, partly elevating the area and linking to the curent urban infrastructure.

Under this construction principle, different possible senarios are provided.



Implementation strategies

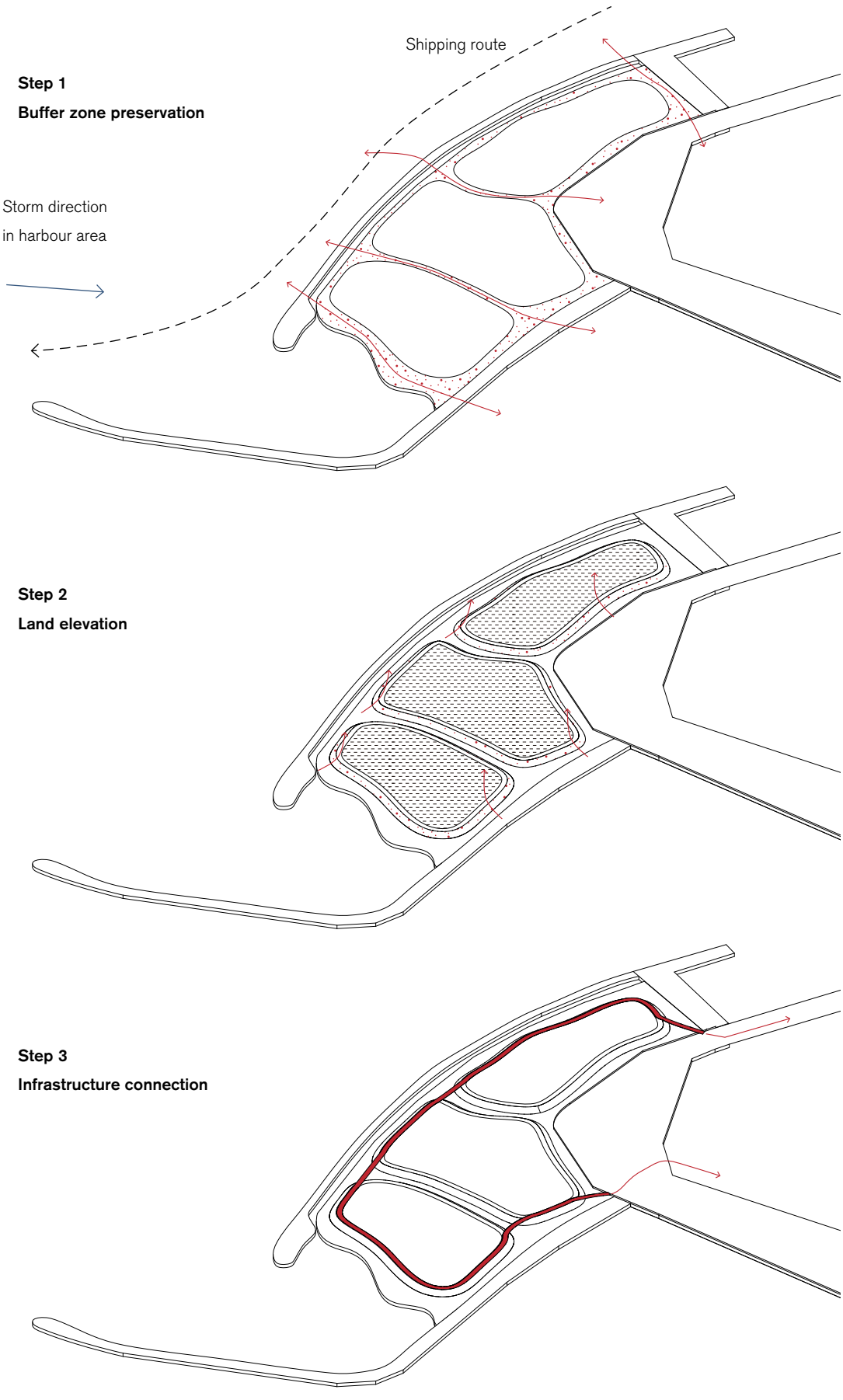


Fig. 9-34 Implementation strategies of new land

Source: made by the author

Possible construction senarios

Ideal option:

Inter tidal beach and marsh land

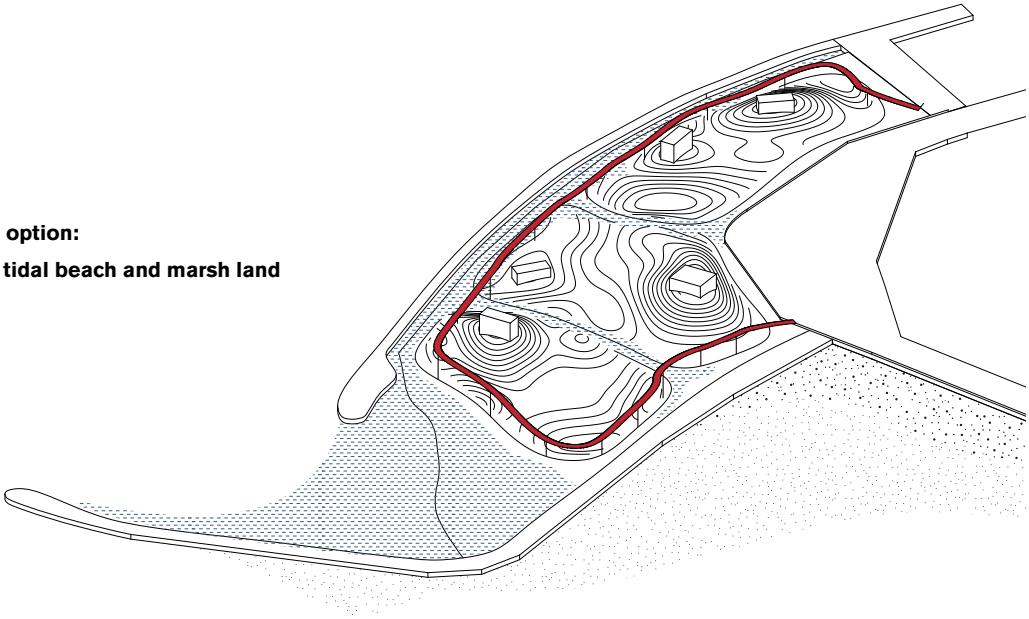


Fig.9-35 Senario: inter tidal beach and march land

Source: made by the author

Other options:

Low density

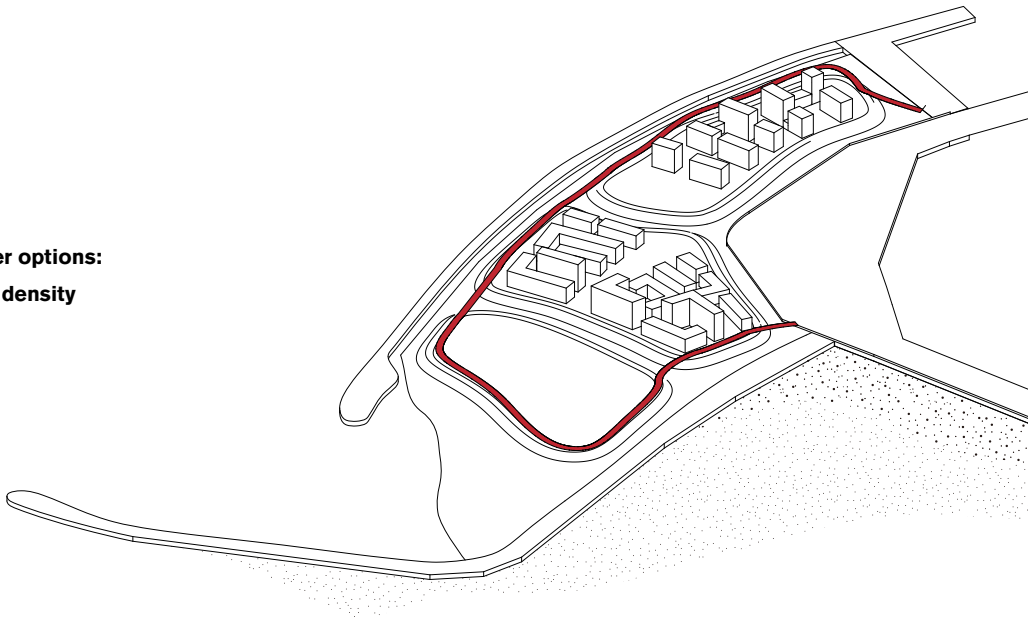
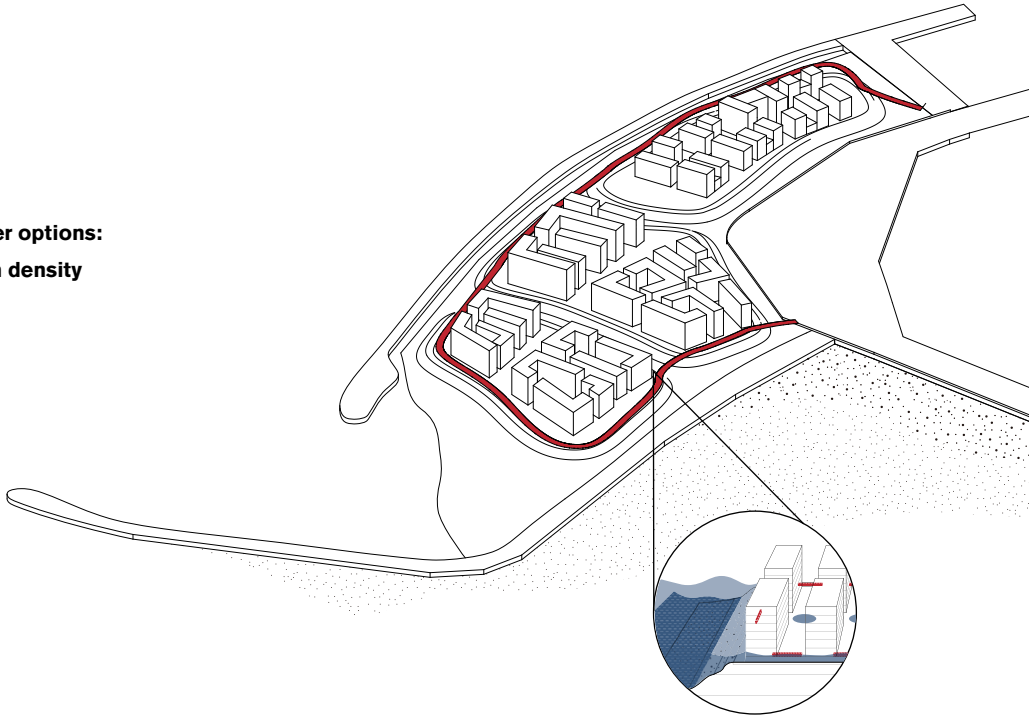


Fig.9-36 Senario: low density

Source: made by the author

Other options:

High density



Removable strom wall installed between buildings for future risks

Fig.9-37 Senario: high density

Source: made by the author

Possible future growth

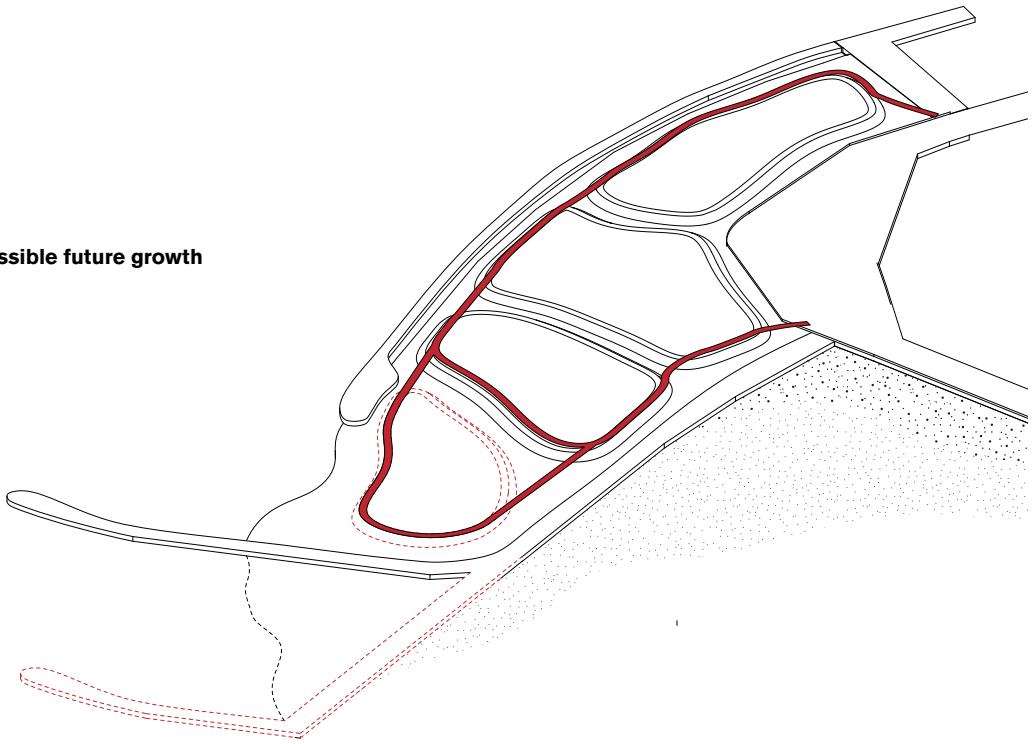


Fig.9-38 Possible future growth

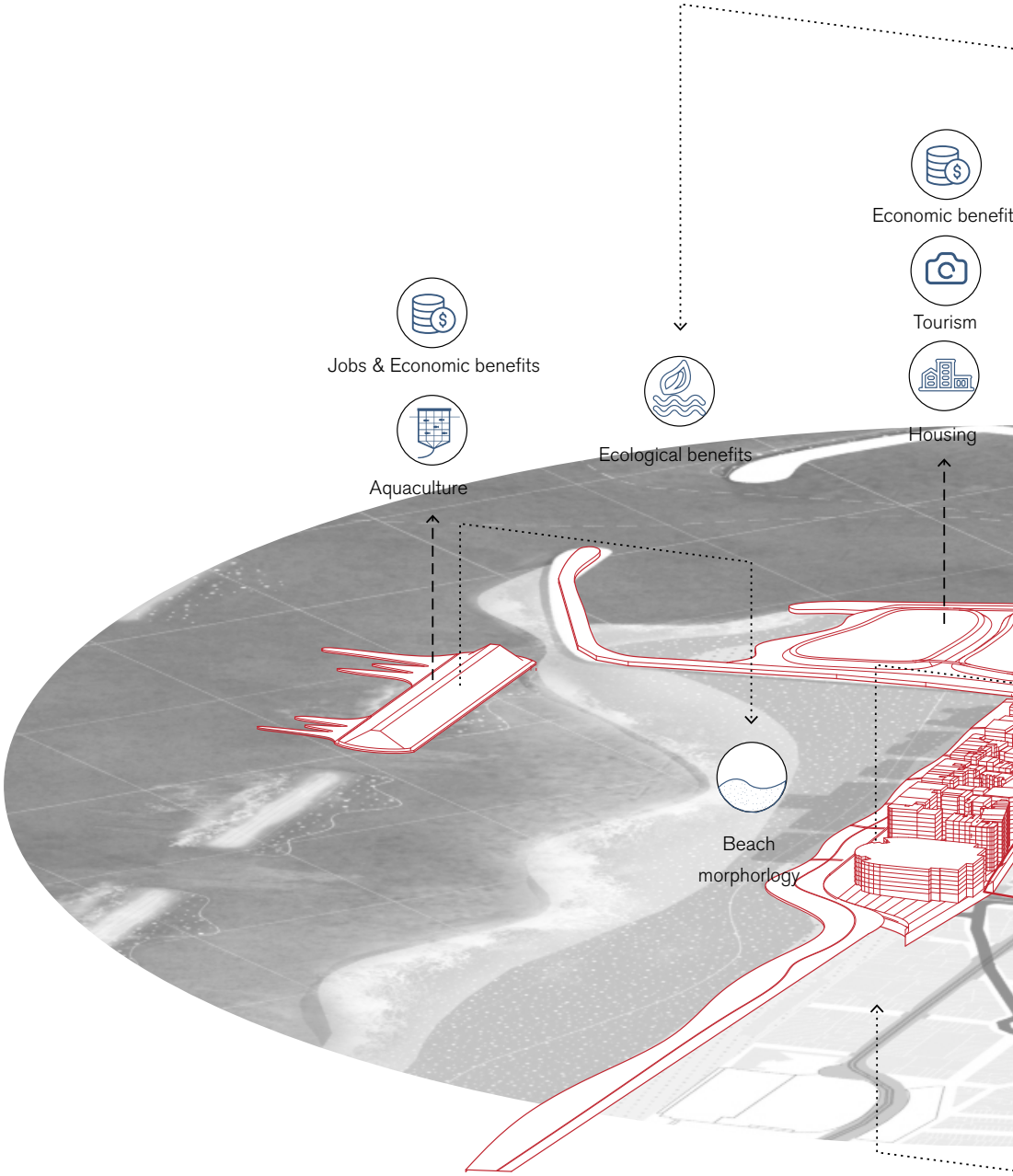
Source: made by the author

Project overview and interrelation

First of all, the different interventions deal with the different part of the risks reduction (probability and impacts), that works together to contribute the safety.

Besides, there are also some other relations that bring side effects and make the whole system more efficient and much stronger. These interrelations mainly reflected in the following aspects.

1.Ecological benefits
The intervention on the sea side provide different habitats, benefiting the marine ecosystem. The dune restoration on the coast and the buffering network on the urban side gives nature more space and increases the biodiversity. Working together, these three parts can create a



more complete and complex coastal ecosystem, also providing ecoservice.

2. Economic and social benefits
The oyster reef can be a start point of the aquaculture, contributing to the current fishery economy. The landscape becomes more diverse that helps the development of tourism. These new and strengthening industries can also offer new jobs to local people.

3. Living environment benefits
The cooperation between coast and urban side reduces the parking and traffic pressure of the city centre, improving the living environment.

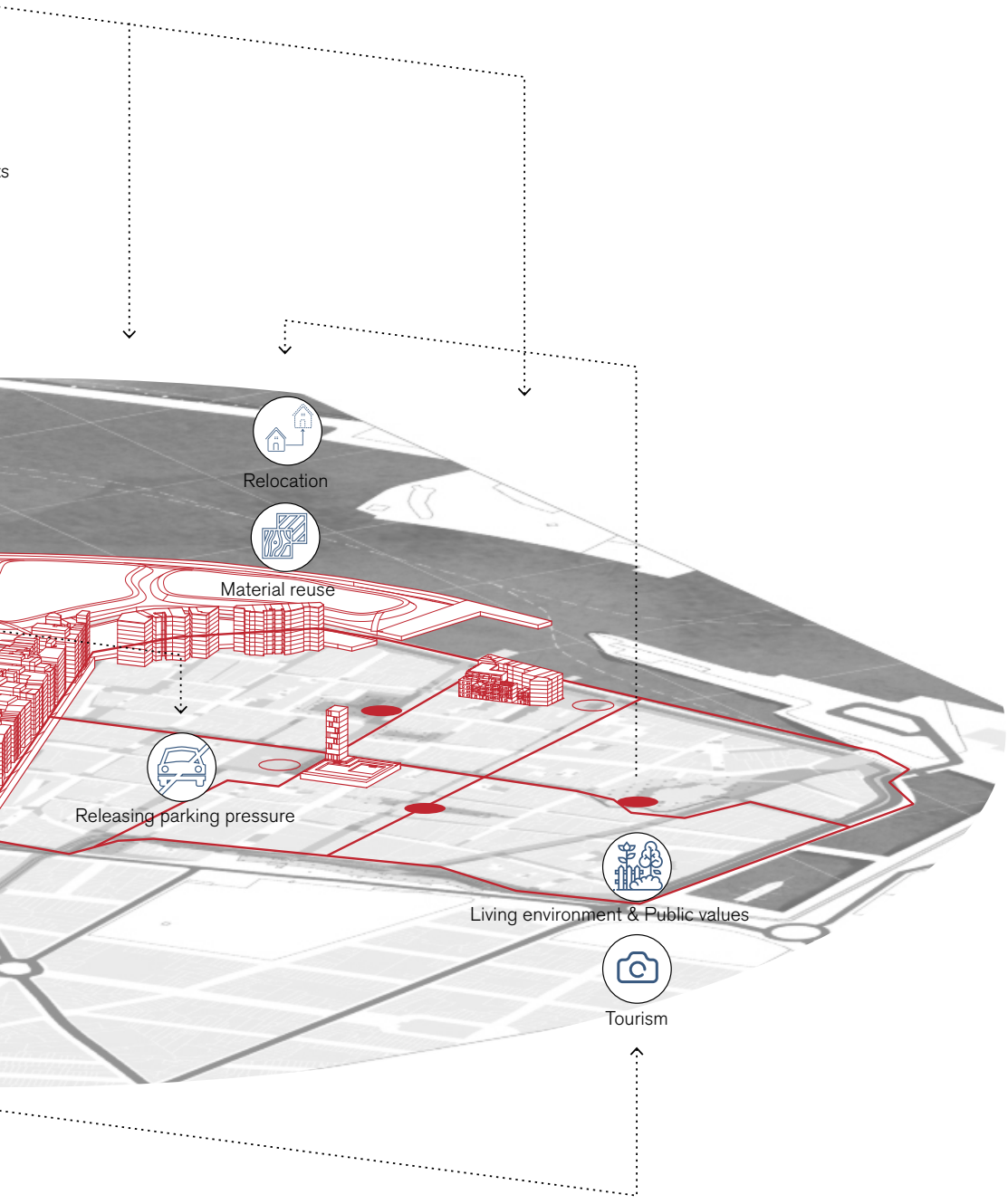


Fig.9-39 Projects overview & interrelations

Source: made by the author

9.6 Risky Period

2070 - 2100 （5m SLR as an extreme)

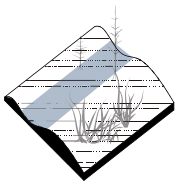
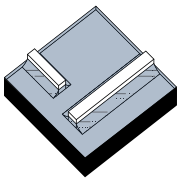
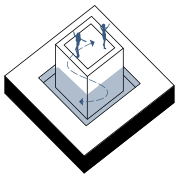
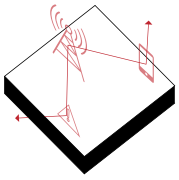
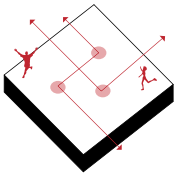
In this period, the interventions in the previous periods will be continued.

On the sea side, expanded intertidal and submerge oyster reef can connect to each other and creat a larger ecosystem.

On the coast, based on the oyster reef, the breakwater can also expanded further into the sea for the future use to compensate the areas in land transformed to the water square.

On the urban side, more water square will be implemented to increase the water capacity. And also more blocks can be renovated.

Besides, the situation in this period could be more uncertain, thus, to deal with this uncertainty, urban evacuation plan is also proposed for the extreme situation.

	Sea Side	**Coast**	**Urban side**
Structure measures	 Ecological engineer	 Ecological breakwater	 Smart shelter
Non-Structure measures	 Early warning system		 Evacuation

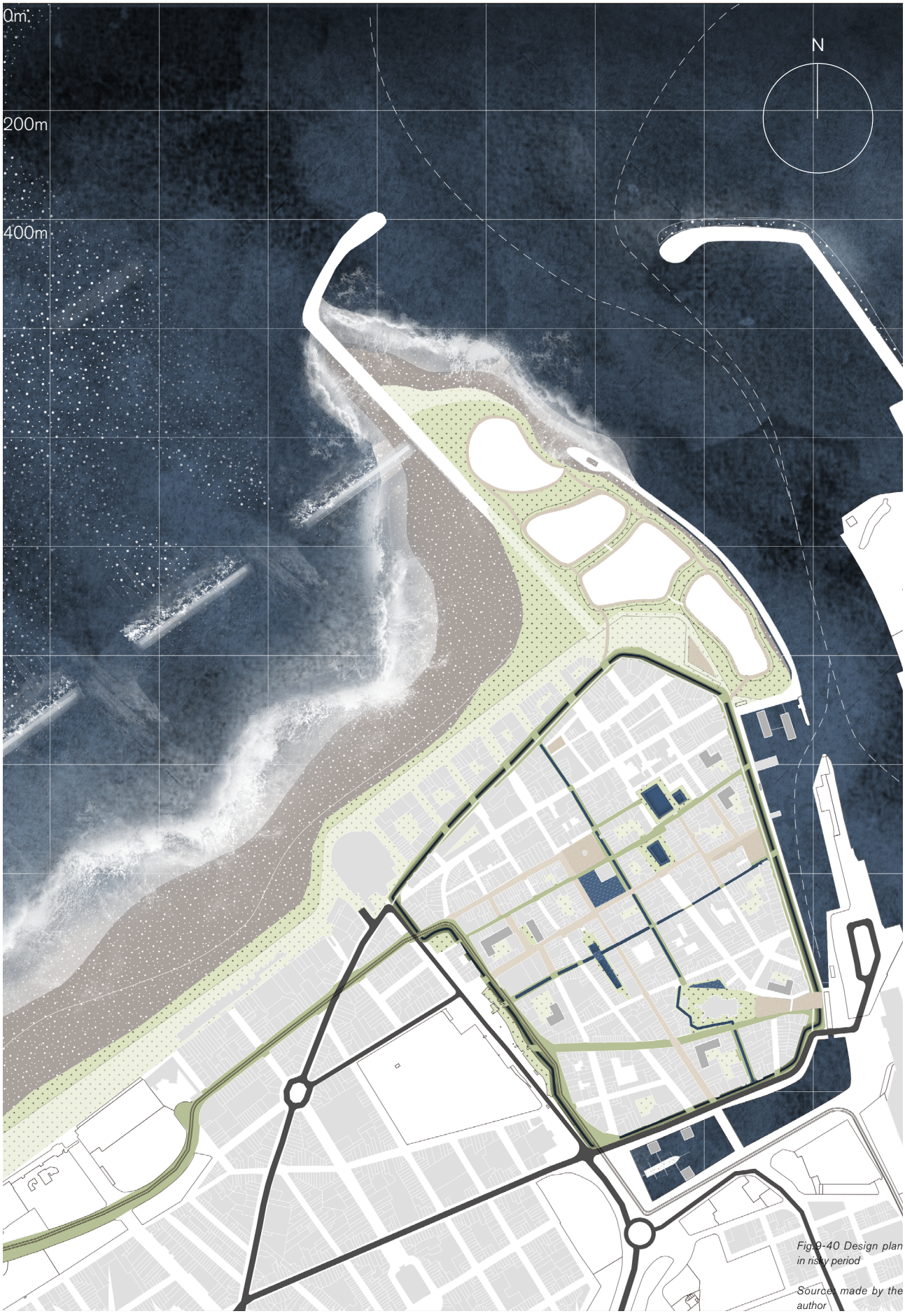


Fig.9-40 Design plan in risky period

Source: made by the author

Project A - Evacuation plan

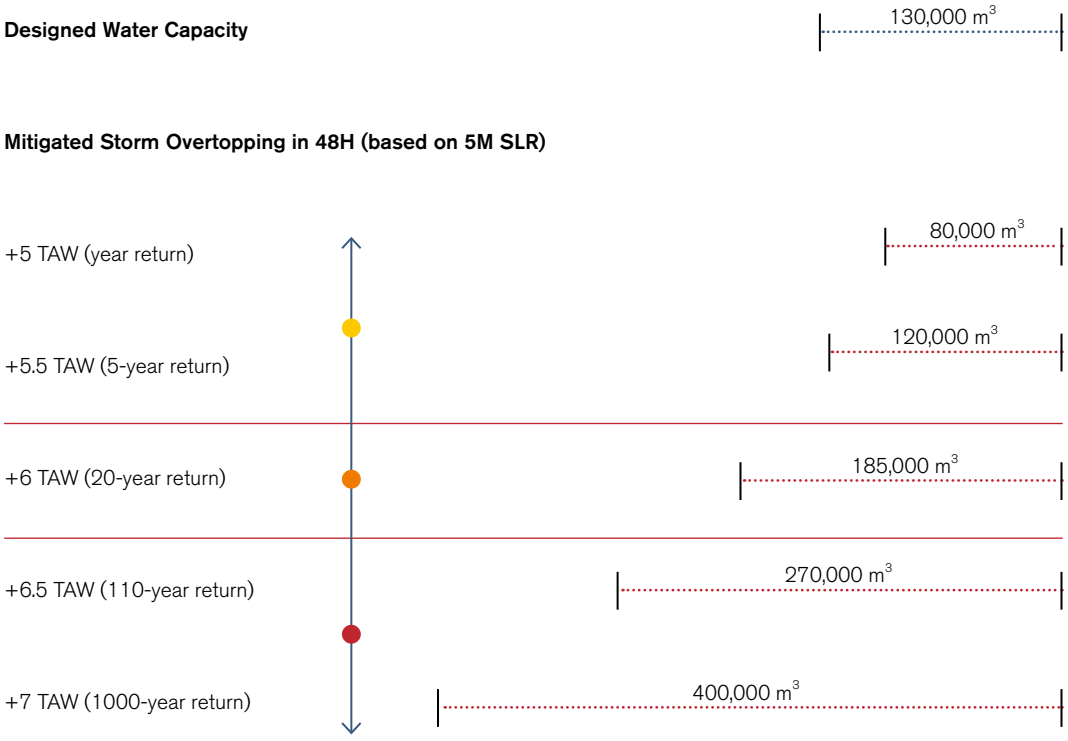
Principles

In this period, the three level of alarm system is created based on the comparison of water capacity and mitigated overtopping volume under different storm surge senarios (the wave hight is relative to the 5m SLR).

Yellow light alarm:
Removable storm wall installation on the Main buffer line

Orange light alarm:
Removable storm wall installation on the Main buffer line
People stay indoor and keep the doors & windows closed (24-36h)

Red light alarm:
Removable storm wall installation on the Main buffer line
Evacuating people to the nearby evacuation site (within 12h)



Safe paths

The safe paths are planned for the evacuation. The main safe paths direct to the high land and other parts of the city, which are accessible for rescue vehicles for the quick evacuation. The secondary safe paths are the walking safe paths that link to the main paths and different evacuation sites that provide the residents quick and safe access to the main paths and evacuation sites.

The safe paths are slightly elevated to extend the time before being flooded.

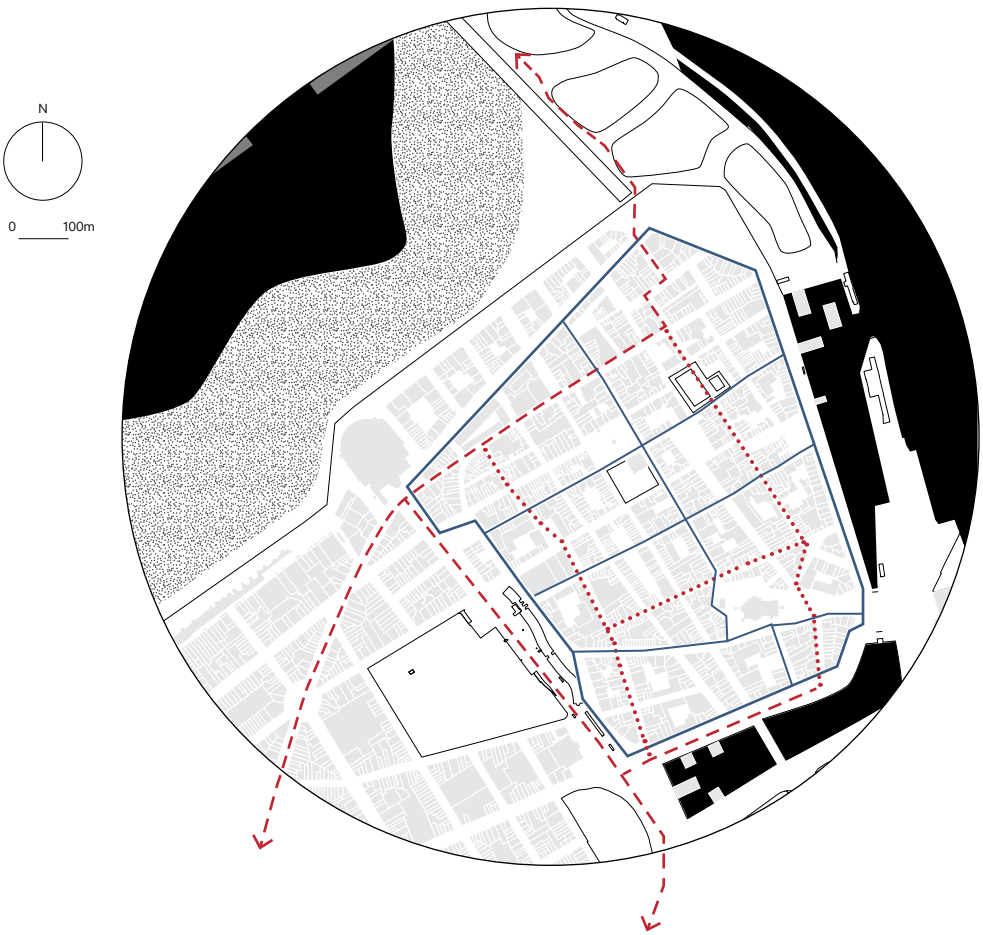


Fig.9-41 Safe paths system

Source: Made by the author

Main evacuation site

Three evacuation sites are planned to offer temporary and emergency staying for residents. They are placed around the site to improve the connectivity with the outside. And due to the different characteristics, different rescue methods are also suggested.

All these three sites are accessible within 10mins walking (500m service radius).

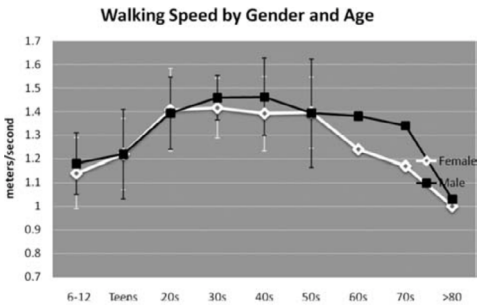


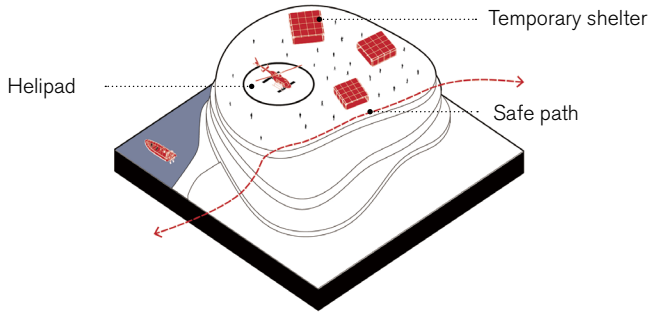
Fig.9-42 Walking speed categorized by gender and age (6-12 and teens,47 20s-50s,42 & 60s-80s48).

Source: Fritz & Lusardi, 2009



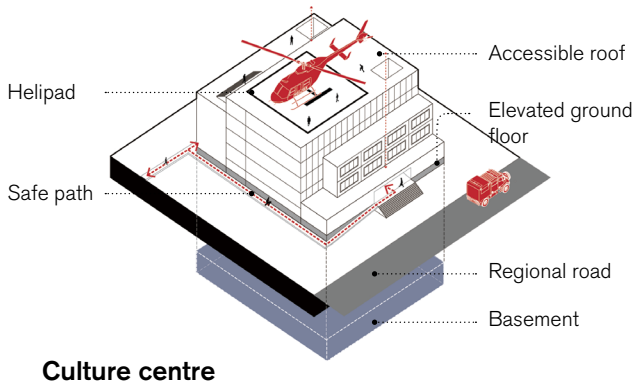
Fig.9-43 Evacuation sites system

Source: Made by the author



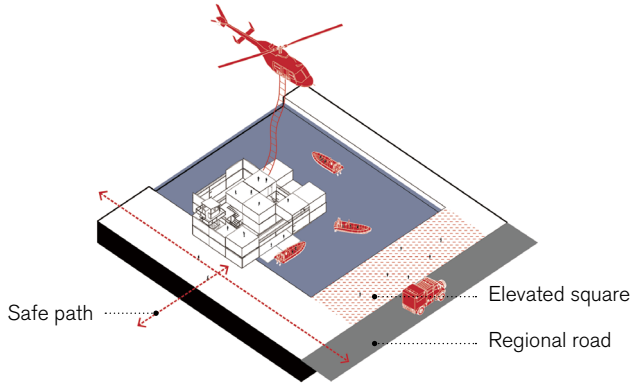
High land

Area:
≥13,000 m^2 Outdoor
Flexible indoor area
Maximum capacity:
≥ 3700 people
Rescue method:
Helicopter, Lifeboat



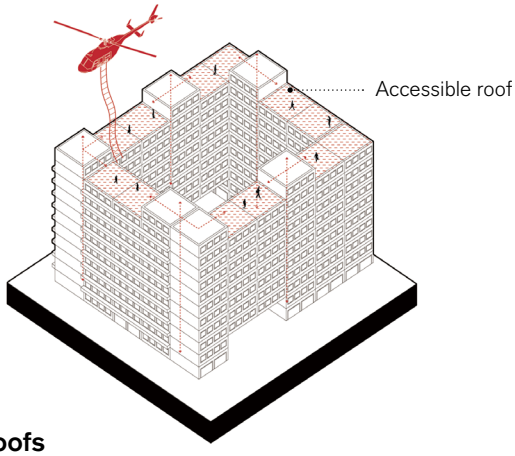
Culture centre

Area:
10,500 m^2 Indoor
Maximum capacity:
3,000 people
Rescue method:
Helicopter, Rescue vehicle



Floating museum

Area:
5,300 m^2 Indoor
3,500 m^2 Outdoor
Maximum capacity:
2,500 people
Rescue method:
Helicopter, Lifeboat, Rescue vehicle



The roofs

Backup plan

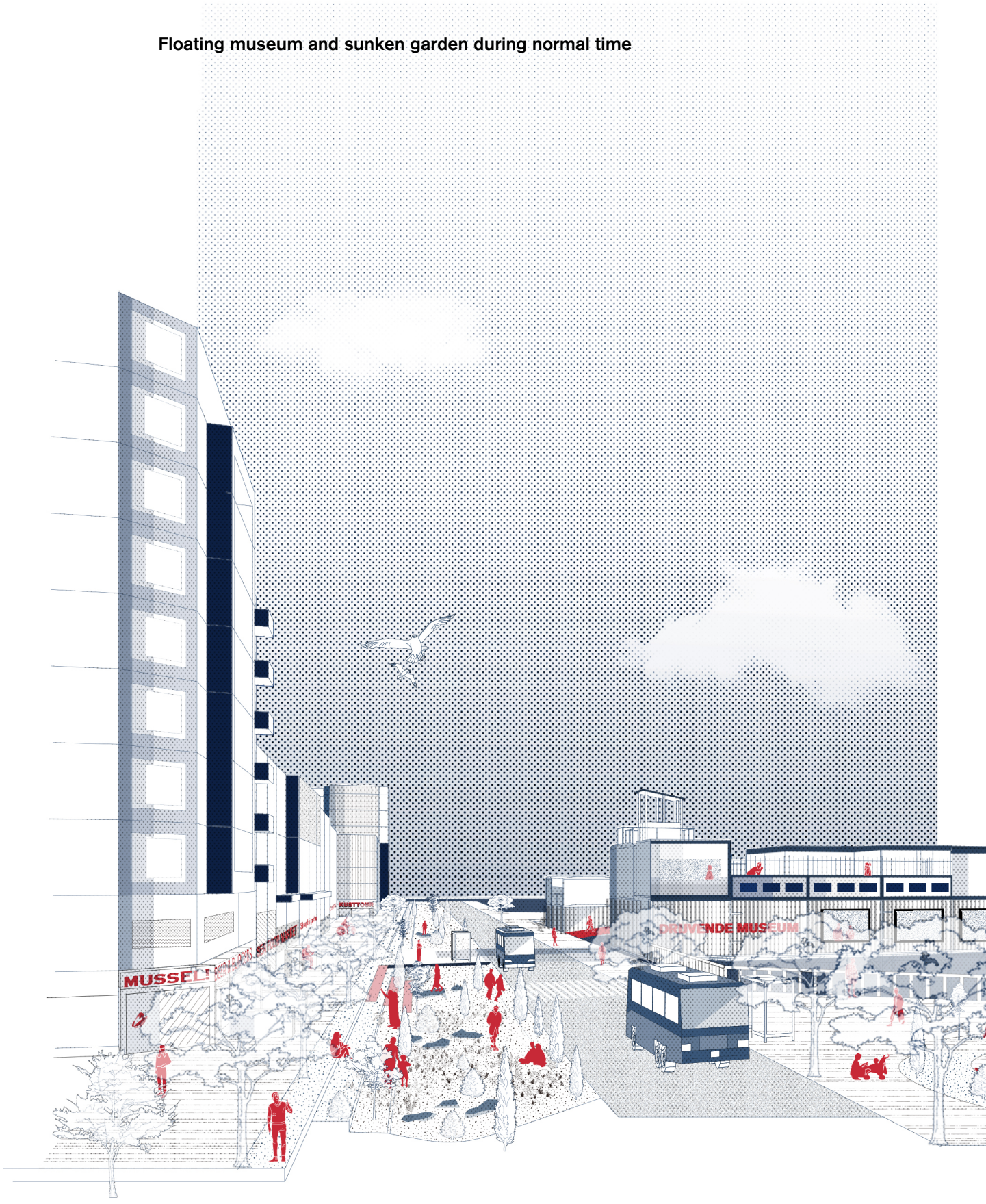
In case the urgent emergency, the accessible roof space of the high-rise apartments can also be the backup evacuation sites.

Fig.9-44 Typology of evacuation sites

Source: Made by the author

The capacity is calculated based on the area of 3.5 m^2, which is the minimum covered space per person, is used for capacity calculation

Floating museum and sunken garden during normal time



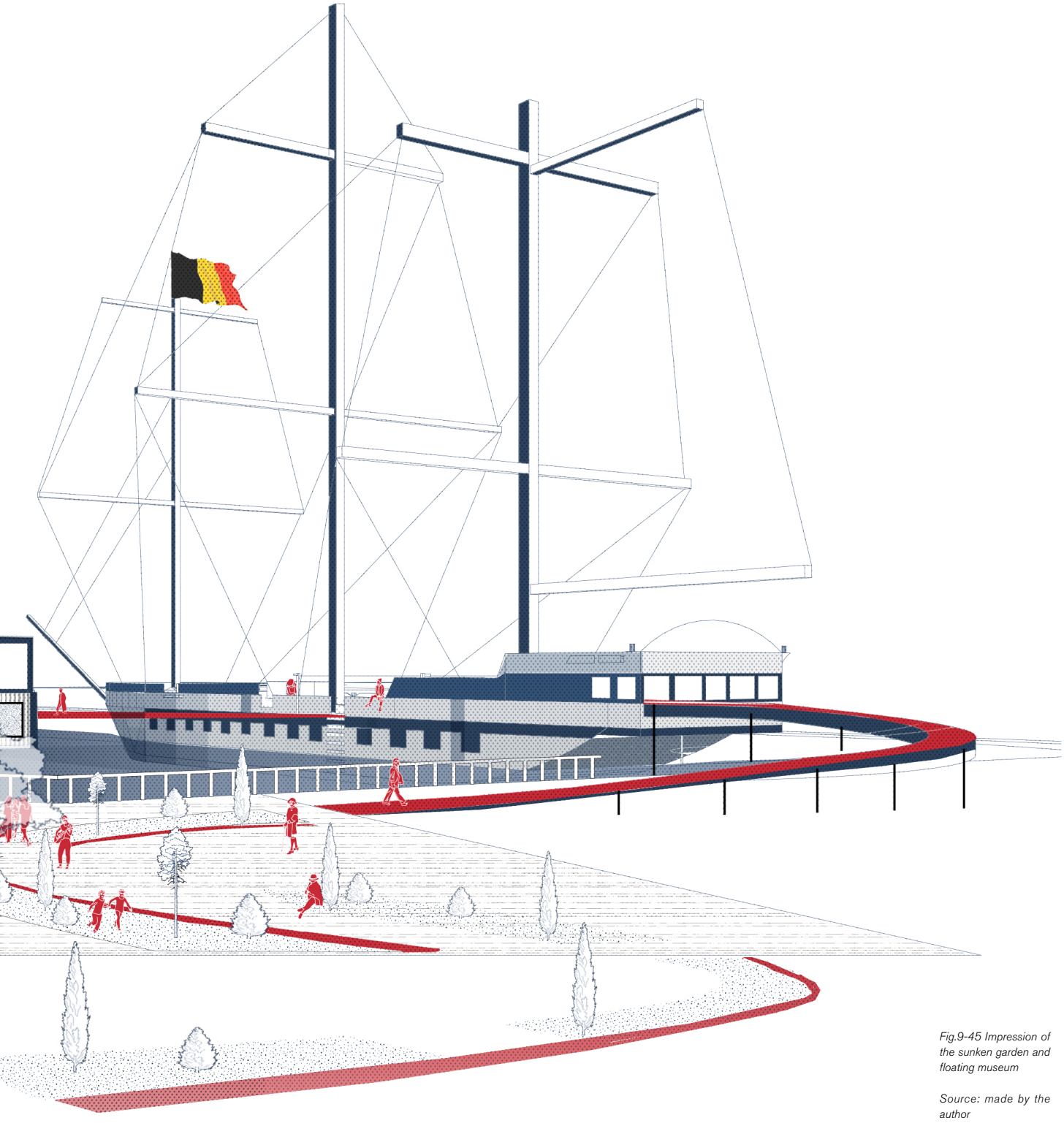


Fig.9-45 Impression of the sunken garden and floating museum

Source: made by the author

Floating museum as evacuation site during extreme storm event





Fig.9-46 During the storm events

Source: made by the author

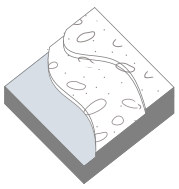
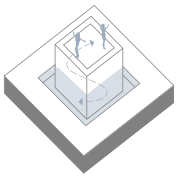
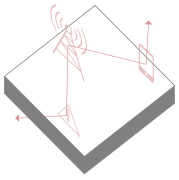
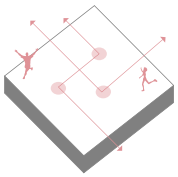
9.7 Limited Period

Possible future

In this period, there are large uncertainties and vague context, thus only imagination is provided to show the possible future.

Here one possibility is showed. The urban side could become different small islands separated by the buffering system that created in the previous periods, linked by safe paths. The new land is densified and taking on more urban functionalities.

This possibility portrays that in the future, the boundaries between land and sea will become increasingly blurred.

	Sea Side	**Coast**	**Urban side**
Structure measures	 New high land	 Smart shelter	
Non-Structure measures	 Early warning system	 Evacuation	

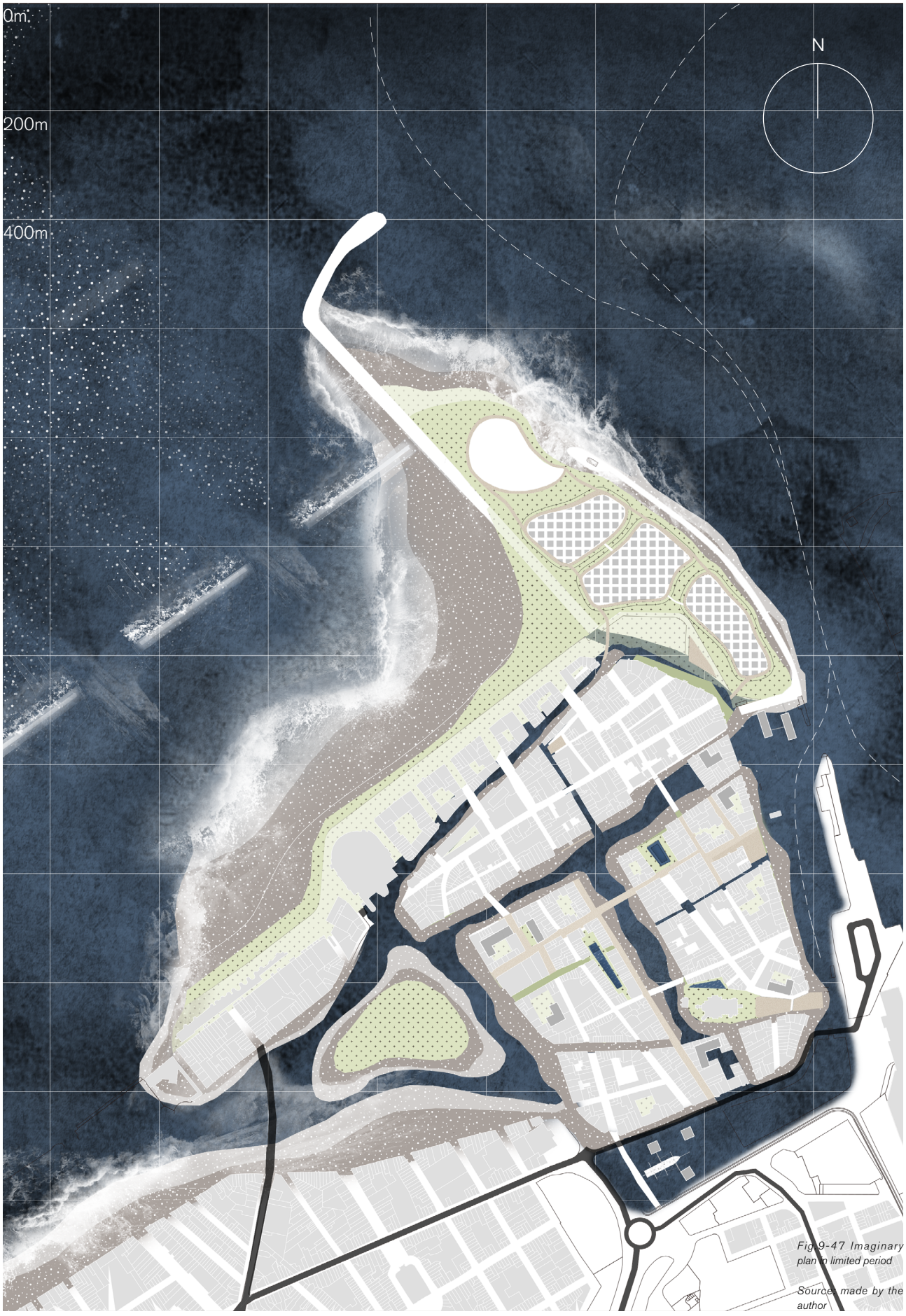


Fig.9-47 Imaginary plan in limited period

Source: made by the author



Fig.10-1 Groynes on Ostend beach infront of the industrial area

Source: Photo by the author

10 Transitional Space

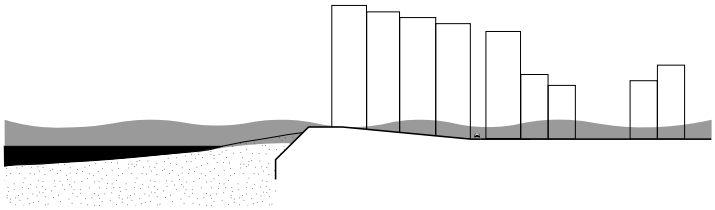
10.1 Transistion of Water Capacity
10.2 Transistion of Risks Reduction
10.3 Transistion of Coastline
10.4 Transistion of Coastal Landscape
10.5 Transistion of Building Typologies
10.6 Transistion of Public Network and Mobility
10.7 Transistion of Human's Experience
10.8 Transition of Coastal Economy
10.9 City Scale Adaptation

10.1 Transistion of Water Capacity

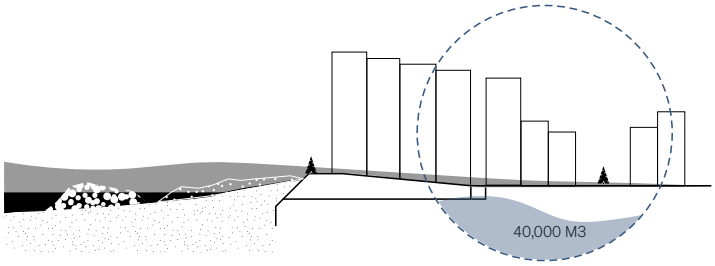
The water capacity in the area is calculated by the maxium volume of buffer line system and the created water square.

Here the calculation outcome has been showed.

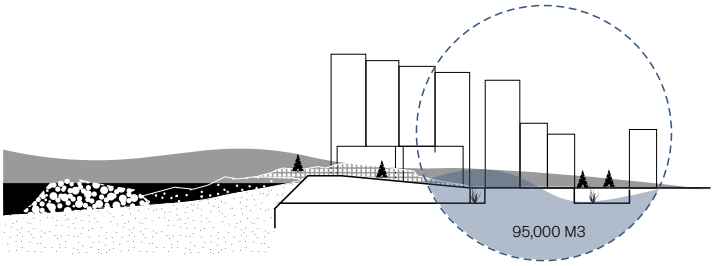
Current situation



Transitional period



Strengthening period



Risky period

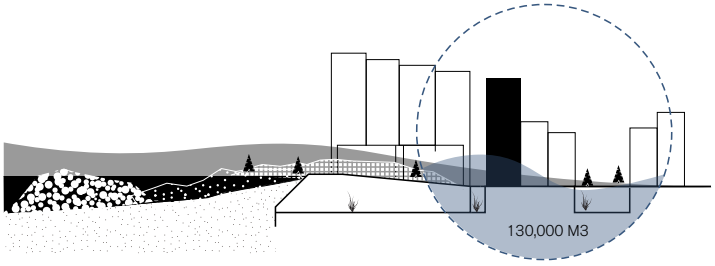


Fig.10-2 Water capacity transition in city centre of Ostend

Source: made by the author

10.2 Transistion of Risks Reduction

For the brobability part, according to the artificial reef design manual, the detached low-crested reef structure can reduce 20% - 30% of the wave energy. And based on the hydraulic testing model, 20% reduction of overtopping water can be expected by the main buffer line.

As for the impact part, the incresing water capacity can help to reduce around 10% of the impact.

Totally, more or less 55% of the risks can be expected by the measures that can be calculated. The remaining measures that are difficult to quantify can be used as a flexible part to deal with 45% of risks and the future uncertainties.

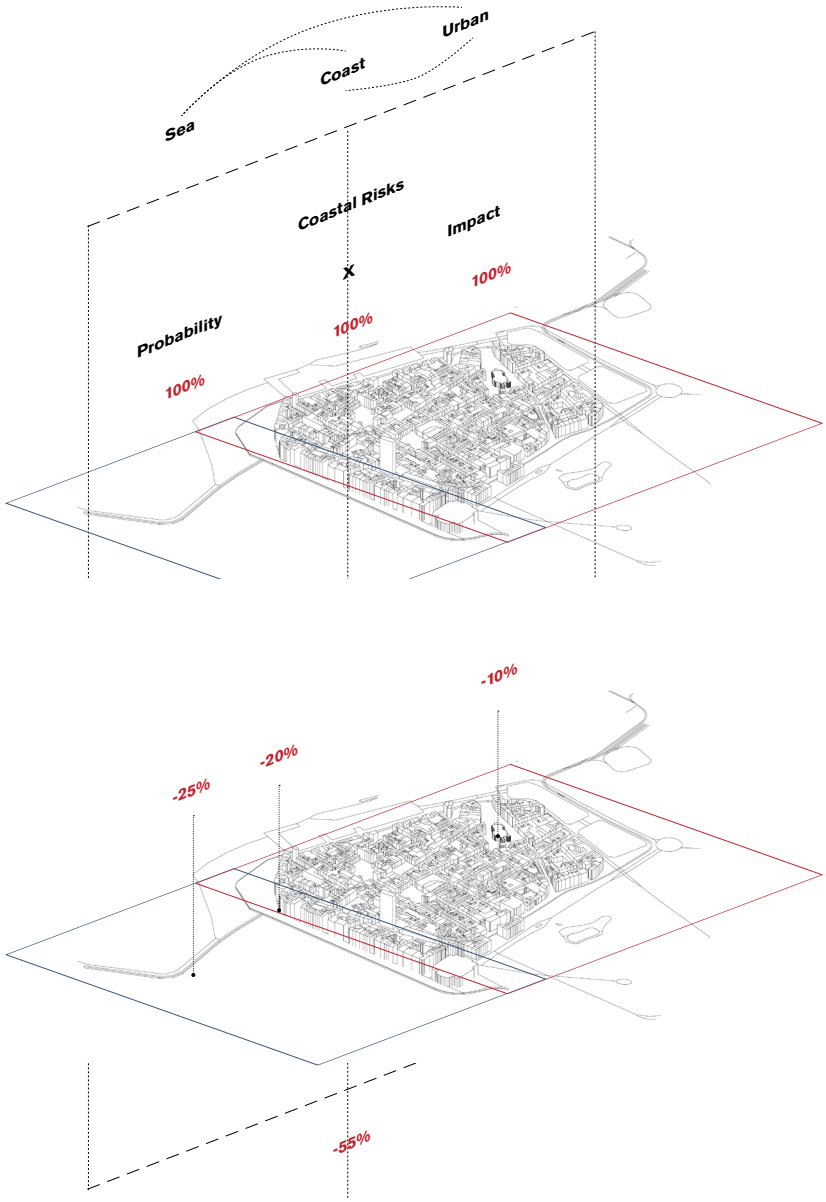


Fig.10-3 Projection of risks reduction

Source: made by the author

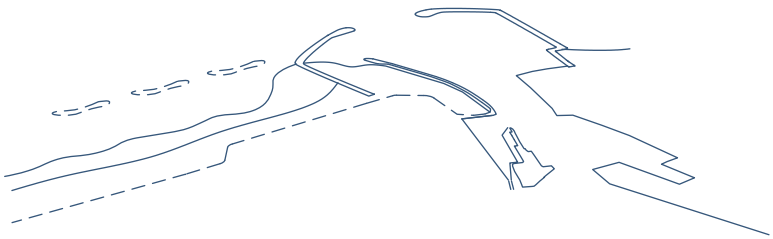
10.3 Transistion of Coastline

Through different periods of interventions, the boundary between the urban and the sea becomes blurred, and the sea, the coast and the urban areas are more like a whole coastal zone.

Current situation



Transitional period



Strengthening period



Risky period

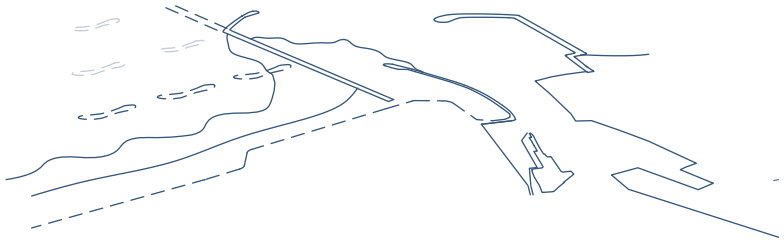


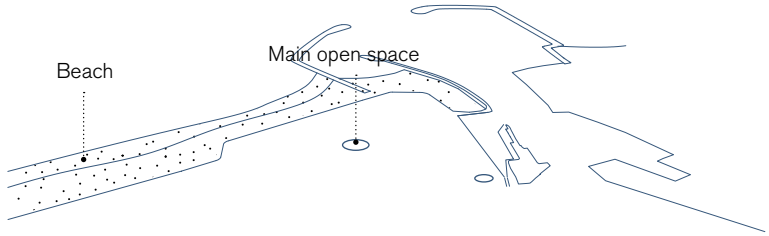
Fig.10-4 Coastline transition in city centre of Ostend

Source: made by the author

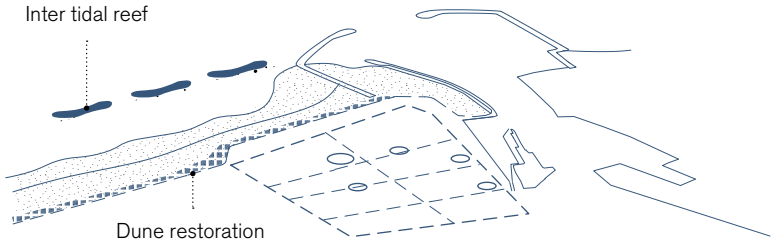
10.4 Transistion of Coastal Landscape

Through different periods of interventions, a more diverse coastal landscape system can be expected.

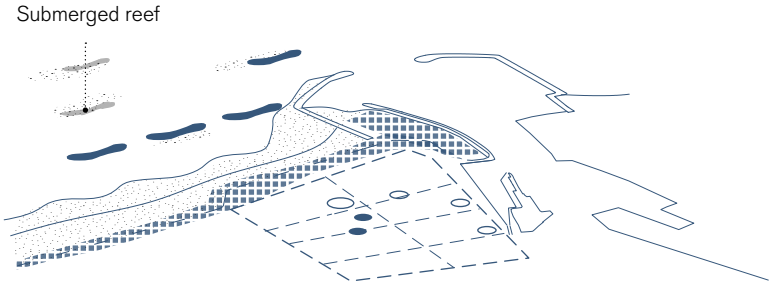
Current situation



Transitional period



Strengthening period



Risky period

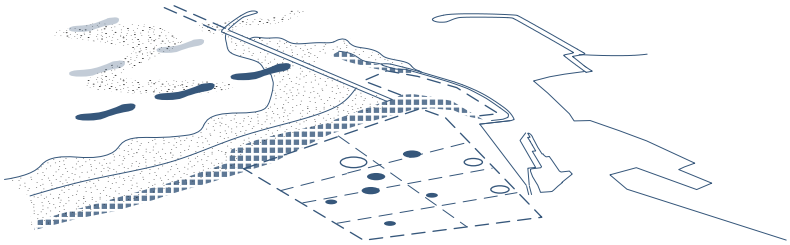


Fig.10-5 Coastal landscape transition in city centre of Ostend

Source: made by the author

10.5 Transistion of Block Typologies

Through different periods of interventions, some residential blocks are also transformed.

'Neighborhood living' blocks located in the risky areas are transformed to be more open, some housing are removed.

'Wrap and encroachment' blocks close to the new public blocks are transformed to be more public. The co-living ideas are applied and they are partly densified for compensating the removed housing.

For the 'New Atlantic wall' blocks, the ground floor becomes public and partly removed to make the coast and sea more accessible. The roof areas are also accessible to provide the emergency usage.

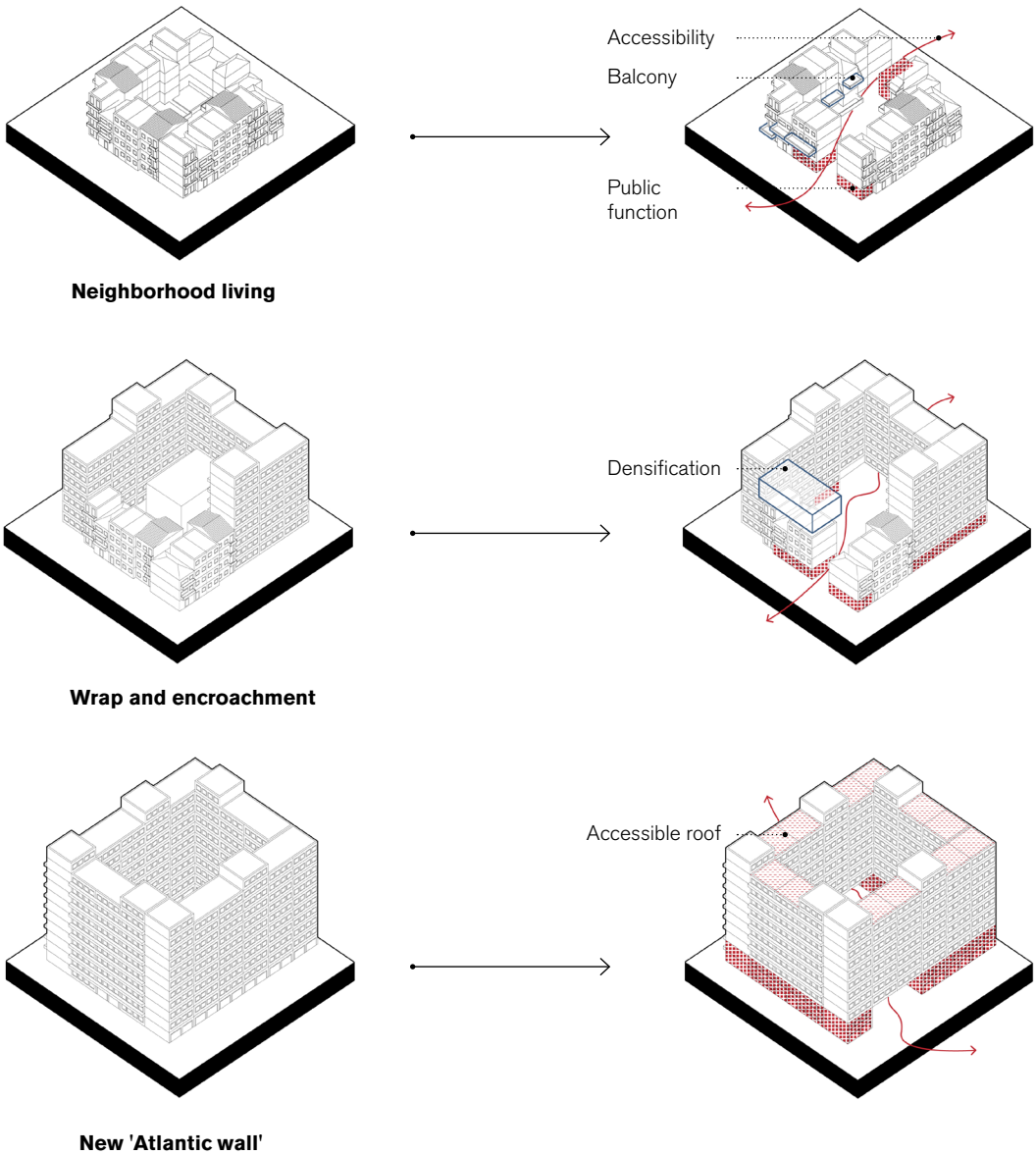
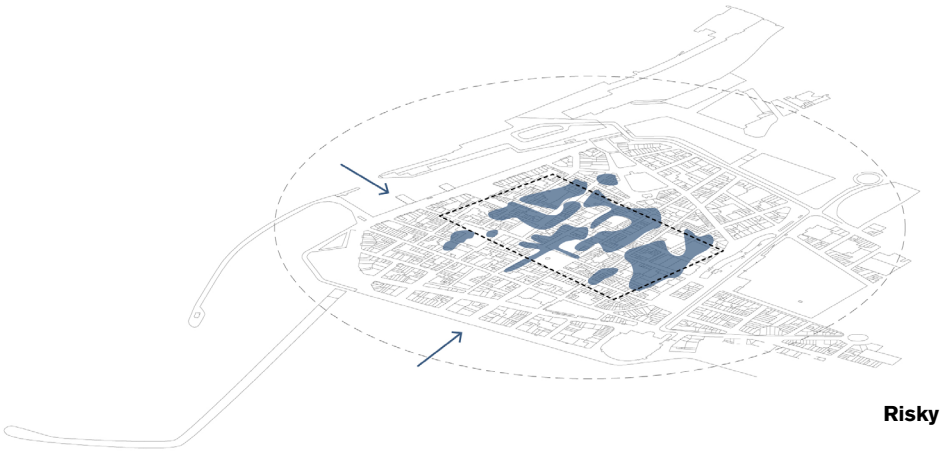
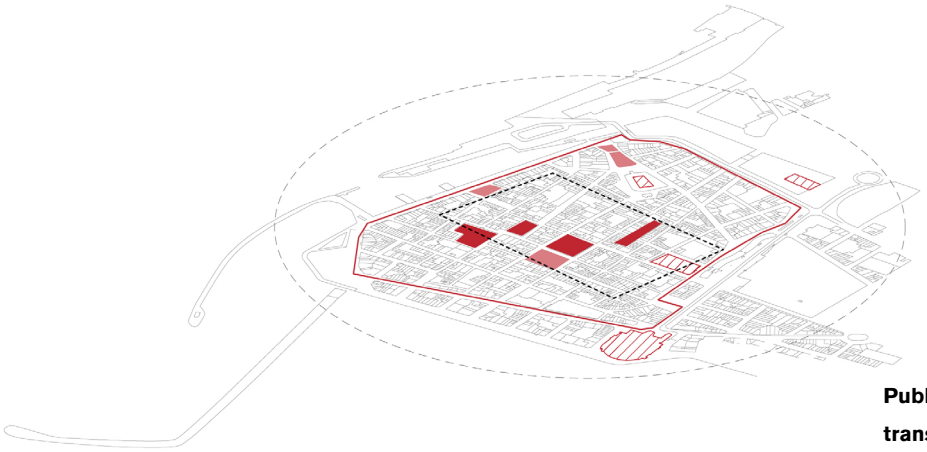


Fig.10-6 Urban block transition in city centre of Ostend

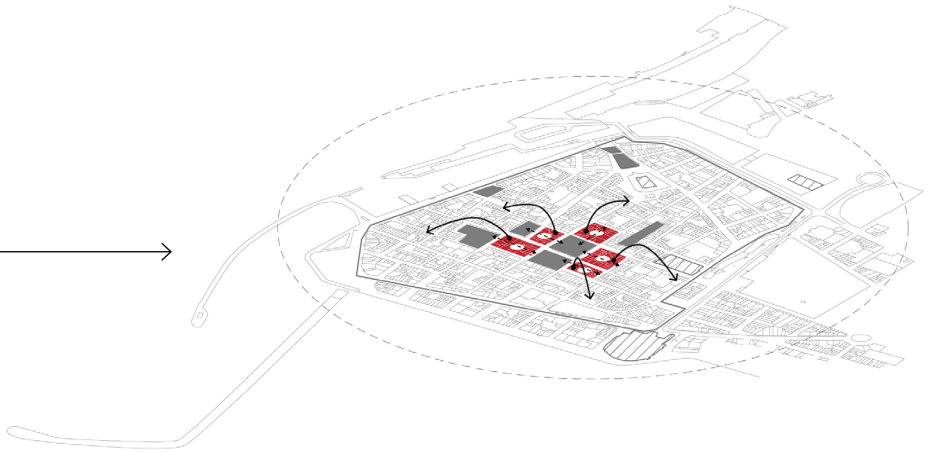
Source: made by the author

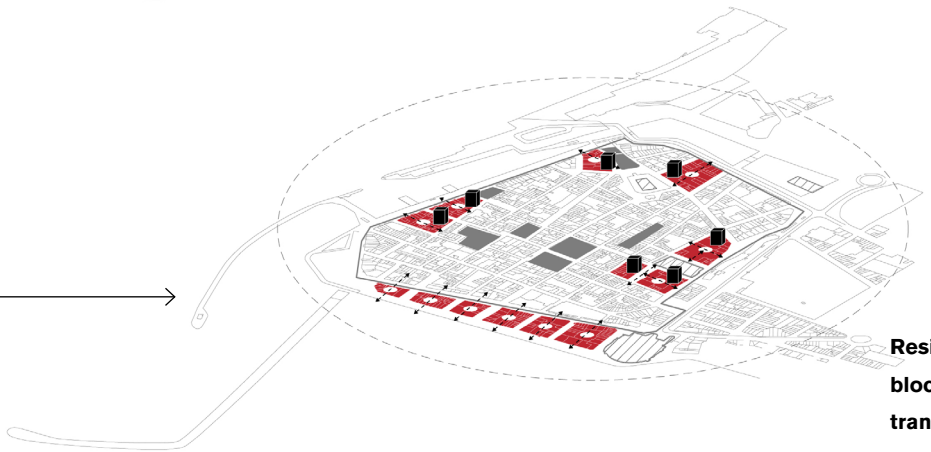


Risky area



Public block transformation





Residential block transformation

Fig.10-7 Urban block transition process in city centre of Ostend

Source: made by the author

10.6 Transistion of Public Network and Mobility

Public network reorganization in city centre

As analyzed before, the current public network in city centre has been separated into two parts and not linked very well. In the proposal, the main idea is to create a public ring and three public belt that linked by the walking system.

By doing so, the former risky area can be transformed into a new public centre, reducing the risks impacts at the same time creating larger public values.

Current situation

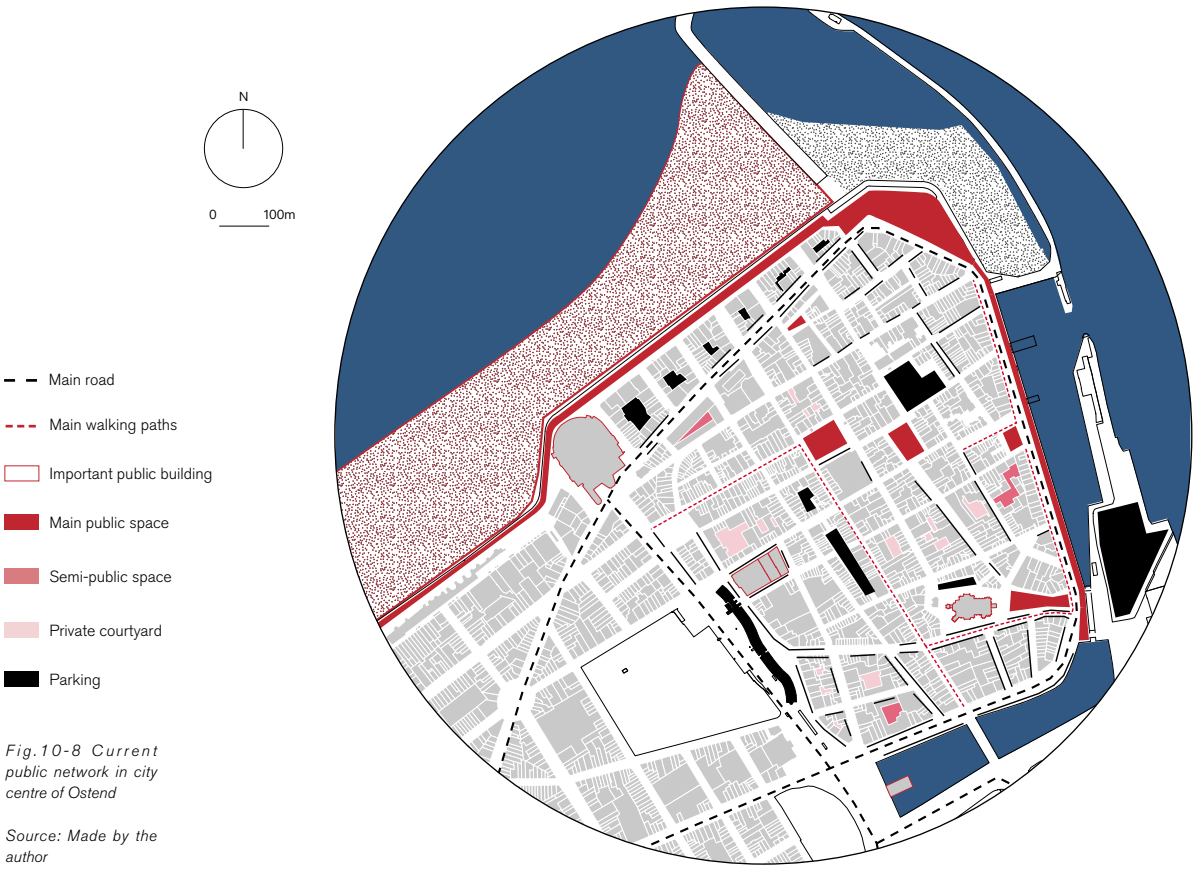
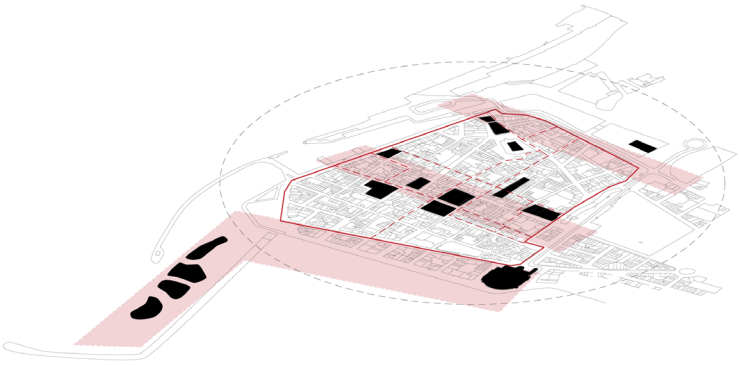
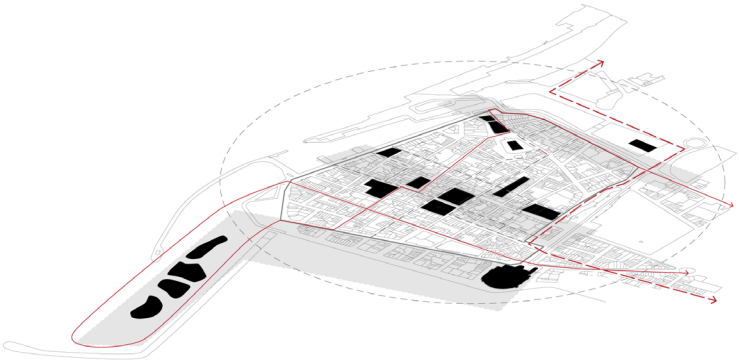


Fig.10-8 Current public network in city centre of Ostend

Source: Made by the author



Public centre &
main walking system



Public transport

Fig.63 Map of heritage in city centre of Ostend

Source: Made by the author

Proposed



Fig.10-9 Proposed public network in city centre of Ostend

Source: made by the author

Regional traffic reorganization

Because of the removal of main roads in city centre, the transportation network in city scale will also be changed.

The main reorganization is that the parking lot beside the train station is linkd to the alternative road, Leopold III--laan, south to Vindictivelaan. And the main road N34 will be directly linked to the underground parking lot on the dike.

The main idea is to keep the heavy traffic outside the city centre and at the same time improve public transportation. From the two main parking lots, the whole city centre area can be reached in 15-20 mins by walking. The public bus stop is also set based on 10mins walking within city centre.

Current situation

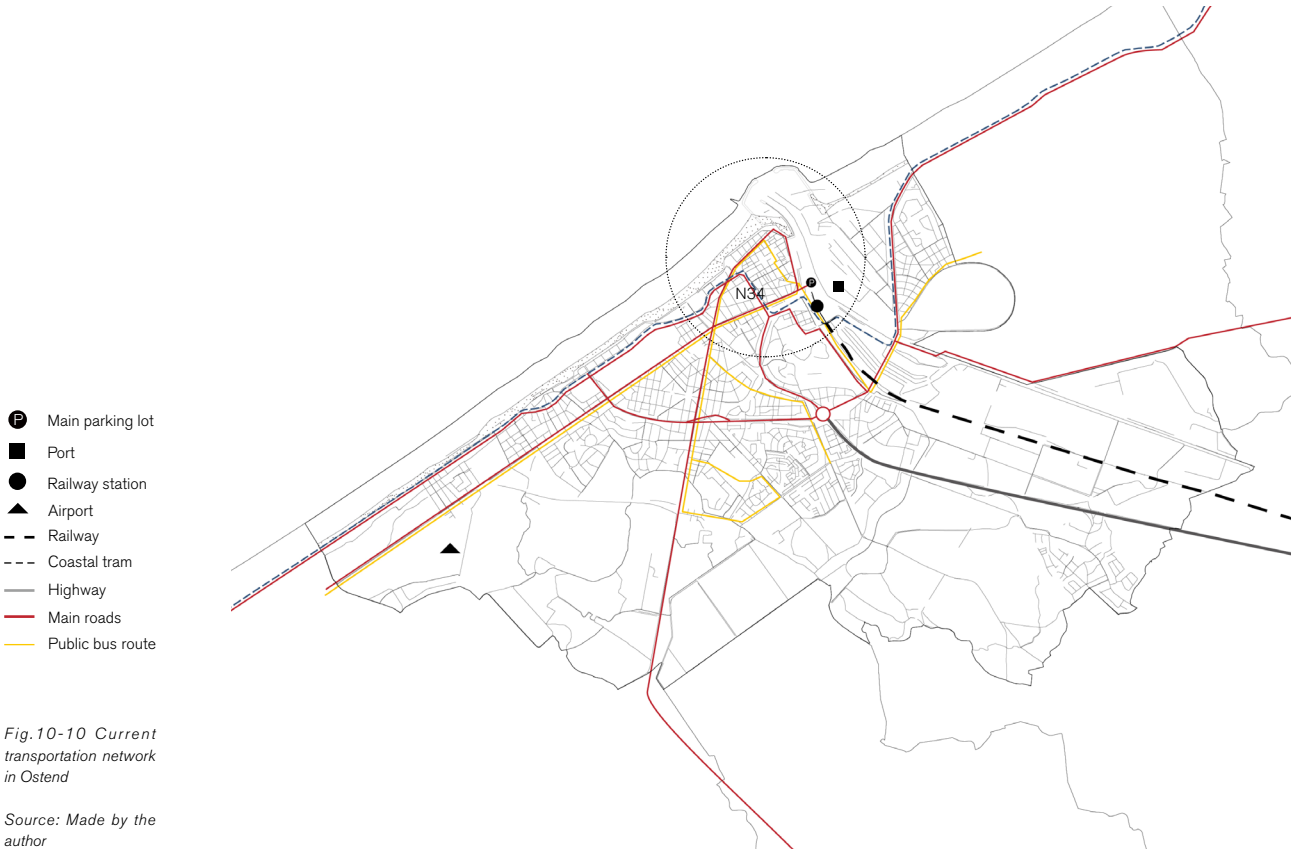


Fig.10-10 Current transportation network in Ostend

Source: Made by the author

Proposed

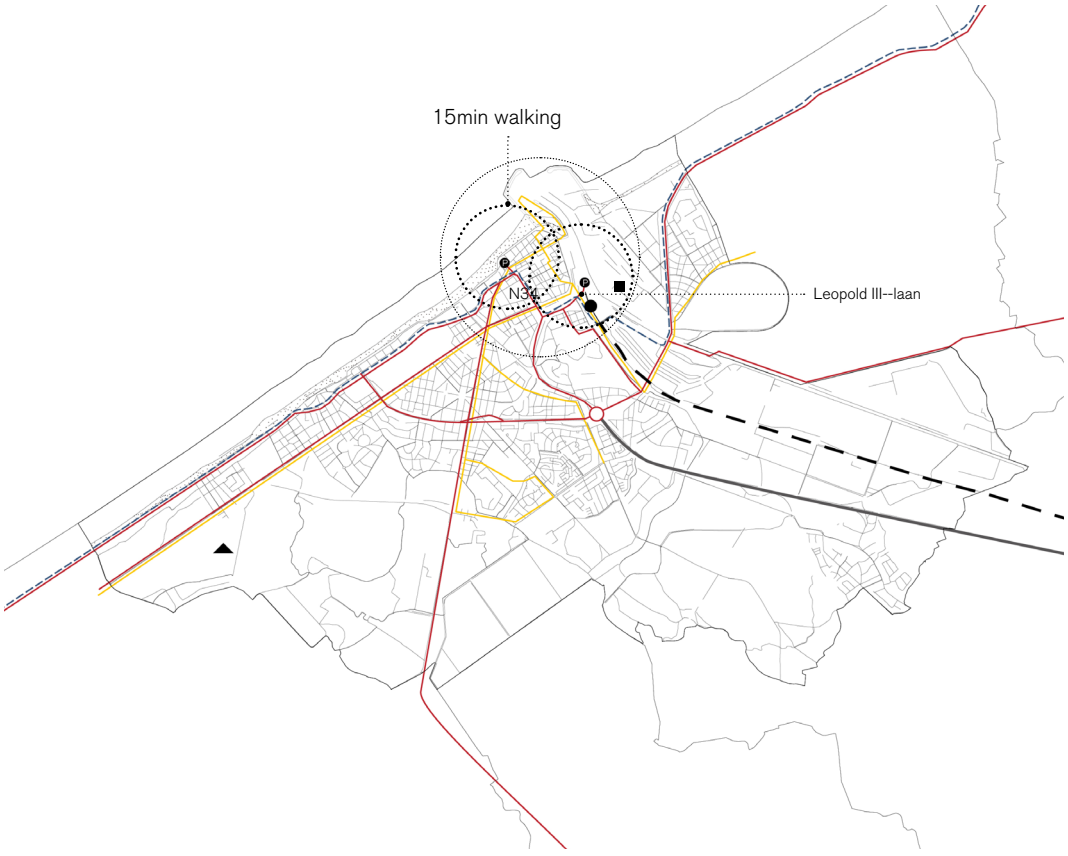


Fig.10-11 Proposed transportation network in Ostend

Source: Made by the author

10.7 Transition of People's Feeling



Fig.10-12 Hearing the sea

Source: Made by the author

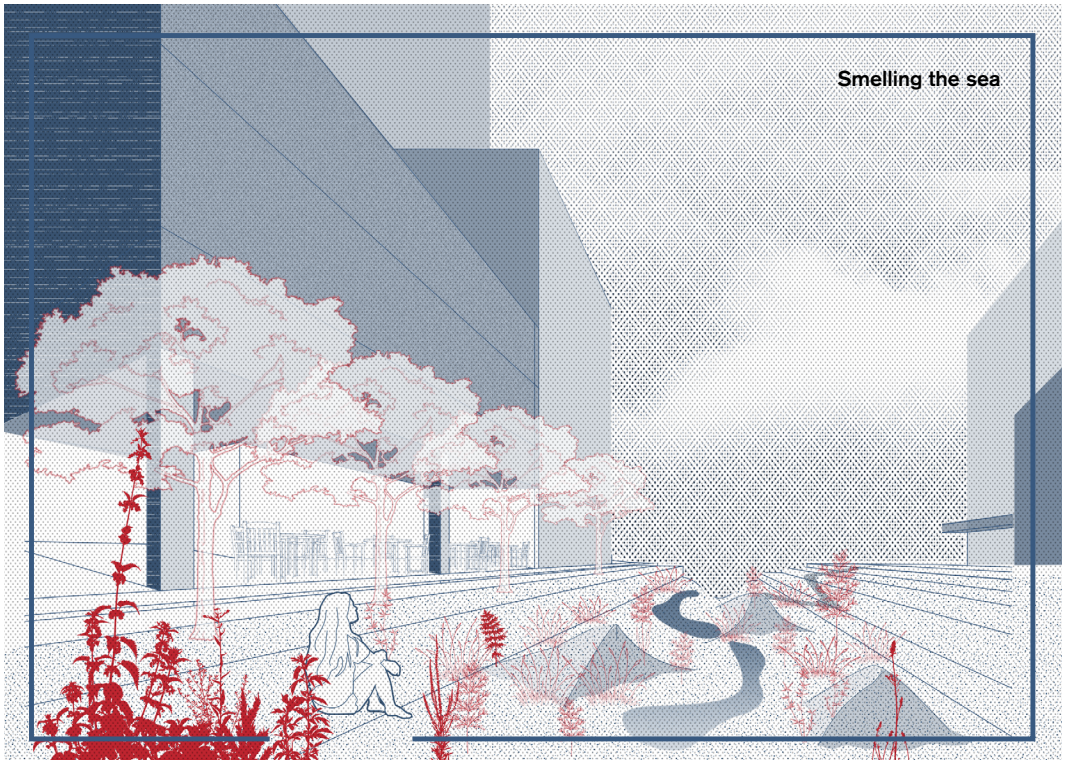


Fig.10-13 Smelling the sea

Source: Made by the author



Fig.10-14 Gazing at the sea

Source: Made by the author



Fig.10-15 Touching the sea

Source: Made by the author

10.8 Transition of Coastal Economy

Through different periods of interventions, some transition in coastal economy of Ostend can also be expected. As it mentioned before, tourism and service, port industry and fishery are the currently main economic sectors.

From traditional fishery to aquaculture

Currently, Belgian aquaculture is mainly focused on freshwater cultivation, but the oyster reef intervention with marine habitats give a great opportunity for sea aquaculture industry.

Thinking of the decline of the fishery industry in Ostend, it can actually be a new direction in this economic sector and it is obvious that stimulating local aquaculture can reduce import costs and reinforce growth in the local food processing industry.

Competitive and healthy tourism

On the one hand, the coastal landscape could become more diverse, which makes the city more distinctive and more competitive to the other coastal cities, benefiting the tourism industry.

On the other hand, the project propose new block types and living pattern between holiday people and local residents, which could contribute to the much healthier tourism.

Port industry transformation

Because the design focusing area of the project is in city centre, so there may be less influences for the port industry area as the physical environment aspects. However, some indirect and side influence might happen.

For example, due to the reduction of beach nourishment, the dredging intensity might be less and current coastal defence sector might also be influenced. This might offers some opportunities to the industrial area to transform the economy and industry, such as turning to renewable energy, which is already an ongoing process in city of Ostend.

On the other hand, the periods setting in the project also offers the guidance of the risks levels in the industrial area. For example, in 'Risky Period', the area has large chance to be submerged, so it will lose its normal functions by then. Thus, some alternatives should be considered.

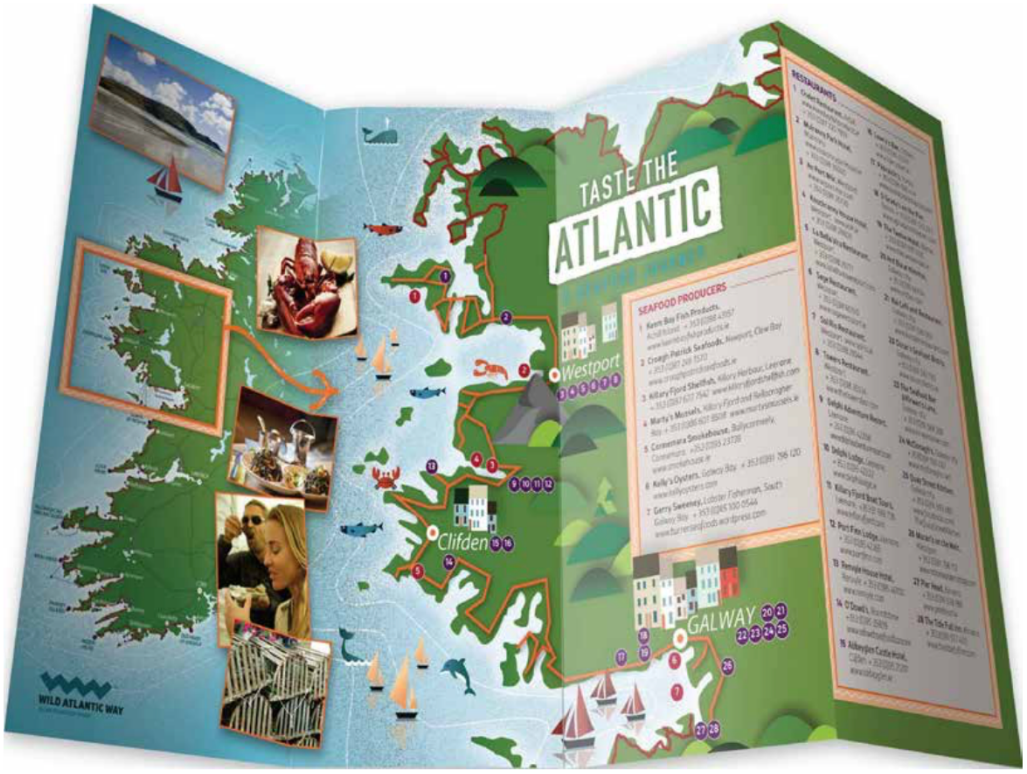


Fig.10-16 Taste the Atlantic

Source: Richard Donnelly, Wild Atlantic way

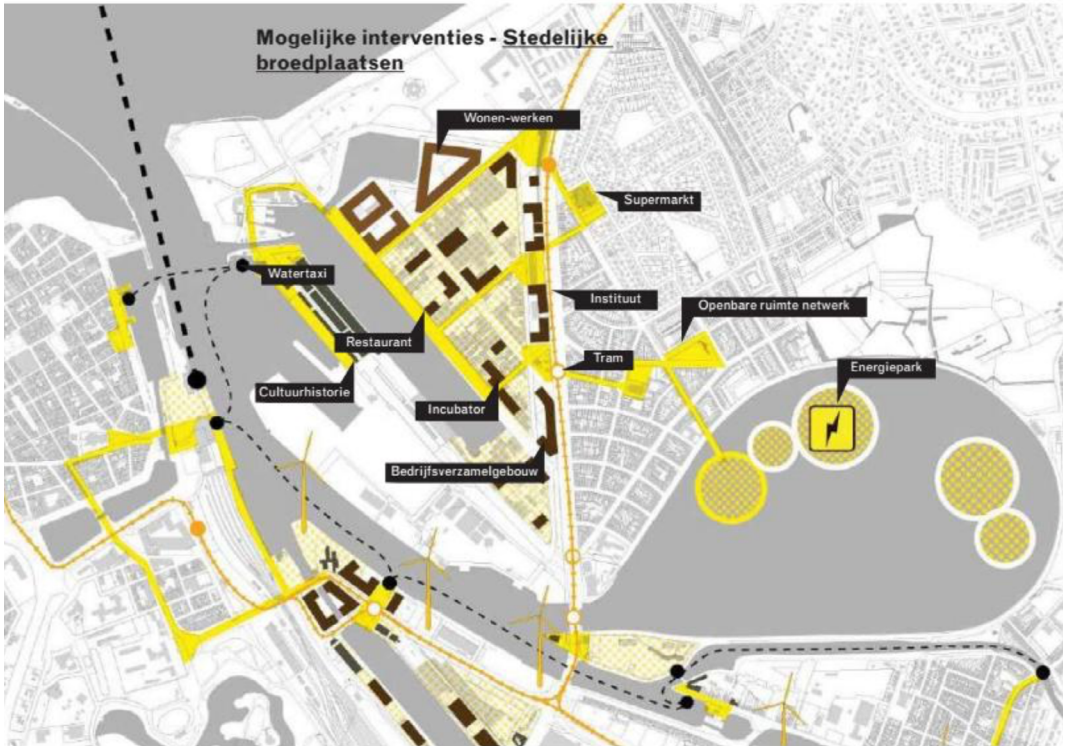


Fig.10-17 Energy transition project in Ostend

Source: FABRICations, 2018

10.9 City Scale Adaptation

The strategies applied in the design area can actually be upscaled and applied to the city scale. The idea is the whole city can also consider the interventions on three parts that deals with different aspects of risks reduction, namely probability and impacts, at the same time figuring out larger benefits.

On the sea side, the oyster reef restoration can be applied to the areas faces risks of erosion, the expanded sea bed intervention can be linked to the existing sea bed with high ecological values, creating a more robust marine ecosystem.

On the coast, the dike transformation and dune restoration can be applied based on the city scale green network. And the areas with natural accumulation process have the potentiality of new land creation.

On the urban side, the multilayer buffering system is also possible to happen in other areas. Here suggested main buffer lines are pointed out. Besides, based on the created public network, some main public sites in suitable area can be the evacuation sites during the extreme storm surge events.



Fig.10-18 City scale adaptation - Sea

Source: Made by the author

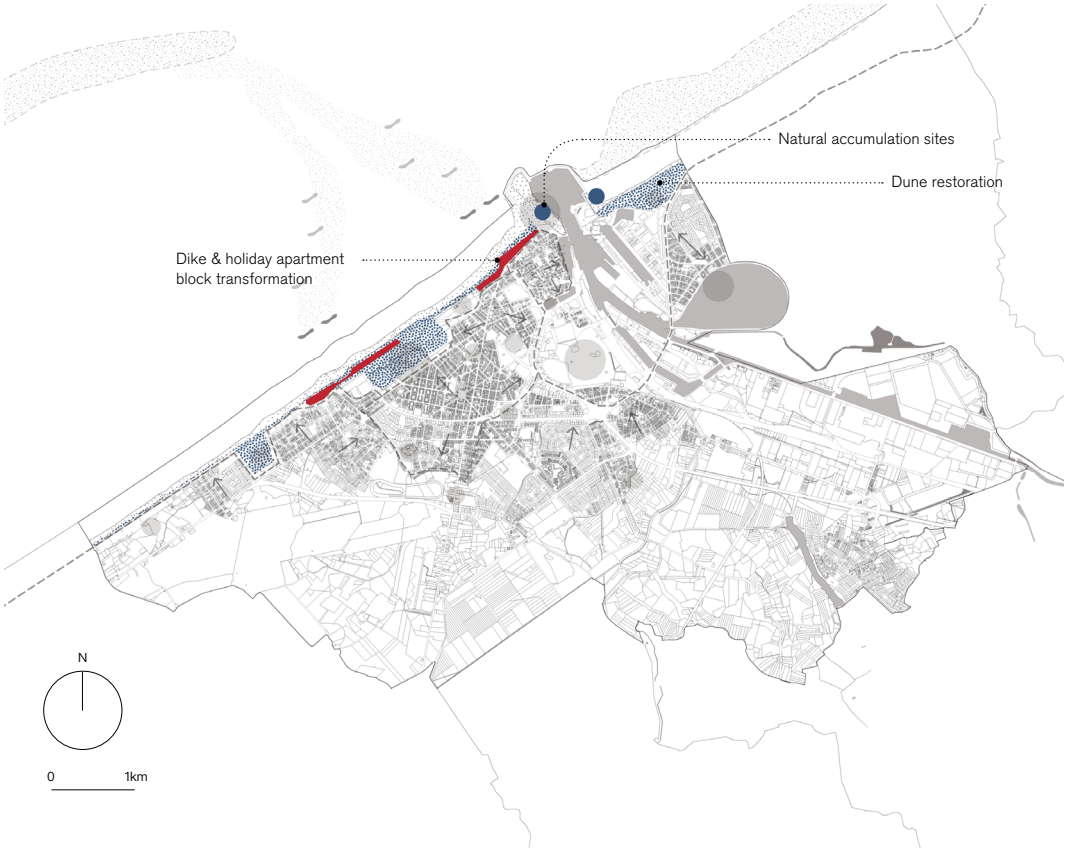


Fig.10-19 City scale adaptation - Coast

Source: Made by the author



Fig.10-20 City scale adaptation - Urban

Source: Made by the author



Fig.11-1 Ostend beach

Source: Photo by the author

11 Conclusion

11.1 The Design Objectives
11.2 The Embodiment of Nature-based Solutions
11.3 Back to the Research Questions
11.4 The Methodology of Research and Design
11.5 Recommendations for Future Research

11.1 The Design Objectives

Safety

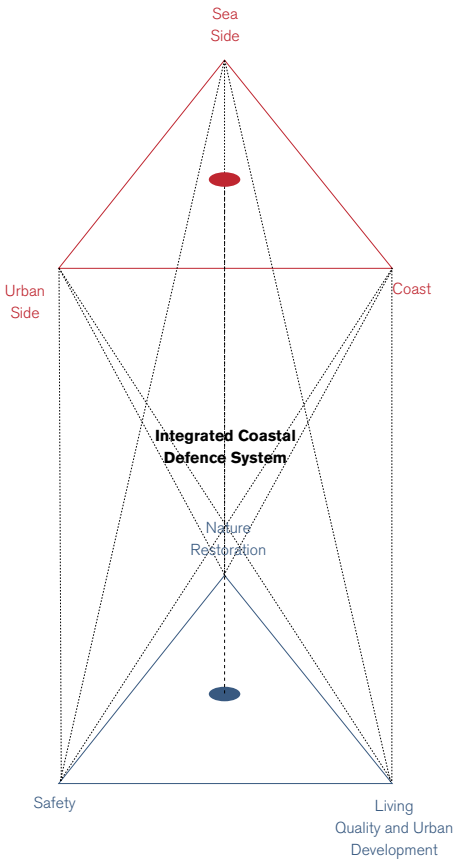
The project creates a new defence system, mitigating the risks of storm surge by dealing with both propability and impacts, increasing the safety level in the design area and also being reflected in the city scale.

Nature Restoration

On the one hand, the project provides different types of habitats for marine creature together with the oyster reef, which is significant in the past but degraded due to coastal engineering. On the other hand, the project also create more room for nature in the coast and urban side. The defence system itself contains more ecological values.

Living Quality and Urban Develoment

The project reorganizes the public network in the city centre, as well as challenges the living patterns. By creating the new defence system, the risky areas becomes strong public network that brings new quality to people's daily life. The project also influences the coastal economy and provide the potential space for future development.



11.2 The Embodiment of Nature-based Solutions

Nature force involvement

As mentioned in the theoretical chapter, one of main principles in NBS is involving the nature process and not block nature dynamic. From this perspective, the project reflects this in two aspects.

Firstly, the accumulation and erosion process caused by the offshore wind and wave are taken into consideration and made use of when implementing the oyster reef and new land reclamation.

The second aspect is the nature process that aroused by offshore and coastal intervention. For example, the oyster reef intervention would influence the beach change natrually, avoiding nourishing the artificial sandy beach all along the coast and also reducing the seasonal maintenance.

Coastal ecosystem and Environment benefits

Beneficial to ecosystem and environment is another principles of NBS. In this project, the main contribution to the coastal ecosystem and environment is the increasing of biodiversity.

First of all, the oyster reef with different substrate units provide habitats for the marine creatures. Secondly, the dune restoration in the coast area and green & blue network creation in the urban side enable to provide more space for coastal creatures that also lives inland, expanding the whole coastal ecosystem, providing larger eco-services and environmental benefits.

Time periods consideration

The consideration of time cycle is also included in this project. First of all, the whole intervention process has been divided into four periods based on the climate change effects. Secondly, the time for coastal ecosystem creation is considered, becasue of this, some engineering solutions are still needed in the early stages for the necessary protection to the cities. Besides, the sequence of different interventions is also considered in different time periods.

Integrated approaches and multiple effects

The coastal cities have prominent economic and social values, requiring the adapting NBS consider nature benefits as well as the urban and public benefits. Because of this, the project not only emphasizes the multi-functionality of each intervention itselft, but also explores larger benefits and effects by combining different interventions together.

11.3 Back to the Research Questions

Sub research questions

SQ1 Background and Theoretical base

Q1

· What are the definitions of resiliency and adaptability for the coastal defence systems?

The resiliency and adaptability of coastal defence system means whether the system can deal with the risks (in this case, storm surge) below a certain level (in this case, +7 TAW), and if the overtopping events happen, if the city functions can return to normal in a short period of time.

Q2

· What is the meaning of nature-based coastal defence solutions and why can it bring resiliency and adaptability?

The nature-based coastal defence solutions mean in the defence system, the natural process is taken into consideration and besides the safety, it can provide more integrated functions and benefits. (For more detailed research, please refer to the theory paper)

Q3

· What are the limitation and potentialities of applying natrure-based solutions in extreme dense urban areas?

The limitation include the space and time, and the potentialities include urban green & blue infrastructure, urban subsurface space and some near shore eco-engineer interventions. (For more detailed research, please refer to the theory paper)

SQ2 Research and design in BCP and Ostend context

Q4

· What are the dynamics of the sea and the urban systems in BCP and city of Ostend, and what challenges will be brought about by these dynamics?

The dynamics of the sea include the risks of strom surge and coastal erosion, but it also contains the high value of ecosystem. The dynamics of the urban include the urbanization process and coastal economy. In this case the main challenges are the surface caused by urban development, together with the centralized drainage system, poses a double threat to the coastal areas. At the same time, the development of coastal economy has caused unhealthy living patterns in the city centre.

Q5

· What is the specific situation of the current coastal defence system in city of Ostend and what is the people's behaviors and awareness towards the risks?

The current coasatl defence system in Ostend mainly focuses on the coastline itself. By maintaining the see wall and beach nourishment, the main idea of the current system is to strengthen the defence line to avoid the overtopping events. This system is currently rather

monofunctional and has bad influences on the environment, it is effective in short term, but from long-term perspective, it is not sustainable.

Q6

· What are the local impacts caused by the main challenges in city of Ostend?

The local impacts in the project are revealed by the storm surge senarios simulation, showing how many areas will be flooded, the maxium water depth and the duration of the storm events.

Q7

· How to use nature-based solutions to transform the coastal defence system in Ostend and let it be a medium of integrating the dynamics of nature and urban systems?

The main idea is dealing with the flooding risks both on probability and impacts, expanding and enlarging the scope of defence system, considering time period and providing more space for implementation. In this way, the urban and the sea can also be parts of coastal defence system by land transformation and new land creation, influencing the public networking, living patterns, nature and coastal economy.

SQ3 Further impacts and reflection

Q8

· What kind of values and broader influences can the new coastal defence system bring to the BCP and the North Sea areas?

As it has been discussed before, the new system not only provides safety, but also have different benefits in the aspects of nature, people's living and urban development. Besides, the methods and ideas of applying NBS in high-density urban areas in this project can be referenced in high-density coastal cities in BCP, the North Sea region and even other areas with similar backgrounds.

Main research question

How can we create a more adaptive and nature-based coastal defence system in extreme urban areas integrated with the dynamics of the sea and urban systems, benefiting nature restoration, urban development and living environment?

As it mentioned above, the project show different aspects of NBS. Except for that, as we know the NBS is already not a new concept, but when refering to the high-density urban area, the application of NBS is hard and uncertain, so project also tries to find out the possibility of applying or adapting NBS in these highly urbanized areas, which is also the main research question that put forward in the beginning.

Through the research and design testing process, some possibilities can actually be found.

Enlarging the scope

First of all, becasue applying NBS need large quantities of open space, which is lacking in the urbanized area, so it is necessary to look further into the urban space and space in the sea instead of only focusing on the coast. By doing this, two possibilities can be found to deal with the space limitation.

1. land transformation
On the urban side, there are still some space that can be transformed to be more nature, contributing the whole ecosystem creation, such as the current parking space and the infrastructure. In this case, some scattered space in the urban can be made use of and linked together to integrate into the whole coastal ecosystem.

2. new land creation
On the sea side and coast area, the new land creation is possible due to the nature process, which provides more land for nature restoration together with urban development directly.

Probability and impacts consideration

By enlarging the defence scope, we will find more possibilities of defence system transformation. Because the urban itself also becomes a part of the defence system, the strategies that dealing with 'impacts' of risks can be created. Thus the burden of reducing the 'probability' on the coastline , which is the main reason for the increasingly engineering-based coastline and the main obstacle to implement the NBS, can be partly relieved.

Necessary 'grey' approaches but more integrated

However, we have to admit that it may not possible to only rely on the nature approached in the highly-urban areas, some engineering measures are still needed due to the socio-economic urgency, such as the harbor area in the design site, the nature solutions is very difficult due to the shipping functions. From this perspective, the adapting NBS in these areas are still more 'Hybrid solutions'. The key thing is the necessary 'grey' approaches can be more integrated and bring more values to the nature and public.

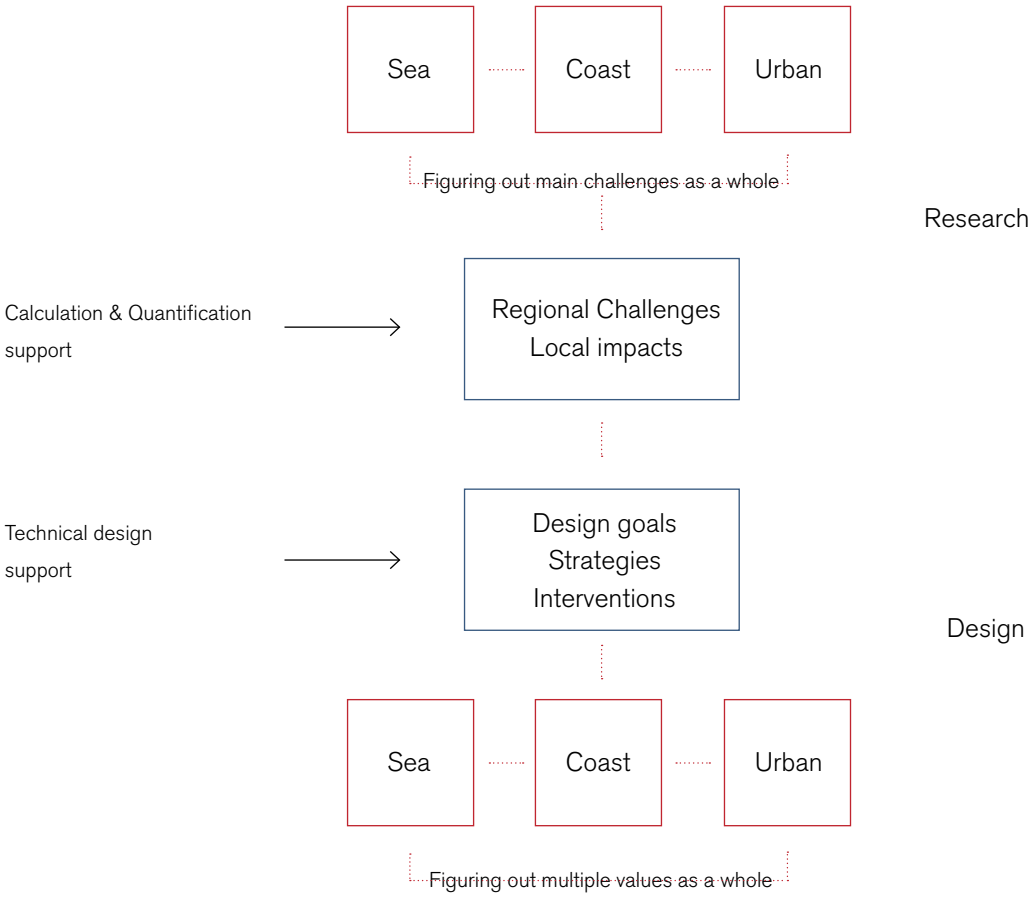
For example, as the project shows, the artificial oyster reef can be integrated with different marine habitats, the existing dike can be integrated with dune restoration, the infrastructure in the city can be integrated with urban green & blue network as well as inproving the public life, and the balance of nature and construction in the new land creation will be considered in the eary stage of planning.

11.4 The methodology of research and design

In the research part, firstly the three objectives (sea, coast and urban) are separately studied in order to find out their own characteristics. And then these three parts are combined as a whole system to summarize the relation among them and the main challenges it causes. In order to understand the challenges and local impact more clearly, the quantitative method of overtopping calculation have been applied at this stage.

The defined challenges and local impacts give a strong base for the design goals, strategy and nature-based interventions. Same as the research, after the overall strategy has been made, the interventions are also divided into three objectives (sea, coast and urban). And finally, these three parts are put together again to optimize the interventions as a whole system and explore the broader effects that the system can bring. In this stage, some technical principles are used for the design feasibility.

The most important feature of this methodology is discovering the challenges and exploring design possibilities from both perspectives of individual objective and the whole, at the same time using a variety of technical methods to quantify the problem, to guide the design process and to evaluate the design outcomes.



11.5 Recommendations for Future Research

For the purposes of this project itself, first of all, the current conclusion is mainly based on the intervention areas, which is the mixed city centre. Even though the upscaling reflection on city scale and regional scale is provided, the design strategy need to be further tested in different context, such as the harbor area that is full of industy activities and the west-east part of Ostend that is currently monofunctional residential area. By testing the strategy in different context, the conclusion can be improved and more complete. Secondly, the current evaluation in the project is more related to the risks reduction and public values, lacking of the specific evaluation of the new coastal ecosystem, such as the relationship between different species in this ecosystems, and the environmental carrying capacity, etc.

For the field of NBS application in high-density urban area, more research directions can be explored in the future such as the following questions,

In the situation of hybrid solutions, how to judge the overall gains and losses of the environment? Is there more positive impacts brought by 'green' approches or more negative effects caused by 'gray' approaches?

Are the effects that caused by 'green' approaches all positive to the environment and the city?

Even more radical, this project is only based on the assumption that coastal urbanization will continue, but perhaps we can question the phenomenon of coastal urbanization itself. Can it be changed and how? Is it more efficient and beneficial to change the urbanization trends in the coatsal cities than applying nature-based defence solutions in these dense areas?



Fig.R-1 Armour stone on breakwater of Ostend

Source: Photo by the author

Reflection

Aspect 1 The relationship between research and design

Climate change as an undeniable fact has and will continue to affect our lives. As the most sensitive region regarding to climate change, the risks faced by high-density coastal cities will be increasing with time. As one of the most dense coastal areas in the world and also the site of the project, city of Ostend and even the whole Belgian coastal areas have always regarded the coastal defence system as an important aspect in regional planning and urban design to address the negative impacts of climate change (mainly sea level rise, storm surges and precipitation changes). This results in the hard defence line runs through the entire coastal area and the main idea behind it is regarding the sea as our enemy and separating the city from the sea as much as possible by blocking and isolating. Even though some theories of more nature-based solutions are already discussed in recent years, they are hard to be applied in dense urban area for the limitation of the space and time. This phenomenon makes me rethink the relationship between land and sea, I wonder if there is a way to adapt nature-based solutions in highly urbanized areas by changing the relation between sea and urban and the goals of defence system. This is the start point of the research in this project.

In the research part, I divided the objective into three, the sea, the coast and the urban. By studying their respective dynamics (for example, the currents movements, wave movements, sediments transportation on the sea side, and the urbanization process, infrastructure and the permeability on the urbanside), I found the dynamics of the sea and land have undergone changes from close connection to gradual separation. The coast zone used to be an important link between sea and land, and also played a buffer for the marine risks. However, due to the process of urbanization and engineering-based defence solutions, this relation was disrupted, and the zone gradually became a line. The line has all the responsibilities of resisting the risks, so as the climate changes, the line have to become more and more solid, letting the sea and land become more and more fragmented, forming a vicious circle.

Thus, the conclusion that drawn from the research consists of 2 aspects. Firstly, the coastal defence system should include all three parts (sea, coast and urban) instead of a single line, which means It is necessary to recreate a buffer zone like once. Because of the limited space, the possibilities to use the urban itself as a part of the buffer can be explored. Secondly, the dynamics of sea side shows possibilities that some nature force can actually be considered in the transformation process of the current defence system.

The conclusions came from the research indicate a clear direction for the design, which also includes three parts of interventions, the sea, the coast and the urban. Generally, the risks can be defined as the combination of probability and impacts. In the current defence system, the main goal is reducing the probability by strengthen the coast line. However, in my design part, the more nature-based (make use of the nature forces and give more room to nature) solutions are applied on the sea side and coast line for 'probability' reduction. At the same time, the interventions of urban infrastructures and new building typologies are proposed to reduce the 'impact'. The three parts can work together to increase the total capacity for coping with the future risks as well as rebuild the dynamic relations among them.

From this perspective, I think the relation between research and design in this project is quite clear. The design comes from the conclusion of research and can also provide evaluation and verification for it.

Aspect 2 The relationship between the project, the topic of research group and Urbanism track

The topic of the Transitional Territories Studio this year is 'North Sea Landscapes of Coexistence: Altered Natures and the Architecture of Extremes', focusing on the interrelation between the land and the sea, investigating the possibility of new spatio-temporal formations and occupation between them, studying the dynamics of both nature and human society, discussing the risks that are caused by it and exploring the interventions through research and design.

In this sense, my project, which aims to rebuild the dynamic relation among the sea, the coast and the urban by transforming the coastal defence system, has a strong connection with the topic of the whole studio.

The almost 2-year studying in the urbanism track has deepened my understanding of the complexity of the city and broadened my vision of the interrelation among different urban elements, especially the dutch experence and originality on water management and coastal intervention. This valuable study experence has inspired me to explore the complexity of coastal area and the uncertainty due to the climate change in my project. Methodologically, the urbanism track also provides me the approches to do research and design, such as layer approach, research by design, design by research, integration of different scale and stake holders analysis.

On the other hand, my project also offers some new perspective of 'nature-based solutions' for the Delta Urbanism research group in this track. Even though this idea is nothing new and has been applied to many projects in the Netherlands, they are mostly located at large open spaces, rather than high-density construction sites. Thus, in my project, the issue of adapting 'nature-based solutions' in the dense urban context has been discussed and some possible potentialities has been proposed, which can be a supplement to the current research.

Aspect 3 Methods assessment, Scientific relevance and the transferability

The scientific relevance of the project mainly lies in the methods that are invloved both in the research process and the design part.

In the research part, methods such as GIS mapping and analysis, transects and maritime dynamics analysis are used especially to understand the movements of currents and waves, the sediments transportation and the maritime ecosystem. Therefore, On this basis, the changing laws of the coastline can be grasped, and the future projections and possible interventions can also be predicted and explored. Moreover, methods including 3*3*3 analysis, permeability evaluation and infrastructure and building typologies study also have helped me have a better understanding about the urbanization process and how that influences the relation between urban and sea. What's more, the study on the local impats of the risks and the quantification also provide me a lot of evidence and scientific base for design.

For the design part, the scientific relevance is mainly reflected in the technical design of each small-scale project, such as oyster reef restoration and urban underground interventions. These methods mainly provide the feasibility of different interventions.

The transferability The project expands the connotation of the 'nature-based solutions' and provides a possibility for the application of nature-based coastal defence solutions in high-density urban areas. Because of the socio-economic characteristics, in the case of climate change, the most threatened areas are always the high-density coastal cities. However, not all of these regions have sufficient peripheral natural space to provide the nature-based protections. So from this perspective, This project has certain reference significance for these areas.

Aspect 4 Societal and Ethical relevance

First of all, the project also tries to arouse the public awearness of the future costal risks by invoving people into the planning designing process. For example, the application of water-proof materials to the housing located high flooding risks areas largely requires people's participation. And the smart shelters can also have some educational public program in the normal time.

Moreover, the design testing area is one of the most vulnerable and unstable communities in city of Ostend, which means most of the high-rise apartment are occupied by people from other cities for holiday use, and most of the local people are living in the low-rise house that face larger risks. Moreover, the most risky seasons (winter and spring) are always inconsistent with the holiday season (summer), which means during the most risky time, the relatively higher buildings are always empty. In this sense, this current social structure actually also exacerbates the risks caused by climate change.

The proposal of the project is not only aiming to deal with the climate risks, but also has

challenged the social structure and living style in the testing areas. By introduing the transformed urban blocks, the relation between holiday people and local people has been rebuilt at the same time larger public values has been created.

Besides, the new land for urban future development, oyster reef restoration and the updated tourism industrial also brings jobs to the local people and attracts younger incomers. By this way, the unstable social structures in the testing area can be improved. And the idea of 'co-living urban blocks' can also be regarded as a prototype that can be introduced to other areas facing the similar challenges.

In this sense, the project has a strong societal and ethical relevance.

Aspect 5 Summary and limitation

The project tries to find a way to apply more nature-based coastal defence solutions in more dense urban areas, and after doing the research and design testing, some possibilities have been found and the most essential part is rebuilding the relation between urban and sea, regarding the whole urban area as a large 'buffer zone' to relief the stress of the current defence line.

This new thinking of coastal defence system can reduce the future risks at the same time bring larger public values to urban and larger ecological values to the nature. Moreover, comparing to the conventional defence system, the proposal also has more flexibility to cope with the future uncertainties by introducing the multi-layer of protection.

However, we have to admit that it is very difficult to totally apply nature-based solutions in the dense urban areas due to the limited space and high urgency for protection. Thus, just like some interventions in this project (artificial breakwater, movable storm walls, etc), some engineering solutions are still inevitable. However, even though we have to put engineering measures, they can also be designed more integrated with other functions and bring more values to the nature and urban public.

Therefore, the 'adapted nature-based solutions' in dense urban areas are actually more like 'hybrid solutions'.



Fig.A-1 Holiday apartments on the dike

Source: Photo by the author

Appendix

Appendix 1: Theory Paper

From resistance to coexistence: The transition to nature-based coastal defence solutions and their adaptation in extreme dense urban areas

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December 5th 2018

Abstract

The coastal areas always play a crucial role in the economic, social and political development of most countries; they support diverse and productive coastal ecosystems that provide valuable goods and services (Airoldi et al., 2005). On the other hand, climate change as an existing and accelerating fact, carrying out a series of ripple effects such as sea level rise and extreme weather. Because of the particularity of geographical location, such climate changes effects have the most direct and strong impacts on the coastal zone, which includes but not limited to coastal erosion, flooding, salinization and landward retreat. In many coastal areas, the conventional coastal engineering solutions such as sea walls are increasingly challenged by these changes and their maintenance may become unsustainable (Temmerman et al., 2013). To cope with this challenge, the transition to more nature-based coastal defence solutions has already taken place by integrating the ideas of Building with Nature, Ecosystem-based Coastal Defence and Integrated Coastal Zone Management. However, these interventions mainly rely on the dynamics of large-scale natural and ecological systems, which requires relatively large and open space for implementation. When they are applied to extreme urban areas, there are always certain knowledge gaps and limitations.

This paper firstly introduce the existing coastal defence approaches and two concepts of solutions based on these approaches. Then, it addresses the current challenges faced by conventional coastal engineering due to the climate change effects. Further, on the basis of theoretical research, the current transition to nature-based defence solutions are put forward as well as their limitations. Following that, the paper discusses the particularities of coastal extreme urban areas and the key elements to be taken into consideration when applying these solutions. As a conclusion, the theoretical framework and principles of adaptation of nature-based coastal defence solutions in extreme dense urban areas are proposed for new direction for the future research.

Key words

Coastal defence, coastal urbanization, nature-based solutions, ecosystem services

1 Introduction

The coastal zone is a zone of transition between the purely terrestrial and purely marine components on Earth's surface (Crossland et al., 2005). Coastal zone has historically been a natural place for human settlements as they typically offer ready access to water and fertile soil (UNU-IHDP, 2015). Nowadays, the coastal zone is still the region with the densest population and economic activity in the world and the trend is expected to continue in the future.

The coastal zone:

- comprises <20% of the Earth's surface
- contains >45% of the human population
- is the location of 75% of cities (megacities) with >10 million inhabitants
- yields 90% of the global fisheries
- produces about 25% of global biological productivity
- is the major sink for sediments
- is a major site of nutrient-sediment biogeochemical processes
- is a heterogeneous domain, dynamic in space and time
- has high gradients, high variability, high diversity

Figure 1: The global characteristics of coastal zone.
Source: (Crossland et al., 2005)

This global trend has caused increasing anthropogenic activities in coastal areas, with both direct (e.g. coastal engineering) and indirect effects (e.g. land cover change) on coastal ecosystems (Small & Nicholls, 2003).

As a conventional solution of coastal defence, the coastal engineering has been playing an essential role in coastal defencing to deal with the hydrodynamic impacts (flooding, erosion, storm surges, salinization, etc.). Its rapid and effective implementation has made this solution widely accepted by the public for a long time. However, such solution is always lacking of long-term sustainability and regular maintenance is needed at high cost. Besides, the health of many coastal ecosystems has also been influenced due to this artificial intervention.

Facing the continuing climate change and accelerating sea-level rise, people have been rethinking the coastal defence solutions and figuring out that integrating nature cycle into coastal defence schemes may offer innovative and cost effective solutions (Bouma et al., 2014). This idea means regarding the coastal area as an ecosystem and using the natural regulating function to protect the coastal area. Thus, in order to create a self-adaptive ecosystem, the key factors to be considered in these solutions are the nature carrying capacity, time cycle and scale.

Although nowadays nature-based coastal defence solutions have been successfully implemented in some projects (e.g. Hondsbossche sea defence, Dutch sand engine, etc.), most of these projects are located in relatively open and natural spaces, but there are still certain limitations for adaptation in extreme urban areas.

This paper firstly introduces the transition from conventional coastal defence to nature-based coastal defence and searches for its limitations. Then, to support the further research, the paper focuses on how the nature-based solutions can be implemented and adapted in extreme dense urban areas.

2 'Grey' Defences and 'Green' Defences

Before talking about solutions, it is important to review the current coastal defence approaches as a background. Normally, there are two kinds of approaches to deal with the coastal morphological issues, namely 'grey' defences and 'green' defences.

'Grey' coastal defences, also called 'hard' defences, are structural measures like series of groynes, series of offshore and submerged breakwaters, revetments and seawalls (Bosboom & Stive, 2012). Basically, they protect the coastal areas by avoiding the sediments to be eroded or be transported in alongshore and cross-shore directions of the coastline.

With less severe impacts on the environment, 'green' coastal defences are 'soft techniques' that are more nature-based, thus also more sustainable and flexible in terms of human interventions. Typical green coastal defences include beach nourishment, beach stabilisation, managed retreat, dune regeneration, marshland creation, revegetation and coral reef enhancement. These measures imply that 'natural' processes and movements are allowed to continue (Bosboom & Stive, 2012).

The choice for a 'grey' or a 'green' defence depends on both the characteristic of the problems concerned and on economic considerations. Actually, both of them have negative impacts on the ecosystem in the beginning (Bosboom & Stive, 2012). For example, beach nourishment in coastal zones that have a rich nearshore ecological value (e.g. seagrass meadows) is also disrupt the existing biological communities and habitats in subaerial zones of beaches and in the borrow sites where dredging occurs (Board, 1995). And it is also unsustainable to create sandy beaches in areas where the sand and sediments are inadequate. So even though the 'green' defence looks like more environmental friendly, the use of 'grey' measures for coastal protection can still not be totally disregarded.

Based on these two different kinds of approaches, the 'conventional coastal engineering' and 'nature-based solutions' are the two major solutions that tackle the climate change effects. Both of these two solutions

are the combinations of different approaches. The main difference is whether it is dominated by structural construction or by natural processes.

3 Challenges to the conventional coastal engineering

Nowadays, conventional coastal engineering are still the most widely used coastal defences. The Belgian coastal plain (BCP) is a very proper example about this. With nearly 90% of conventional coastal engineering (mainly sea walls and breakwaters), the Belgian coastline has become extreme hard, firm and engineering-based.

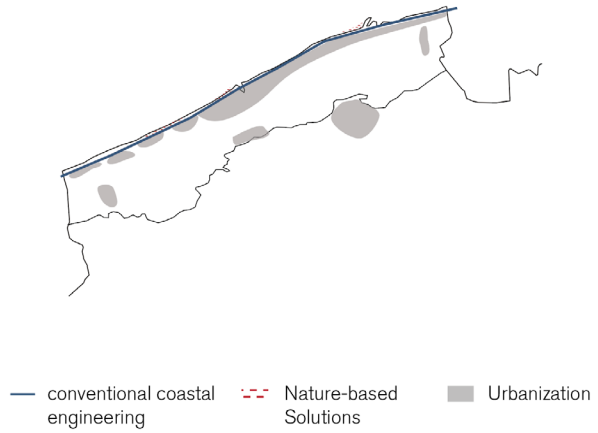

Figure 2: The hardness of Belgian coastal plain.
Source: Made by the author

Another example is the Netherlands. Even though the Dutch people are already advanced in the fields of water management, there are still largely relying on the conventional solutions and already facing the insufficiency. The upgrading of the flood defence system in the Netherlands that are required to deal with increasing flooding risks, are estimated to cost up to €1.6 billion per year by 2050, whereas the possible damage from insufficient defence facilities may amount to €3,700 billion (Kabat et al., 2009).

On the other hand, the conventional coastal engineering has culminated in projects such as the Dutch Delta Works or the Thames barriers in London, where the whole estuaries were cut off from the sea by permanent dams, dikes or movable storm surge walls (Temmerman et al., 2013). With the accelerating climate change, this traditional and unsustainable solution are facing enormous new challenges.

Moreover, the conventional engineering has been frequently occurring adverse side effects on ecosystems, including the loss of tidal habitats and the appearance of toxic algal blooms that kill aquatic creatures in the enclosed or semi-enclosed estuaries (Temmerman et al., 2013).

To sum up, the challenges faced by conventional coastal engineering mainly include the following aspects.

1. Lack of flexibility and adaptability to the uncertain future.
2. Need of ever-rising maintenance costs that causes large economic pressure.
3. Adverse impacts on environmental and ecological system.

4 Towards nature-based coastal defence solutions

The challenges to the conventional coastal engineering have called for the alternative solutions. In this background, nature-based coastal defence solutions (NBS) have got people's attention in the late 2000s. According to The International Union for the Conservation of Nature (IUCN), the official definition of NBS is 'actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits' (IUCN, 2016).



Figure 3: NBS as an umbrella term for ecosystem-related approaches.
Source: (IUCN, 2016)

The definition is rather abstract and doesn't mention much about the operations and the development of built environment. When comes to the practices, NBS actually acts more like an umbrella above different components. To make it much clear, four aspects under the concept of NBS will be discussed here, the overall principle, spatial intervention, key factors and the governance.

4.1 Principle - Building with Nature (BwN)

First of all, it is necessary to figure out the meaning of 'Nature-based'. In order to explain this, the idea of Building with Nature (BwN) can be seen as a basis. Generally, BwN is a conceptual principle that uses the natural dynamics to create more flexible and sustainable infrastructure while enhancing nature values and other ecosystem services (IADC, 2017).

In 1979, the Dutch engineer Honzo Svašek firstly developed this concept. This was further expanded by Ronald E. Waterman. In 2008, he published these ideas in his book 'Integrated Coastal Policy via Building with Nature' (IADC, 2017).

Specifically, there are two main points of BwN. Firstly, the natural forces (e.g. the hydraulic forces, geological forces and atmospheric forces) can be used as part of the intervention. Secondly, extra opportunities for the development of nature and ecosystem services could be provided (IADC, 2017).

These two points are main reasons that make BwN different from traditional principles and help us understand the meaning of 'Nature-based'.

4.2 Spatial implementation - Ecosystem-based Coastal Defence (ECD)

The rest part – the 'Coastal Defence Solutions' is talking about the application of the BwN principle in the coastal defence fields. Thus, the idea of Ecosystem-based Coastal Defence (ECD) can be considered.

The main idea of ECD is creation or restoration of large coastal ecosystems to attenuate storm waves and surges, accumulating sediments with sea-level rise (Temmerman et al., 2013). At present, there are two situations.

1. Creation or restoration of large tidal marshes or mangroves (tropical or subtropical areas) in estuaries or deltas.
2. Creation or restoration of beaches, dunes or oyster reefs in sandy coastlines.

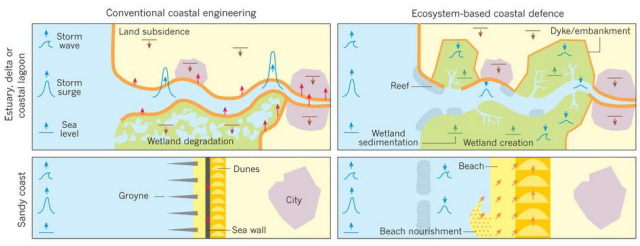

Figure 4: Conventional coastal engineering compared with ecosystem-based defence.
Source: (Temmerman et al., 2013)

When we look into the formation and impacts of ECD, it is clear that the principles of BwN are deeply implemented in it.

For the first situation, the participation of natural forces is reflected in the use of tidal movement and the metabolism of the plants. For the second one, the natural distribution (tide, wave or wind forces) of sand and the growth of oyster are taking part in mitigating the risks of flooding and erosion.

Besides, both situations contribute to the creation of natural habitats for sea and land creatures as well as provide extra ecosystem services for the nearby settlements.

4.3 Key factors - Carrying capacities, Time cycle, Scale

The spatial implementation is aiming at creating a self-adaptive ecosystem that can take advantage of the natural self-regulation ability to deal with the risks. Therefore, it is necessary to understand the key factors in an ecosystem.

First of all, the environmental resource base is finite and has its own capacity, but the carrying capacities are not fixed and static. They are contingent on the everchanging state of interactions between the physical and biotic environment (Arrow et al., 1995). In order to keep the ecosystem resilient, we should understand the existing and expected capacity. The implementation should be continuous with the existing ecosystem and any interventions cause irreversible changes (such as depletion of groundwater reservoirs, desertification and loss of biodiversity, etc.) should be avoided.

Secondly, the evolution of ecosystem is always time-consuming. For example, it takes 1 to 50 years for immigration of appropriate plant species and at least 100 years for formation of distinctive horizons in the soil profile. Ecosystems need special time spans for their own regeneration, and the natural dynamics and trends can also alter their functionality and capacity periodically, episodically or permanently (Bastian, Grunewald, & Syrbe, 2012). This special time span causes great uncertainties, not only ecosystems properties will change through time, but other relevant values like economy and stakeholders' interests can also change. Thus, scenarios imagination, ecological simulation, long-term monitoring are needed for the implementation.

Besides, certain ecosystem has its own characteristics of space, For example, a forest can only be able to influence the microclimate with a size of several hectares; a body of groundwater must have a minimum size or rate of recharge to supply usable amounts of drinking water (Bastian et al., 2012). Sub-ecosystems

with different sizes and positive covary effects could form a more sustainable ecosystems. In order to keep the dynamic balance of ecosystems and fully generate the ecological services, a combination of multi-scale and several patterns of sub-ecosystems is necessary. Thus, the implementation also calls for multi-scale cooperation and synergy, which includes both regional intervention and local adaptation.

4.4 Governance - Integrated Coastal Zone Management (ICZM)

Because of these key factors, the governance becomes essential for providing the long-term vision and organized guideline. In this case, theory of Integrated Coastal Zone Management (ICZM) can be used as a reference.

According to the European Commission (EC), ICZM is a dynamic, multidisciplinary and iterative process to promote sustainable management of coastal zones, covering the full cycle of information collection, planning, decision-making, management and implementation.

ICZM is aiming at the application of different policies related to the coastal zone and activities such as nature protection, aquaculture, agriculture, industries, energy transition, trading, tourism, development of infrastructure, adaptation to climate change, etc. It will eventually contribute to the sustainable development of coastal zones within the limits of natural resources (EC, 2013). Thus, ICZM actually expands the influence of NBS in an integrated way.

To be more practical, there are certain key points of the integration (Wescott, 2004).

1. Vertical integration: the necessity of involving various levels of government (e.g. local, provincial, national).
2. Horizontal integration: the involvement of the activities of all agencies and stakeholders.
3. The land, coastline and the sea should be regarded, planned and managed as a whole and interdependant system.
4. The need of integrating of different disciplines that study specific sections of the coastal area (e.g. science, social science, economics and politics).
5. The integration of educational and research programs to provide the support for the improvement.

4.5 Limitations

NBS has several additional benefits compared with conventional engineering, including the improvement of water quality, carbon dioxide sequestration, nature conservation and the creation of recreational space (Temmerman et al., 2013). However, there are still limitations that can't be ignored especially when it is applied to the urban areas.

Basically, NBS tends to require more space than conventional structures, the positive effectiveness and the sizes of the ecosystems are actually directly proportional. However, for extreme urban areas very close to the sea or mouth of estuaries (e.g. Belgian coastal plain), the space is so limited that only conventional engineering can be feasible (Temmerman et al., 2013). On the other hand, in the undergoing fast urbanization process, applying nature-based solutions can also lead to space competition with other land uses such as land-reclamations.

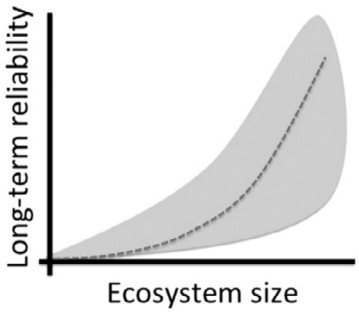

Figure 5: Conventional coastal engineering compared with ecosystem-based defence.
Source: (Bouma et al., 2014)

Besides, due to the natural variability, the creation of defence system is relatively complex and time consuming (World Bank, 2017). Thus it should be planned in really advance to ensure the functions of mitigation and protection can work before the risks are further aggravated. Even though NBS can promote the whole ecosystem, for example, the tidal wetlands can improve the water quality by delivering scarce nutrients such as silica (Struyf, Temmerman, & Meire, 2007) and by acting as a sink for abundant contaminants such as heavy metals (Teuchies, Beauchard, Jacobs, & Meire, 2012), the experience in the UK shows that it could take several decades before the artificial tidal marshes have similar biogeochemical functions to the natural ones (Burden, Garbutt, Evans, Jones, & Cooper, 2013).

Thus, the limitation of nature-based defence solutions lies in two points.

1. Need of large space to fully achieve their effects which is hard to fit in extreme urban areas.
2. Need of a relatively long period to complete the system creation so is different to offer the urgent protection and eco-service for extreme urban areas.

5 The adaptation of nature-based coastal defence solutions in the extreme urban areas

In order to cope with the limitations, it is necessary to study the characteristic and the demands of coastal urbanization, exploring the potentiality of applying NBS in extreme dense urban areas.

5.1 The complexity and conflicts in coastal urban areas

From the complex point of view in the theory of Delta Urbanism, the coastal urbanization can be seen as a layered system. It is perceived as a dynamic and complex whole that comprises essential values from base layer (natural environment) to occupation layer (anthropogenic influences) (Meyer et al., 2015).

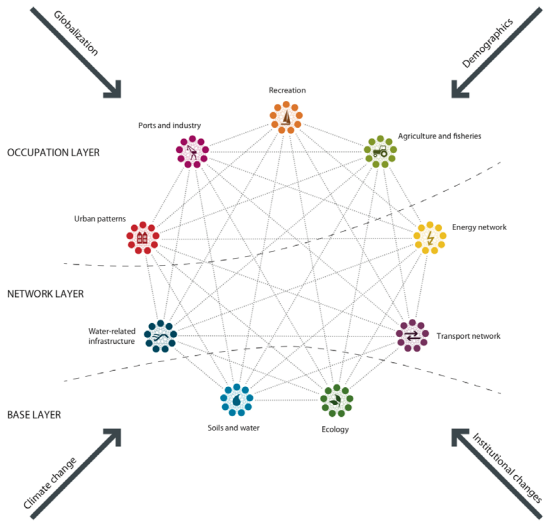

Figure 6: Coastal urbanization as a layered system.
Source: Meyer et al. (2015)

For example, the Belgian Coastal Plain (BCP) comprises an open wave-exposed coast and the more sheltered upper reaches of the Scheldt estuary (Lebbe, Van Meir, & Viaene, 2008), concentrating socio-economic importance with eight cities, four important harbours and four nature reserves. This kind of concentration proves the importance of coastal urbanization while also shows potential conflicts.

From very beginning, BCP was settled by Cistercian "Dune Abbey", which became an integral part of the coastal dynamic by productive afforestation and pumping water into protective drainage canals (Wambecq & De Meulder, 2018). During the Industrial Revolution, the notion of urbanized landscape were growing, promoting the transformation from coastal natural forests to coastal national park. Gradually, on the back of the park, many holiday houses had emerged due to the development of the urban leisure industry. These clusters slowly expanded to the sea and encroached on the open space along the coast. On the one hand, this movement is the slow occupation of nature by urbanization. On the other hand, this encroachment has also led to the appearance of the linear and hard coastal defence line.



Figure 7: Human land use of the Belgian coastline from 1850 to 1982.
Source: (Pillen, Scheerlinck, & Van Daele)

Moreover, the expansion and development of urban require more space, resources and better environment. However, many coastal land's quality are degraded mainly due to the seawater intrusion (Xu, Peng, Xu, Xiao, & Benoit, 2009). BCP is also facing the risk of salinization especially at De Panne, where the freshwater lens has been threatened by saltwater flowing seaward from the polders toward the dunes because of the overexploitation and the sea level rise (Lebbe et al., 2008).

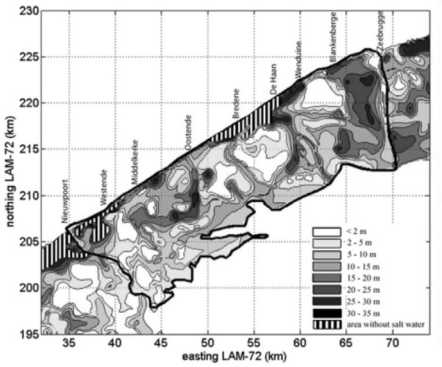

Figure 8: Depth of the fresh-salt water interface in the central Belgian coastal plain.
Source: (Vandenbohede, Courtens, Lebbe, & De Breuck, 2010)

The example of BCP helps us to summarize the following conflicts in coastal urban areas.

1. The conflict between land resource utilization and natural environmental conservation.
2. The conflict between increasing land demand and degraded land quality.
3. The conflict between dynamics of sea & urbanization and static states of conventional coastal engineering.

5.2 The particular demands of coastal urban areas

Because of the complexity and the conflicts, the coastal urban areas have specific demands for defence.

The centrality of important values and the complexity of critical systems make the areas more sensitive to the impacts of external environmental changes. Thus there is always the urgent need of protection. And due to the highly dynamics of the nature and urban systems, there are even greater uncertainties than other coastal areas (such as economic transformation, political and social structure changes, etc.), so such protection solutions need to be more flexible and adaptive.

Moreover, the contradiction between limited land research and development needs of different systems demand for the more integrated and multifunctional intervention.

5.3 The potentialities of applying NBS in extreme urban areas

Although the limitations of NBS are still existing, there are also some potentialities in the urban areas to adapt this concept.

Green and blue infrastructure (GBI) theory is talking about the integration of urban landscape and water management that contributes to the climate adaptation, biodiversity, air quality, sustainable energy production, etc (Pötz & Bleuzé, 2012). Spatially, it actually act as a network of many small interventions based on green & blue patches in the urban areas. These patches not only includes green or blue open space (urban park, wetland, nature reservation, etc.), but also can be 'green' constructions (green roofs, green walls, etc.). Even though it is not a large natural ecosystem, the network itself actually create a urban ecosystem that can also provide an ecological framework and the ecoservices for both urban and nature. Therefore, integrate the NBS with the urban GBI could be a potentiality for the adaptation.

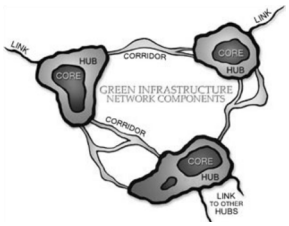

Figure 9: The concept of GBI.
Source: (Natural England, 2009)

The theory of System Exploration Environment & Subsurface (SEES) also offer some potentialities for us. The main idea of the theory is regarding surface and subsurface as one united space in the urban areas (Hooimeijer & Maring, 2018). The urban construction is bound to bring about the exploitation of underground space, but at present the underground space is mostly regarded as an accessory to the ground space and is not well made full use of. Actually, the integration of the surface and the subsurface systems in urban planning and design can offer us more potentialities to tackle the current trends such as climate change effects (Hooimeijer & Maring, 2018). Thus, the application of NBS can also be considered from the perspective of urban underground space and subsurface infrastructure.

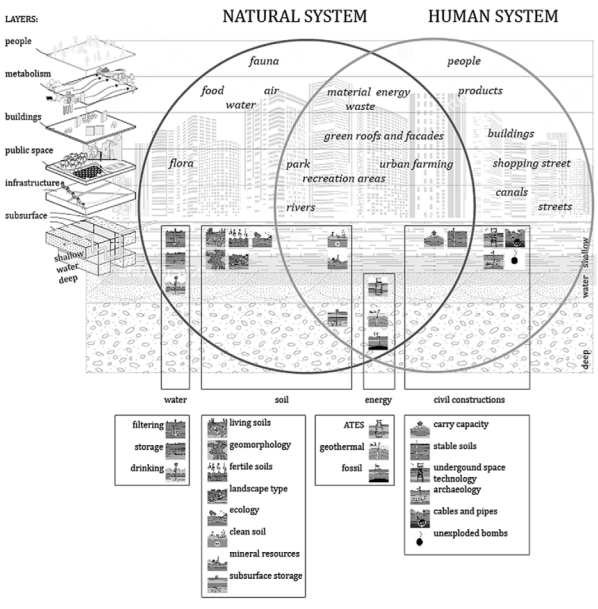

Figure 10: Surface and subsurface as a single space.
Source: (Hooimeijer & Maring, 2018)

Moreover, the idea of Adaptive Management emphasizes the adaptation in the whole management process. It is a systematic approach built on a predictive outcome or target (World Bank, 2017).

Compared to Coastal Zone Management (ICZM), the difference is mainly manifested in two aspects.

1. Monitoring and evaluating
   After the implementation, long-term monitoring is needed because of the uncertainties. Besides, evaluating if the objectives are running well during the monitoring also help us to deal with the ever-changing risks.
2. Adapting
   Adaptation happens after the evaluation and could lead to the revision of the former interventions. It is an essential stage for repeating at a regular cycle during the lifetime of the implementation.

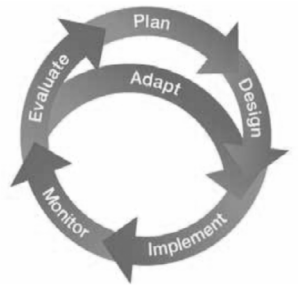

Figure 11: Adaptive Management Process.
Source: (CEDA, 2015)

For high-dynamic coastal urban areas, this kind of management can be considered as a supplement to ICZM and they can be synthesized together as a new method of management, the Adaptive Integrated Coastal Zone Management (AICZM).

6 Conclusion

Because of the climate change effects and socio-economic demands, the coastal defence solutions are facing the transition. The concept of Nature-based Coastal Defence Solutions (NBS), as a new trend of defence system intervention, has been experiencing a wider and frequent application due to its long-term sustainability. However there are still limitations especially when it is applied in the extreme dense urban areas. As a result of the natural dynamics and processes, the limitations lie in two aspects, the spatial limits and the temporal limits.

On the other hand, after studying the coastal urban system and its related theories, it is also clear that there are potentialities of overcoming the limits.

Based on the discussion, the first conclusion can be summarized by the diagram of theoretical framework. Basically, NBS has its own theoretical basis (Building with Nature, Ecosystem-based Coastal Defence and Integrated Coastal Zone Management) and the main factors (carrying capacities, time cycle and scale) that need to be taken into consideration.

And when it is applied into the dense urban contexts, related theories like Delta Urbanism, Green & Blue Infrastructure and System Exploration Environment & Subsurface can be supportive for the adaptation.

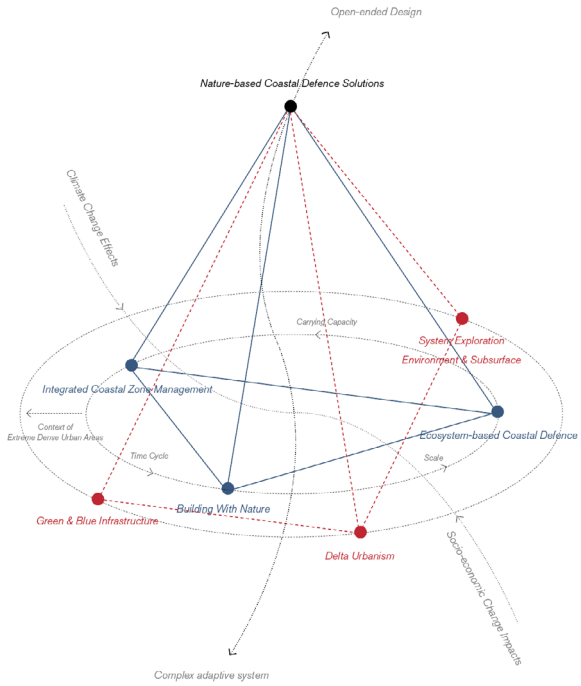

Figure 12: Theoretical framework.
Source: Made by the author

Secondly, based on the theoretical framework, the proposal principles of this adaptation are put forward for further research.

1. Combination of 'sustainable' engineering and NBS.
   Transforming the conventional coastal engineering to be more sustainable and multifunctional (For example, it can be integrated with energy production, creatures habitats and recreational function). Combining engineering and ecology to provide short-term urgent defence and long-term eco-services and development.
2. Multi-scale strategies and local, small-scale, scattered intervention.
   Because the creation and effects of ecosystems can not limited to single scale, strategies in different scales are needed. When it comes to the urban scale, the existing blue-green system and underground space

can be made use of to build up the whole ecosystem by small parts, combining small-scale intervention with large-scale connectivity. For example, buffer stripes, habitat connection and wildlife corridors are common approaches to create the ecosystem in the urban context.

3. Coastal defence system as a transitional zone between sea and urban.
   Regarding the sea and coastal urban areas as a whole ecosystem, so the coastal defence system can act as a gradient medium that integrate the dynamics of both sea and urban, mitigating the coastal risks and at the same time taking on some urban functions.
4. From Integrated Coastal Zone Management (ICZM) to Adaptive Integrated Coastal Zone Management (AICZM).
   As the integration of NBS and urban systems should be a long-term vision, AICZM offers the evaluation and adaptation stage based on multiple scenarios making, long-term modelling and monitoring, ensuring the consistent and coherent governance after the implementation and offers experience for future improvement.

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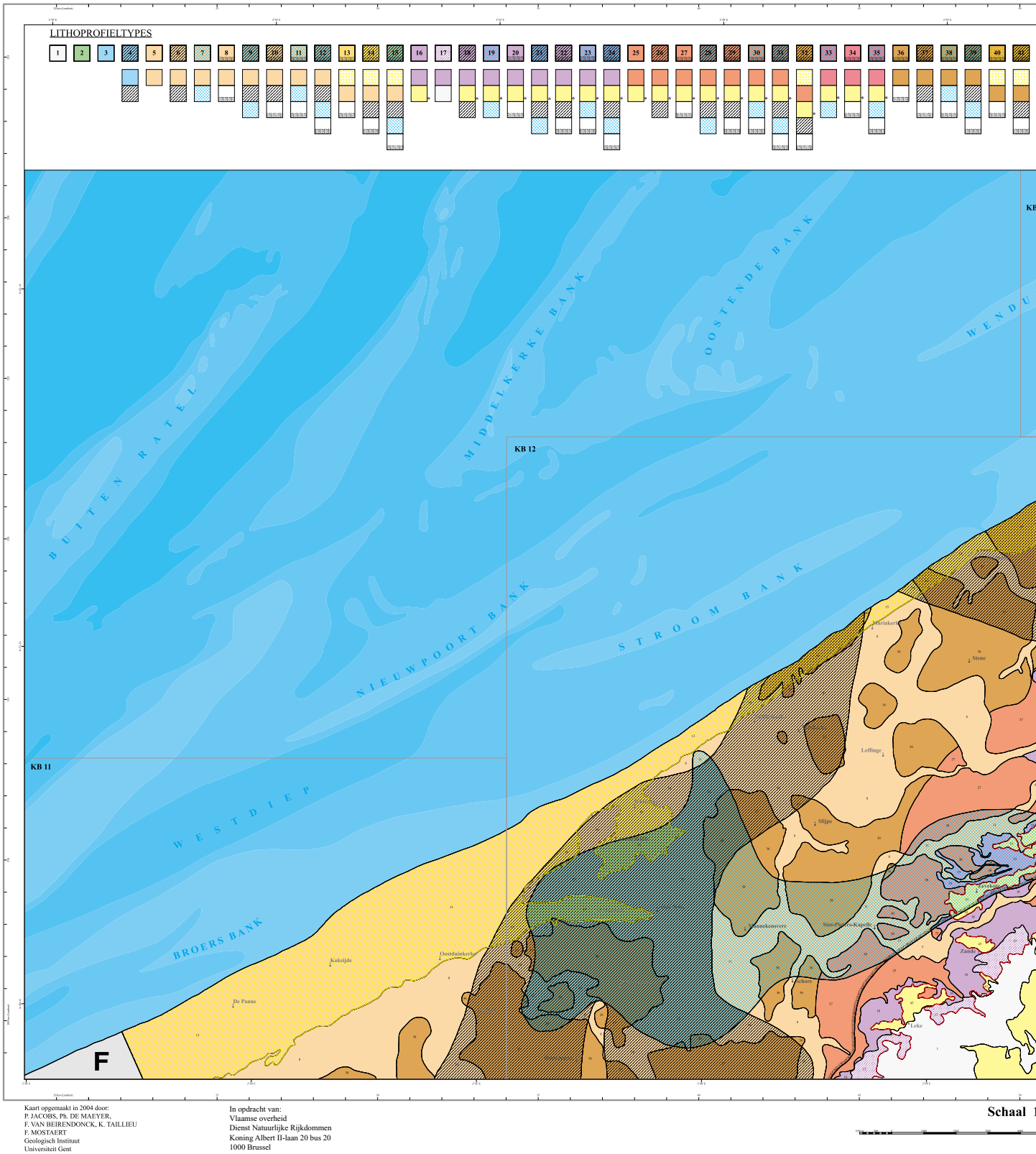
Appendix 2: Data - Soil Data



Kaart opgemaakt in 2004 door:
P. JACOBS, Ph. DE MAEYER,
F. VAN BEIRENDONCK, K. TAILLIEU
F. MOSTAERT
Geologisch Instituut
Universiteit Gent

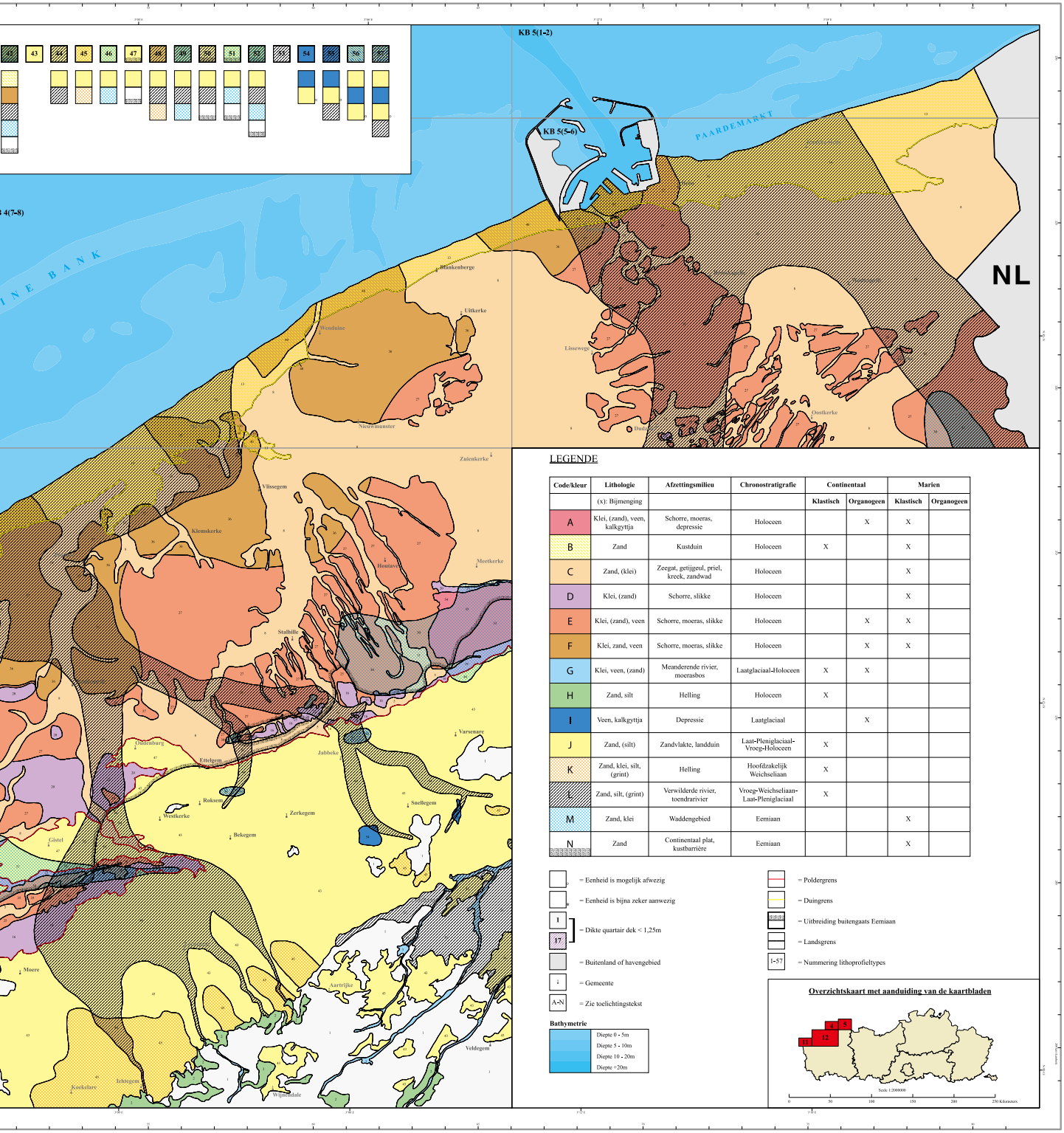
In opdracht van:
Vlaamse overheid
Dienst Natuurlijke Rijkdommen
Koning Albert II-laan 20 bus 20
1000 Brussel

Schaal 1

N DE QUARTAIRE AFZETTINGEN

-8) - 5(5-6) - 11 - 12)

E - OOSTDUINKERKE - OOSTENDE



LEGENDE

Code/kleur	Lithologie	Afzettingsmilieu	Chronostratigrafie	Continentaal		Marien	
	(x): Bijmenging			Klastisch	Organogeen	Klastisch	Organogeen
A	Klei, (zand), veen, kalkgyttja	Schorre, moeras, depressie	Holoceen		X	X	
B	Zand	Kustduin	Holoceen	X		X	
C	Zand, (klei)	Zeegat, getijgeul, priel, kreek, zandwad	Holoceen			X	
D	Klei, (zand)	Schorre, slikke	Holoceen			X	
E	Klei, (zand), veen	Schorre, moeras, slikke	Holoceen		X	X	
F	Klei, zand, veen	Schorre, moeras, slikke	Holoceen		X	X	
G	Klei, veen, (zand)	Meanderende rivier, moerasbos	Laatglaciaal-Holoceen	X	X		
H	Zand, silt	Helling	Holoceen	X			
I	Veen, kalkgyttja	Depressie	Laatglaciaal		X		
J	Zand, (silt)	Zandvlakte, landduin	Laat-Pleniglaciaal-Vroeg-Holoceen	X			
K	Zand, klei, silt, (grint)	Helling	Hoofdzakelijk Weichseliaan	X			
L	Zand, silt, (grint)	Verwilderde rivier, toendrarivier	Vroeg-Weichseliaan-Laat-Pleniglaciaal	X			
M	Zand, klei	Waddengebied	Eemiaan			X	
N	Zand	Continentaal plat, kustbarrière	Eemiaan			X	

= Eenheid is mogelijk afwezig

= Eenheid is bijna zeker aanwezig

1 / 17 = Dikte quartair dek < 1,25m

= Buitenland of havengebied

= Gemeente

A-N = Zie toelichtingstekst

= Poldergrens

= Duingrens

= Uitbreiding buitengaats Eemiaan

= Landsgrens

1-57 = Nummering lithoprofieltypes

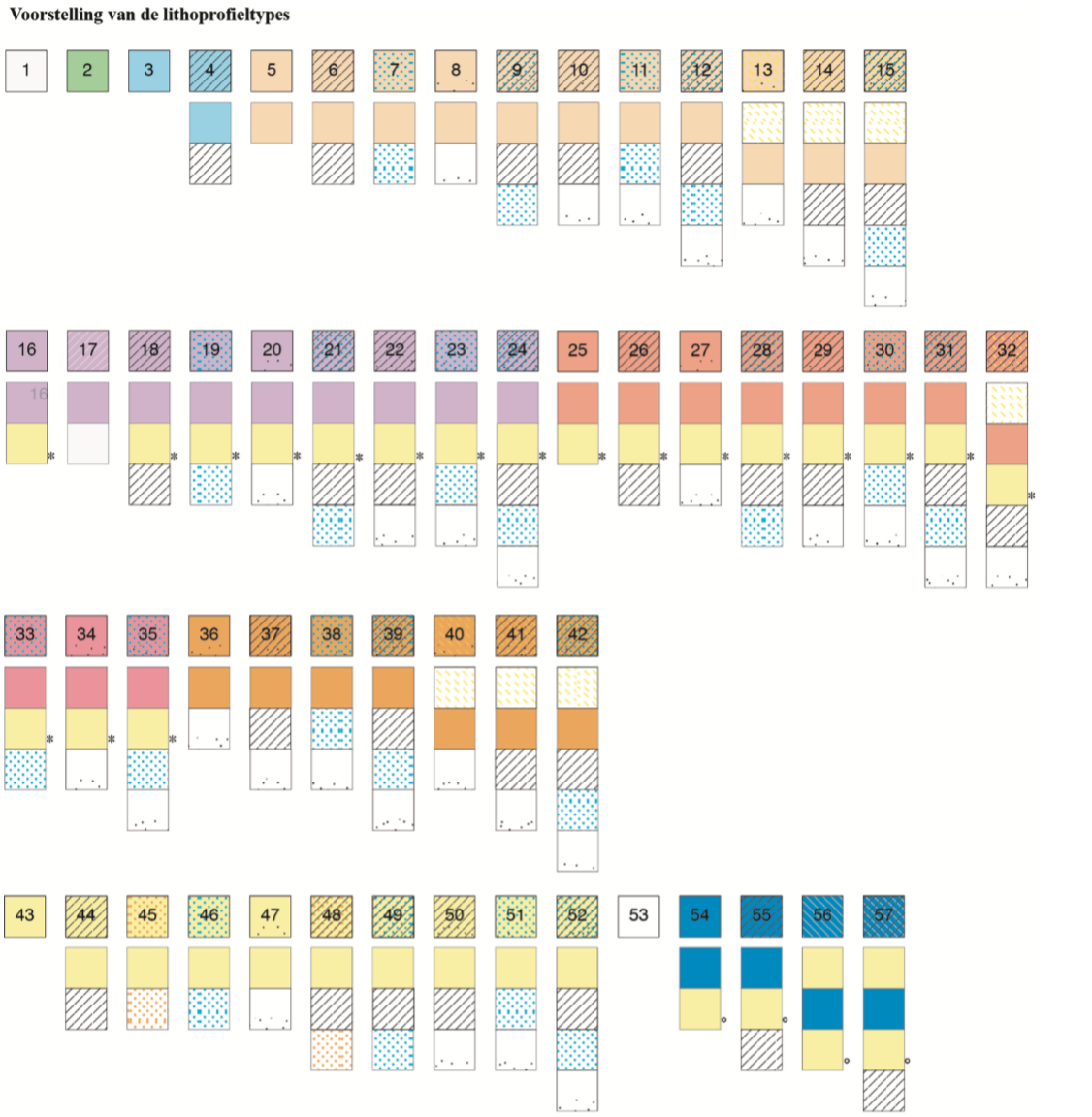
Bathymetrie

Diepte 0 - 5m
Diepte 5 - 10m
Diepte 10 - 20m
Diepte +20m

Overzichtskaart met aanduiding van de kaartbladen

1 : 50 000

Internationale ellipsoïde 1924 • EENGEMAAKT EUROPEES GEODETISCH NET 1951.
Belgische LAMBERT-projectie • Oorsprong van de waterpassing : zero D in Oostende.
Ellipsoïde international 1924 • BESSAU GEODESIQUE EUROPEEN UNITE 1951.
Projection LAMBERT belge • Origine du nivellement : Zero D à Oostende.
Internationales Ellipsoid 1924 • SYSTEM DES EUROPÄISCHEN DREIECKSNETZES 1951.
Belgische LAMBERT-Projektion • Höhenbezugspunkt : D Null in Oostende.
International Spezial 1924 • UNIFIED EUROPEAN GEODETIC SYSTEM 1951.
Belgian LAMBERT projection • Levelling datum : Zero D at Oostende.



Code/kleur	Lithologie	Afzettingsmilieu	Chronostratigrafie	Continentaal		Marien	
	(x): Bijmenging			Klastisch	Organogeen	Klastisch	Organogeen
A	Klei, (zand), veen, kalkgyttja	Schorre, moeras, depressie	Holoceen		x	x	
B	Zand	Kustduin	Holoceen	x		x	
C	Zand, (klei)	Zeegat, getijgeul, priel, kreek, zandwad	Holoceen			x	
D	Klei, (zand)	Schorre, slikke	Holoceen			x	
E	Klei, (zand), veen	Schorre, moeras, slikke	Holoceen		x	x	
F	Klei, zand, veen	Schorre, moeras, slikke	Holoceen		x	x	
G	Klei, veen, (zand)	Meanderende rivier, moerasbos	Laat glaciaal-Holoceen	x	x		
H	Zand, silt	Helling	Holoceen	x			
I	Veen, kalkgyttja	Depressie	Laat glaciaal		x		
J	Zand, (silt)	Zandvlakte, landduin	Laat-Pleniglaciaal-Vroeg-Holoceen	x			
K	Zand, klei, silt, (grint)	Helling	Hoofdzakelijk Weichseliaan	x			
L	Zand, silt, (grint)	Verwilderde rivier, toendrarivier	Vroeg-Weichseliaan-Laat-Pleniglaciaal	x			
M	Zand, klei	Waddengebied	Eemiaan			x	
N	Zand	Continentaal plat, kustbarrière	Eemiaan			x	

Poldergrens
Duingrens
Uitbreiding buitengaats Eemiaan
Buitenland of havengebied

Eenheid is mogelijk afwezig
Eenheid is bijna zeker aanwezig
Dikte quartair dek < 1,25m

Fig.A-3 Soil profile in BCP

Source: Quartair Geologische kaart, 2004

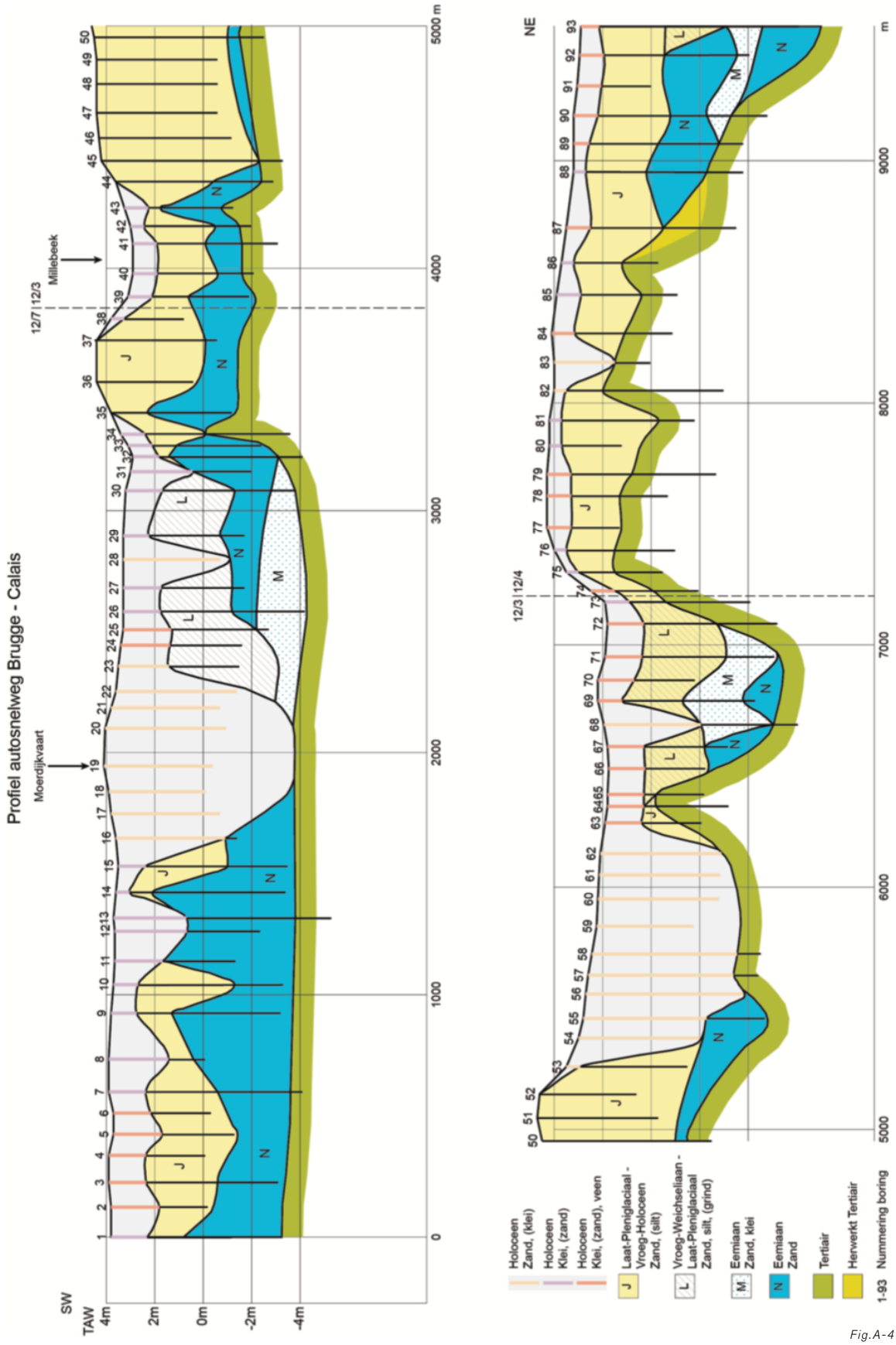


Fig.A-4 Soil profile from Brugge to Calais

Source: Quartair Geologische kaart, 2004

Appendix 3: Calculation - Storm Overtopping in Design Area

SOURCE: Wave Overtopping of Seawalls Design and Assessment Manual, 1999

NOTATION

a	Weibull scale parameter
b	Weibull shape parameter
A,B	Empirical coefficients
$\mathbf{N}_{ow}$	The number of overtopping waves
$\mathbf{N}_{w}$	The number of waves in the sequence
C	Empirical coefficient
$\mathbf{R}_{*}$	Dimensionless crest freeboard
$\mathbf{R}_{c}$	Freeboard of the seawall (the height of the crest of the wall above still water level)
r	Roughness coefficient
$\mathbf{V}_{bar}$	Mean individual overtopping volume (m^3)
Q	Mean overtopping discharge rate per metre run of seawall
$\mathbf{Q}_{*}$	Dimensionless mean discharge (sloped seawalls)
$\mathbf{T}_{m}$	Mean period of the waves at the toe of the structure (s)
$\mathbf{T}_{po}$	Peak offshore wave period
$\mathbf{S}_{op}$	Offshore sea steepness
$\mathbf{V}_{max}$	Maximum individual overtopping volume
$\mathbf{H}_{s}$	Significant wave height

Typical roughness coefficients table

Type of Seawall	Roughness Coefficient, r
Smooth concrete or asphalt	1.0
Smooth concrete blocks with Little or no drainage	1.0
Stone blocks, pitched or mortared	0.95
Stepped	0.95
Turf	0.9-1.0
One layer of rock armour on impermeable base	0.80
One layer of rock armour On permeable base	0.55 - 0.60
Two layers of rock armour	0.50 - 0.55

Empirical coefficients - number of waves overtopping simply sloping seawall

Seawall Slope	C
1:1	63.8
1:2	37.8
1:4	110.5

Empirical Coefficients – Simply Sloping Seawalls

Seawall Slope	A	B
1:1	7.94E-3	20.1
1:1.5	8.84E-3	19.9
1:2	9.39E-3	21.6
1:2.5	1.03E-2	24.5
1:3	1.09E-2	28.7
1:3.5	1.12E-2	34.1
1:4	1.16E-2	41.0
1:4.5	1.20E-2	47.7
1:5	1.31E-2	55.6

PARAMETER

Sea wall slope = 1/4

r = 1.0

C = 110.5

A = 0.0116 **B** = 41.0

$\mathbf{T}_m$ = 8s $\mathbf{T}_{po}$ = 12s

EQUATION

$\mathbf{N}_{ow} / \mathbf{N}_w = \exp(-\mathbf{C} (\mathbf{R}_* / \mathbf{r})^2)$

$\mathbf{R}_* = \mathbf{R}_c / (\mathbf{T}_m (g\mathbf{H}_s)^{1/2})$

$\mathbf{V}_{bar} = \mathbf{Q}\mathbf{T}_m\mathbf{N}_w / \mathbf{N}_{ow}$

$\mathbf{Q}_* = \mathbf{Q}_* \mathbf{T}_m g\mathbf{H}_s$

$\mathbf{S}_{op} = 2\varpi\mathbf{H}_{so}/(\mathbf{g}\mathbf{T}_{po}^2)$

a=0.85 $\mathbf{V}_{bar}$, **b**=0.76 for $\mathbf{S}_{op}$ = 0.02
and **a**=0.96$\mathbf{V}_{bar}$, **b**=0.92 for $\mathbf{S}_{op}$ = 0.04

$\mathbf{Q}_* = \mathbf{A}\mathbf{e}^{(-\mathbf{B}\mathbf{R}_*)}$

$\mathbf{V}_{max} = \mathbf{a} (\ln(\mathbf{N}_{ow}))^{1/\mathbf{b}}$

TRANSITIONAL PERIOD

For Dike

$\mathbf{R}_c$ = 7.6m
$\mathbf{T}_m$ = 8s
$\mathbf{g}$ = 10m/s^2
$\mathbf{H}_s$ = 5m

Thus,

$\mathbf{R}_* = \mathbf{R}_c / (\mathbf{T}_m(g\mathbf{H}_s)^{1/2}) = 0.134$
$\mathbf{N}_{ow} / \mathbf{N}_w = \exp(-\mathbf{C}(\mathbf{R}_*/\mathbf{r})^2) = 0.14$
$\mathbf{Q}_* = \mathbf{Ae}^{(-\mathbf{BR}^*)} = 0.00005$
$\mathbf{Q} = \mathbf{Q}_* \mathbf{T}_m \mathbf{g} \mathbf{H}_s = 0.019$
$\mathbf{V}_{bar} = \mathbf{Q}\mathbf{T}_m\mathbf{N}_w / \mathbf{N}_{ow} = 1.09$
$\mathbf{S}_{op} = 2\varpi\mathbf{H}_s/(\mathbf{g}\mathbf{T}_{po}^2) = 0.02$

Thus,

$\mathbf{a}$=0.85 $\mathbf{V}_{bar}$ = 0.93, $\mathbf{b}$=0.76
$\mathbf{N}_{ow}$ = 21600 * 0.14 = 3,024
$\mathbf{V}_{max} = \mathbf{a}(\ln(\mathbf{N}_{ow}))^{1/\mathbf{b}} = 14.5$ 14.5 * 600 = 8,700 m^3

For Harbor

$\mathbf{R}_c$ = 5m
$\mathbf{T}_m$ = 8s
$\mathbf{g}$ = 10m/s^2
$\mathbf{H}_s$ = 5m

Thus,

$\mathbf{R}_* = \mathbf{R}_c / (\mathbf{T}_m(g\mathbf{H}_s)^{1/2}) = 0.088$
$\mathbf{N}_{ow} / \mathbf{N}_w = \exp(-\mathbf{C}(\mathbf{R}_*/\mathbf{r})^2) = 0.425$
$\mathbf{Q}_* = \mathbf{Ae}^{(-\mathbf{BR}^*)} = 0.0003$
$\mathbf{Q} = \mathbf{Q}_* \mathbf{T}_m \mathbf{g} \mathbf{H}_s = 0.12$
$\mathbf{V}_{bar} = \mathbf{Q}\mathbf{T}_m\mathbf{N}_w / \mathbf{N}_{ow} = 2.26$
$\mathbf{S}_{op} = 2\varpi\mathbf{H}_s/(\mathbf{g}\mathbf{T}_{po}^2) = 0.02$

Thus,

$\mathbf{a}$=0.85 $\mathbf{V}_{bar}$ = 1.92, $\mathbf{b}$=0.76
$\mathbf{N}_{ow}$ = 21600 * 0.425 = 9,180
$\mathbf{V}_{max} = \mathbf{a}(\ln(\mathbf{N}_{ow}))^{1/\mathbf{b}} = 35.5$ 35.5 * 600 = 21,300 m^3

Thus,

8,700 + 21,300 = 30,000 m^3

STRENGTHENING PERIOD

For Dike

$\mathbf{R}_c$ = 5.6m

$\mathbf{T}_m$ = 8s

$\mathbf{g}$ = 10m/s^2

$\mathbf{H}_s$ = 7m

Thus,

$\mathbf{R}_* = \mathbf{R}_c / (\mathbf{T}_m(g\mathbf{H}_s)^{1/2}) = 0.08$

$\mathbf{N}_{ow} / \mathbf{N}_w = \exp(-\mathbf{C}(\mathbf{R}_*/\mathbf{r})^2) = 0.49$

$\mathbf{Q}_* = \mathbf{Ae}^{(-\mathbf{BR}^*)} = 0.00044$

$\mathbf{Q} = \mathbf{Q}_*\mathbf{T}_m\mathbf{gH}_s = 0.25$

$\mathbf{V}_{bar} = \mathbf{QT}_m\mathbf{N}_w / \mathbf{N}_{ow} = 4.08$

$\mathbf{S}_{op} = 2\varpi\mathbf{H}_s/(\mathbf{gT}_{po}^2) = 0.03$

Thus,

$\mathbf{a}$=0.85 $\mathbf{V}_{bar}$ = 3.47, $\mathbf{b}$=0.76

$\mathbf{N}_{ow}$ = 21600 * 0.49 = 10,584

$\mathbf{V}_{max} = \mathbf{a}(\ln(\mathbf{N}_{ow}))^{1/\mathbf{b}} = 65.6$ 9.56 * 600 = 39,360 m^3

For Harbor

$\mathbf{R}_c$ = 3m

$\mathbf{T}_m$ = 8s

$\mathbf{g}$ = 10m/s^2

$\mathbf{H}_s$ = 7m

Thus,

$\mathbf{R}_* = \mathbf{R}_c / (\mathbf{T}_m(g\mathbf{H}_s)^{1/2}) = 0.045$

$\mathbf{N}_{ow} / \mathbf{N}_w = \exp(-\mathbf{C}(\mathbf{R}_*/\mathbf{r})^2) = 0.8$

$\mathbf{Q}_* = \mathbf{Ae}^{(-\mathbf{BR}^*)} = 0.0018$

$\mathbf{Q} = \mathbf{Q}_*\mathbf{T}_m\mathbf{gH}_s = 1.008$

$\mathbf{V}_{bar} = \mathbf{QT}_m\mathbf{N}_w / \mathbf{N}_{ow} = 10.08$

$\mathbf{S}_{op} = 2\varpi\mathbf{H}_s/(\mathbf{gT}_{po}^2) = 0.03$

Thus,

$\mathbf{a}$=0.85 $\mathbf{V}_{bar}$ = 8.57, $\mathbf{b}$=0.76

$\mathbf{N}_{ow}$ = 21600 * 0.8 = 17,280

$\mathbf{V}_{max} = \mathbf{a}(\ln(\mathbf{N}_{ow}))^{1/\mathbf{b}} = 173.34$ 173.34 * 600 = 104,004 m^3

Thus,

39,360 + 104,004 = 143,364 m^3

RISKY PERIOD

For Dike
$\mathbf{R}_c$ = 2.6m
$\mathbf{T}_m$ = 8s
$\mathbf{g}$ = 10m/s^2
$\mathbf{H}_s$ = 10m

Thus,
$\mathbf{R}_*$ = $\mathbf{R}_c$ / ($\mathbf{T}_m$($g\mathbf{H}_s$)$^{1/2}$) = 0.03
$\mathbf{N}_{ow}$ / $\mathbf{N}_w$ = exp(-$\mathbf{C}$ ($\mathbf{R}_*$/$\mathbf{r}$)^2) = 0.91
$\mathbf{Q}_*$ = $\mathbf{Ae}^{(-\mathbf{BR}^*)}$ = 0.003
$\mathbf{Q}$ = $\mathbf{Q}_*\mathbf{T}_m g\mathbf{H}_s$ = 2.4
$\mathbf{V}_{bar}$ = $\mathbf{QT}_m\mathbf{N}_w$ / $\mathbf{N}_{ow}$ = 21.12
$\mathbf{S}_{op}$ = 2ϖ$\mathbf{H}_s$/($\mathbf{gT}_{po}^2$) = 0.04

Thus,
$\mathbf{a}$=0.96 $\mathbf{V}_{bar}$ = 20.3, $\mathbf{b}$=0.92
$\mathbf{N}_{ow}$ = 21600 * 0.91 = 19,656
$\mathbf{V}_{max}$ = $\mathbf{a}$ (ln($\mathbf{N}_{ow}$))$^{1/\mathbf{b}}$ = 246.6 246.6 * 600 = 147,960 m^3

For Harbor
$\mathbf{R}_c$ = 0m
$\mathbf{T}_m$ = 8s
$\mathbf{g}$ = 10m/s^2
$\mathbf{H}_s$ = 10m

Thus,
$\mathbf{R}_*$ = $\mathbf{R}_c$ / ($\mathbf{T}_m$($g\mathbf{H}_s$)$^{1/2}$) = 0
$\mathbf{N}_{ow}$ / $\mathbf{N}_w$ = exp(-$\mathbf{C}$ ($\mathbf{R}_*$/$\mathbf{r}$)^2) = 1
$\mathbf{Q}_*$ = $\mathbf{Ae}^{(-\mathbf{BR}^*)}$ = 0.0116
$\mathbf{Q}$ = $\mathbf{Q}_*\mathbf{T}_m g\mathbf{H}_s$ = 9.28
$\mathbf{V}_{bar}$ = $\mathbf{QT}_m\mathbf{N}_w$ / $\mathbf{N}_{ow}$ = 74.24
$\mathbf{S}_{op}$ = 2ϖ$\mathbf{H}_s$/($\mathbf{gT}_{po}^2$) = 0.04

Thus,
$\mathbf{a}$=0.96 $\mathbf{V}_{bar}$ = 71.27, $\mathbf{b}$=0.92
$\mathbf{N}_{ow}$ = 21600 * 1 = 21,600
$\mathbf{V}_{max}$ = $\mathbf{a}$ (ln($\mathbf{N}_{ow}$))$^{1/\mathbf{b}}$ = 874.9 874.9 * 600 = 524,940 m^3

Thus,

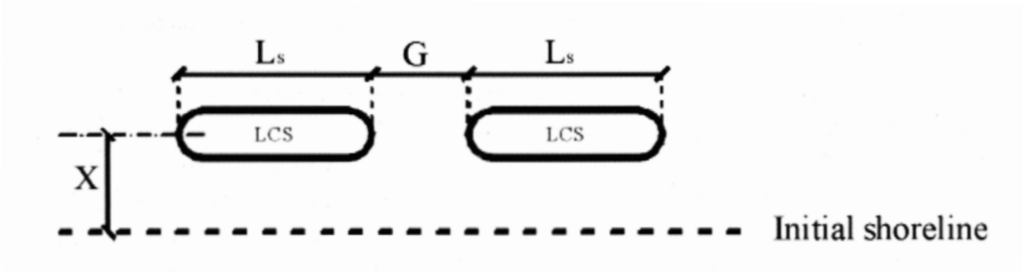
147,960 + 524,940 = 672,900 m^3

LIMITED PERIOD

In this period, the still sea level will already exceed the current dike, so the overtopping formula is not suitable under this situation. Thus, the storm flooding volume in this period is estimated and calculated by the area and the average water depth.

Appendix 3: Calculation - Scale of Oyster Reef

SOURCE: Environmental design guidelines for low crested coastal structures, 2010



Emergent structure		
Conditions for formation of		*Reference*
Tombolos	**Salients**	
$L_s/X \geq 1.5$	$1/2 < L_s/X < 2/3$	Dally and Pope (1986)
$L_s/X > 1$	$1/2 < L_s/X < 1$	Herbich (1989)
$L_s/X > 0.9$ to 1	$L_s/X < 0.6$ to 0.7	Mangor (2001)
Submerged structures		
Conditions for formation of		*Reference*
Tombolos	**Salients**	
$L_s/X > (1.0 \text{ to } 1.5)/(1 - K_t)$	$L_s/X > 1/(1 - K_t)$ $GX/L^2_s > 0.5(1 - K_t)$	Pilarczyk (2003)

The width of the gap is usually according to Pilarczyk (2003)

$$L \leq G \leq 0.8\, L_s$$

where $L = T\,(g \cdot h)^{0.5}$, T being the wave period and h the water depth at the structure.

Seiji, Uda and Tanaka (1987), referred to Loveless (1999), gave the following conditions for the erosion of the beach behind the gap:

$G/X < 0.8$	no erosion
$0.8 \leq G/X \leq 1.3$	erosion likely
$G/X \geq 1.3$	surely erosion

Appendix 4: Questionaire

1 Your age

1. <18 2. 18-30 3. 30-45 4. 45-60 5. >60

2 Years at Current Address

1. 0-5 2. 5-10 3. 10-20 4. >20

3 What kind of properties are you living in now?

1. Own house 2. Rented house 3. Own apartment 4. Rented apartment 5. Others_____

4 Do you understand the situation of coastal flooding risks in city of Ostend? (for example, the previous extreme flooding event and the possible frequency of these events)

1. Yes, I fully understand (>80%)
2. Yes, I undersrtand most of them (60%-80%)
2. Yes, I partly understand (40%-60%)
3. Yes, I understand a little bit (20%-40%)
4. No, I don't understand most of them (<20%)

5 Do you understand the situation of coastal flooding risks in city of Ostend? (for example, the previous extreme flooding event, the defence standard of the city, the current defence system of the city and the weak points of the current defence)

1. Yes, I fully understand (>80%)
2. Yes, I undersrtand most of them (60%-80%)
2. Yes, I partly understand (40%-60%)
3. Yes, I understand a little bit (20%-40%)
4. No, I don't understand most of them (<20%)

6 In general, thinking about where you live, would you say that your home is at risk of coastal flooding?

1. Yes, major risks 2. Yes, minor risks 3. No

7 Has any house or apartment /complex ever flooded while you were living there?

1. Yes, this house or this apartment/complex
2. Yes, another house or another apartment/complex
3. No

8 Have you ever experienced flooding evacuation drills or related activities?

1. Yes, a lot of times
2. Yes, few times
3. No, never

9 In thinking about preparing for a major flooding event in your home or area, which category below best represents your preparedness?

1. I am currently fully prepared
2. I intend to prepare in the next few months
3. I am not planning to undertake any preparations
4. I haven't thought much about it

10 Which, if any of these actions have you taken to protect yourself or your property from flooding?

1. Checked flood information brochures/ websites
2. Checked insurance cover
3. Moved valuables upstairs
4. Created an emergency flood kit
5. Had flood protection products (sandbags etc.)
6. Installed flood-proof household measures

11 Have you ever participated in activities related to coastal flooding defence?

1. Yes, a lot of times
2. Yes, few times
3. No, never

If yes can you give a example?

_____

12 Are you willing to take part in coastal flooding defence related activities?

1. Yes 2. No 3. I don't mind

13 If you could, what kind of activities are you willing to take part in?

1. Hearings about defence measures and policy making (to know and understand the measures and policies)
2. Public consultation meetings and provide advice for the decision making (to participate in making the measures and policies)
3. Education of flooding defence knowledge (ie. self-rescue measures, evacuation, etc.)

Others?

_____

Appendix 5: Other Drawings

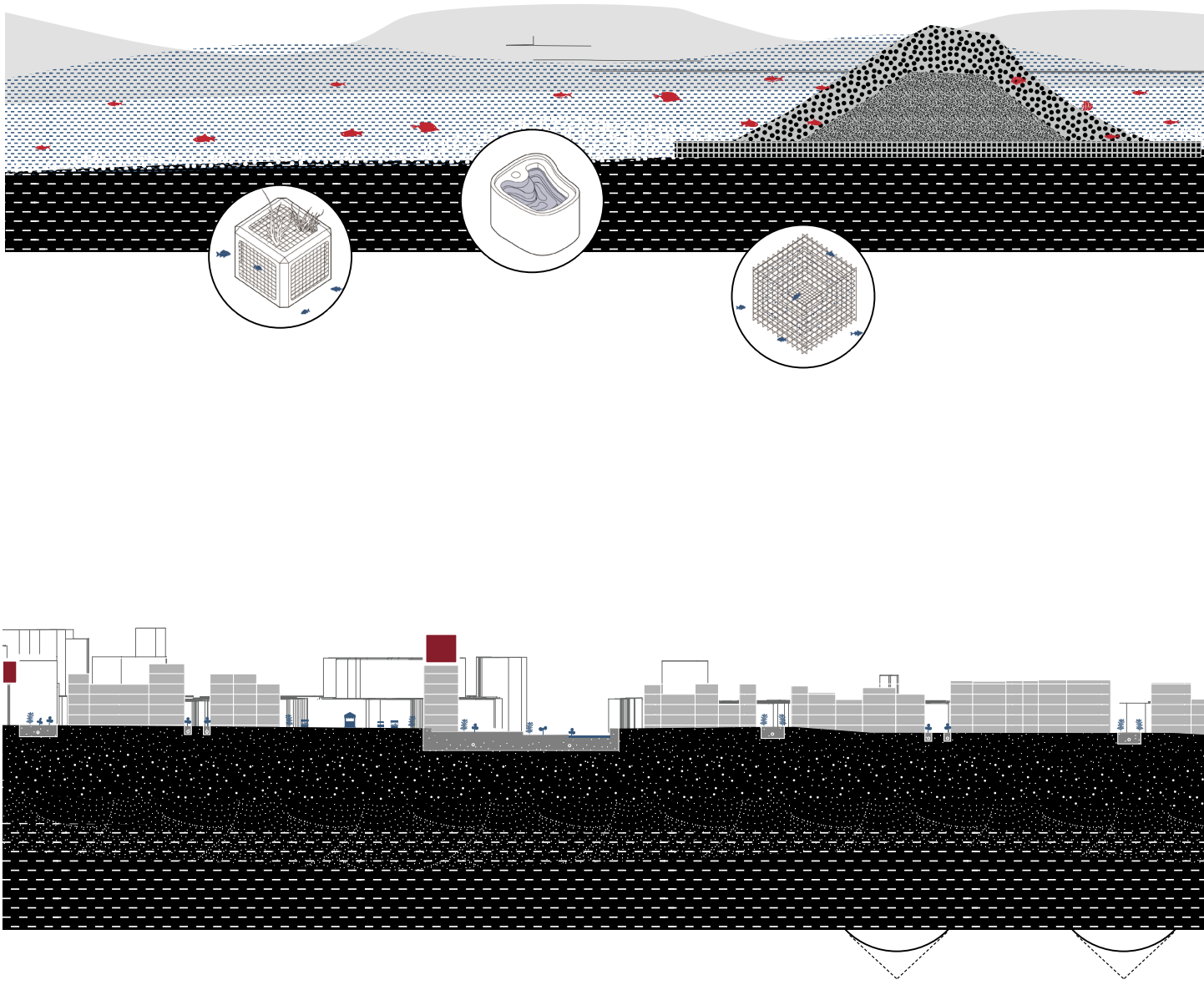
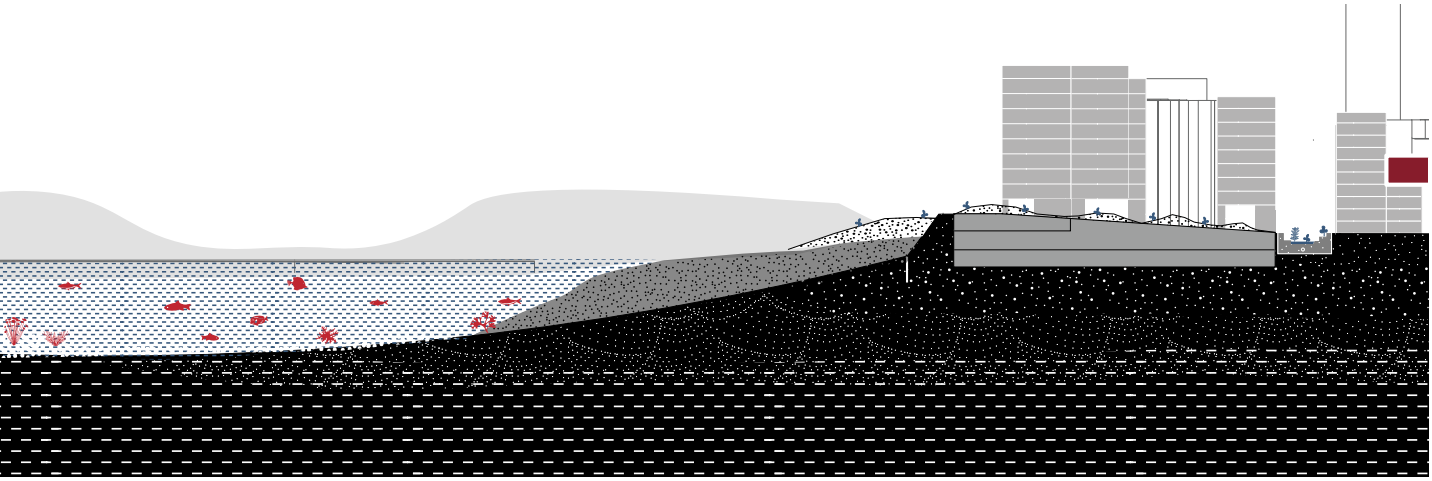
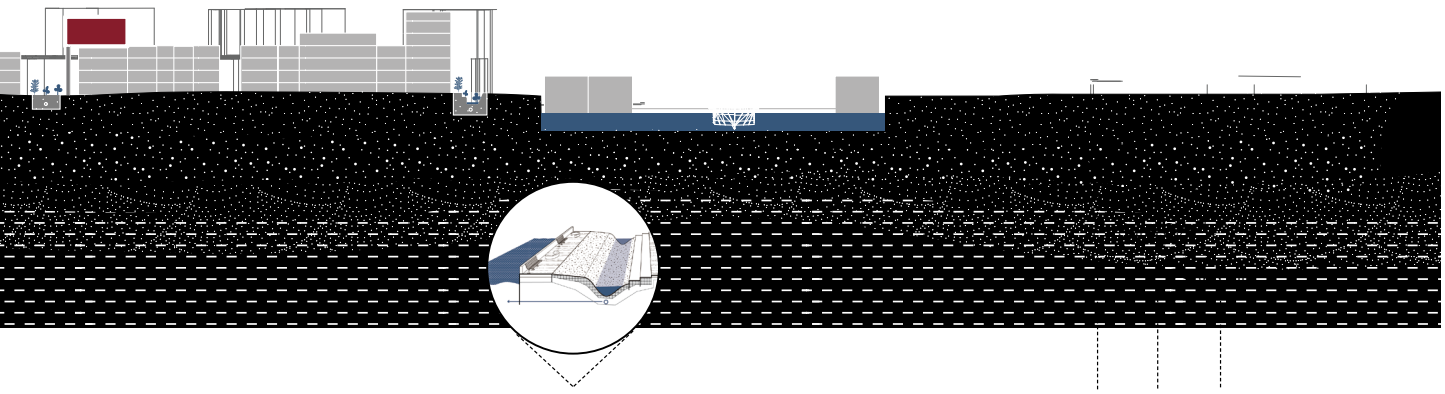


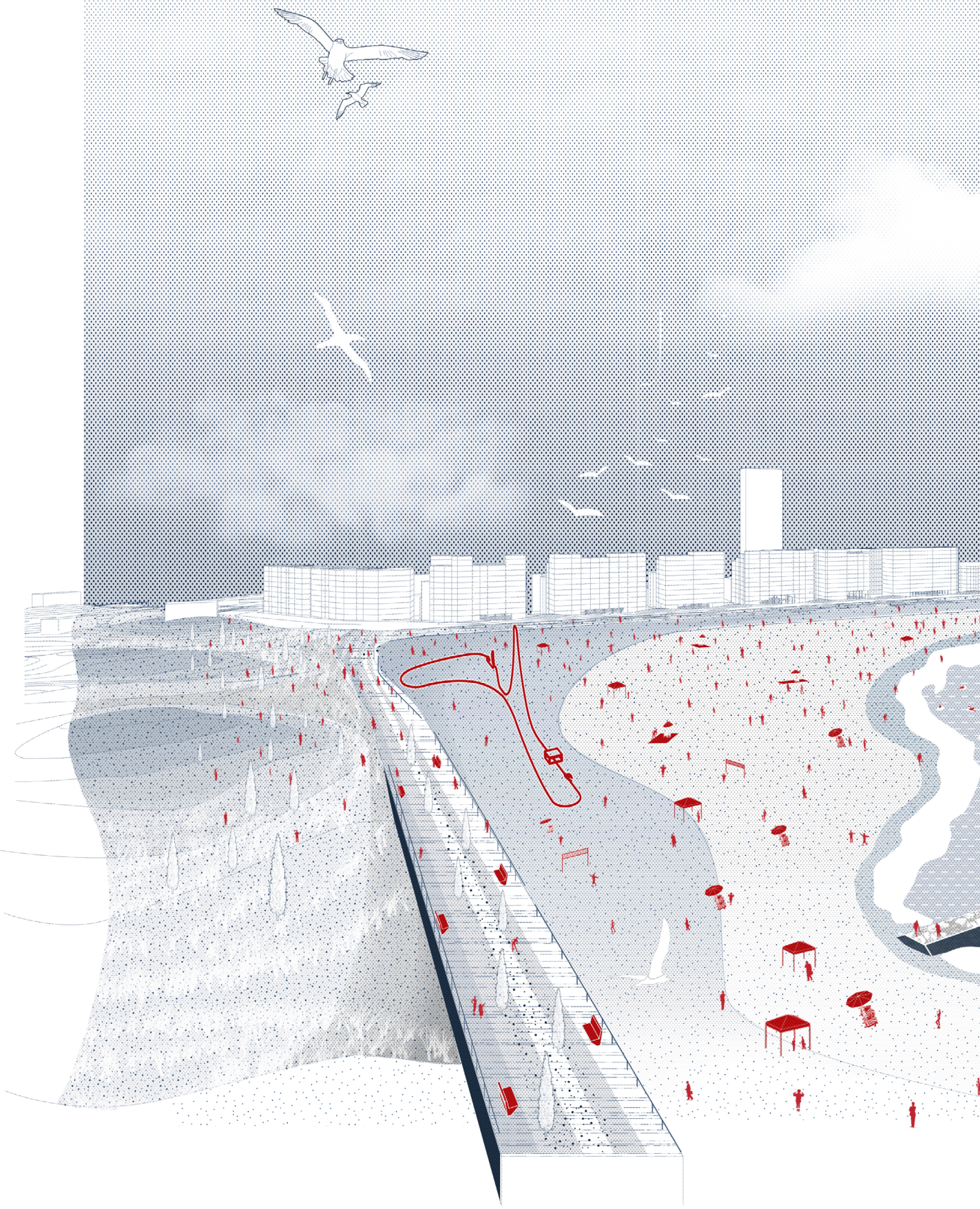
Fig.A-3 Summary section

Source: Made by author





Appendix 5: Other Drawings



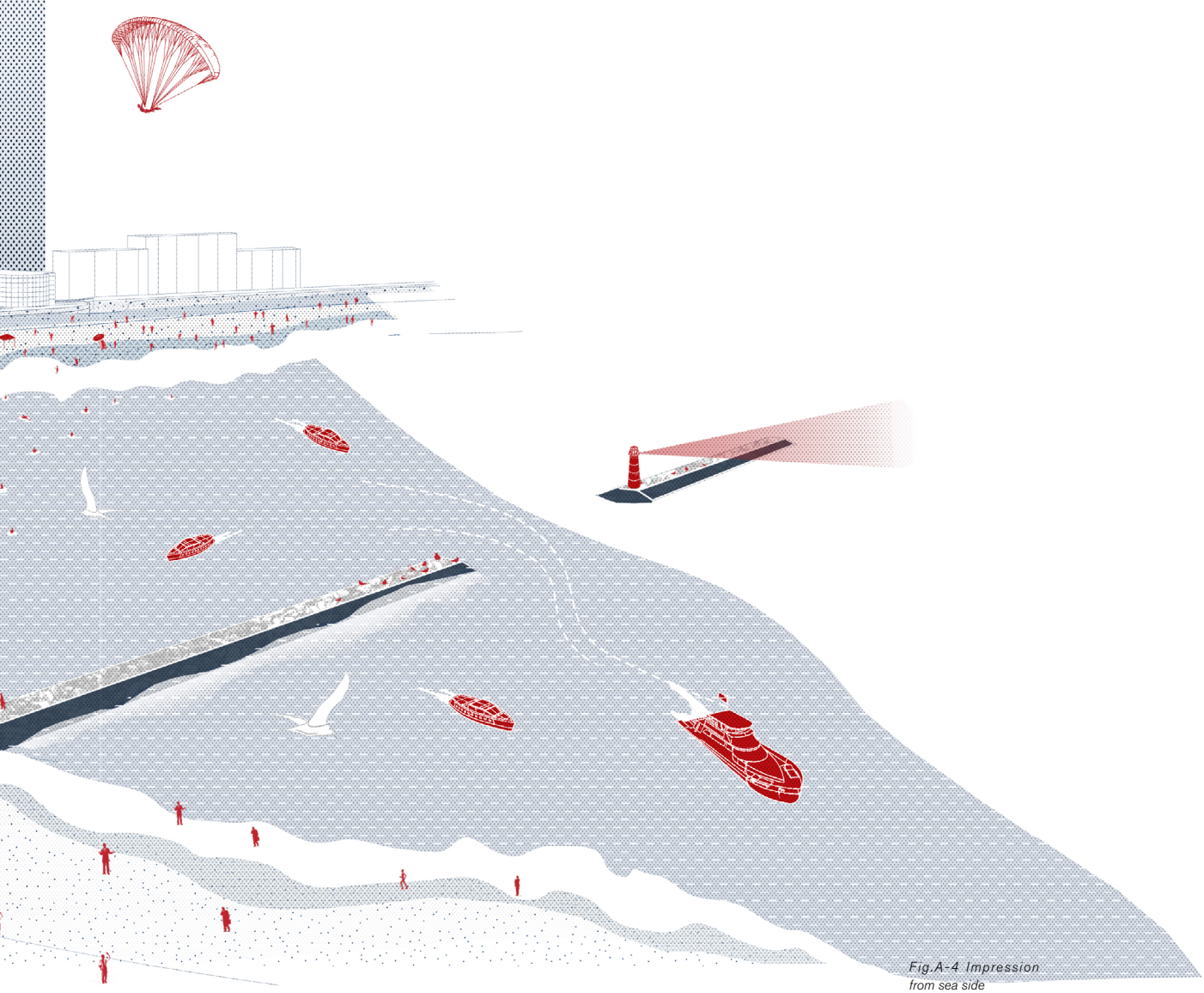


Fig.A-4 Impression from sea side

Source: Made by author

Appendix 6: Preliminary Sketch - Transitional Period

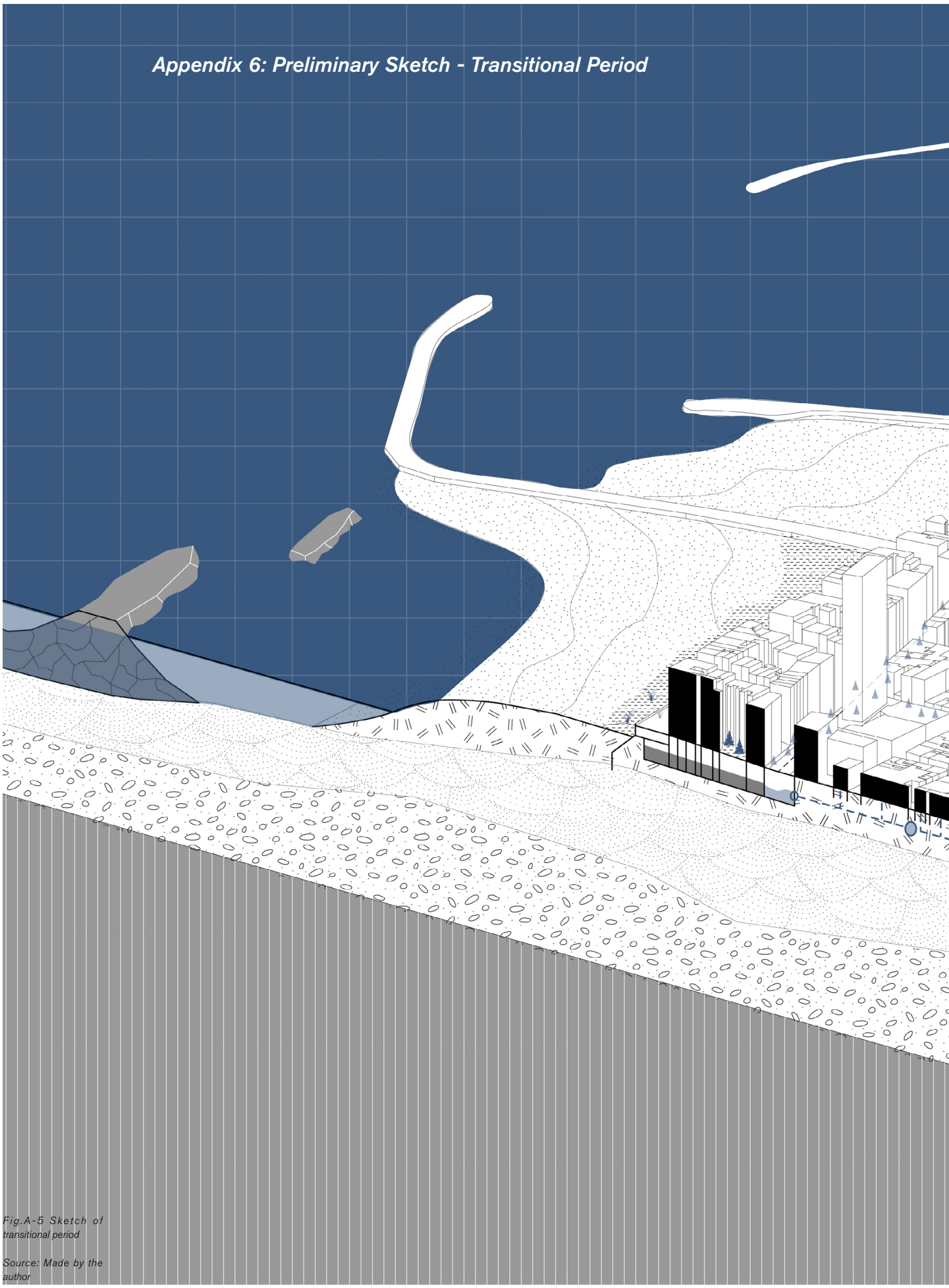
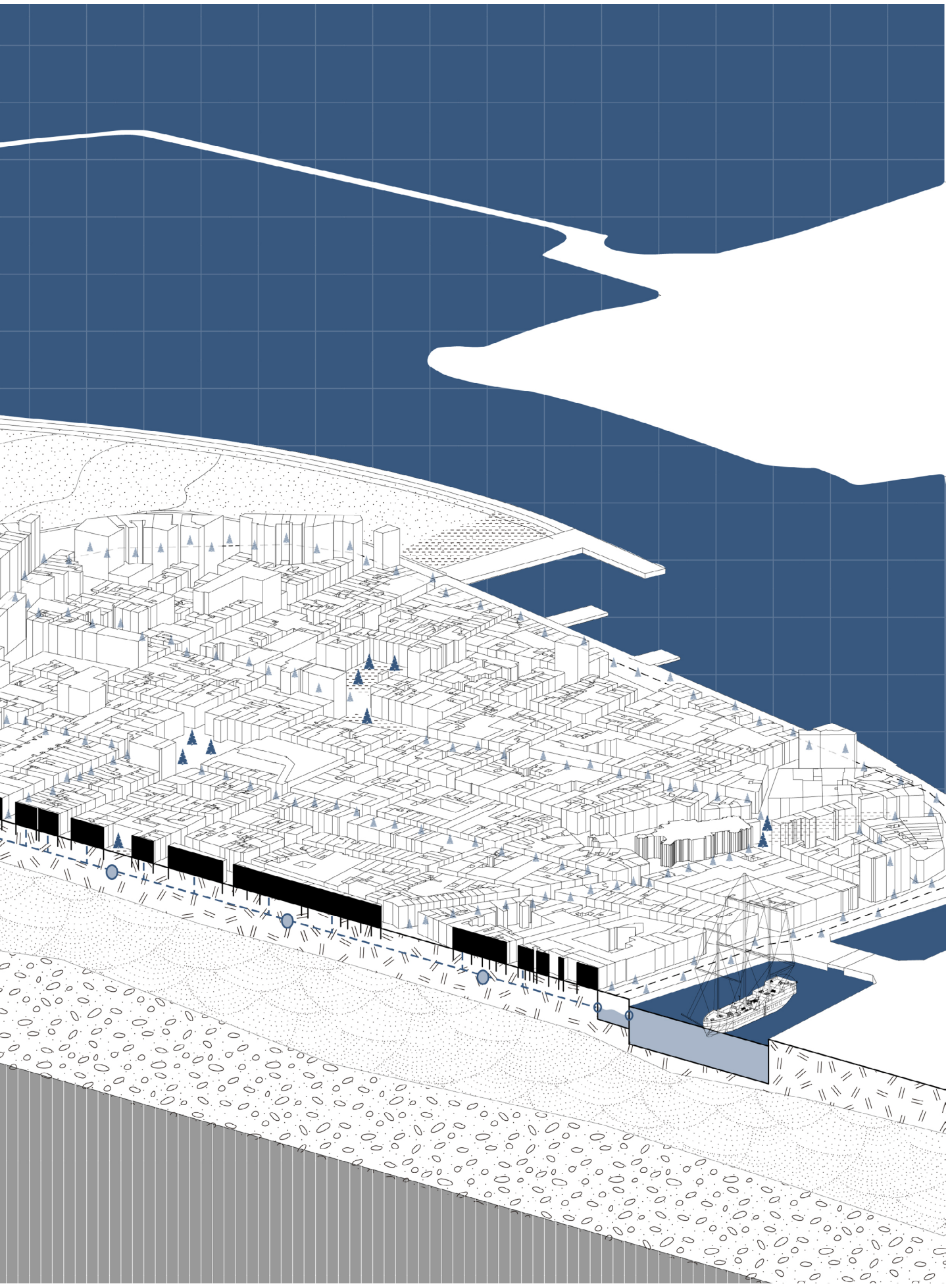


Fig.A-5 Sketch of transitional period

Source: Made by the author



Appendix 6: Preliminary Sketch - Strengthening Period

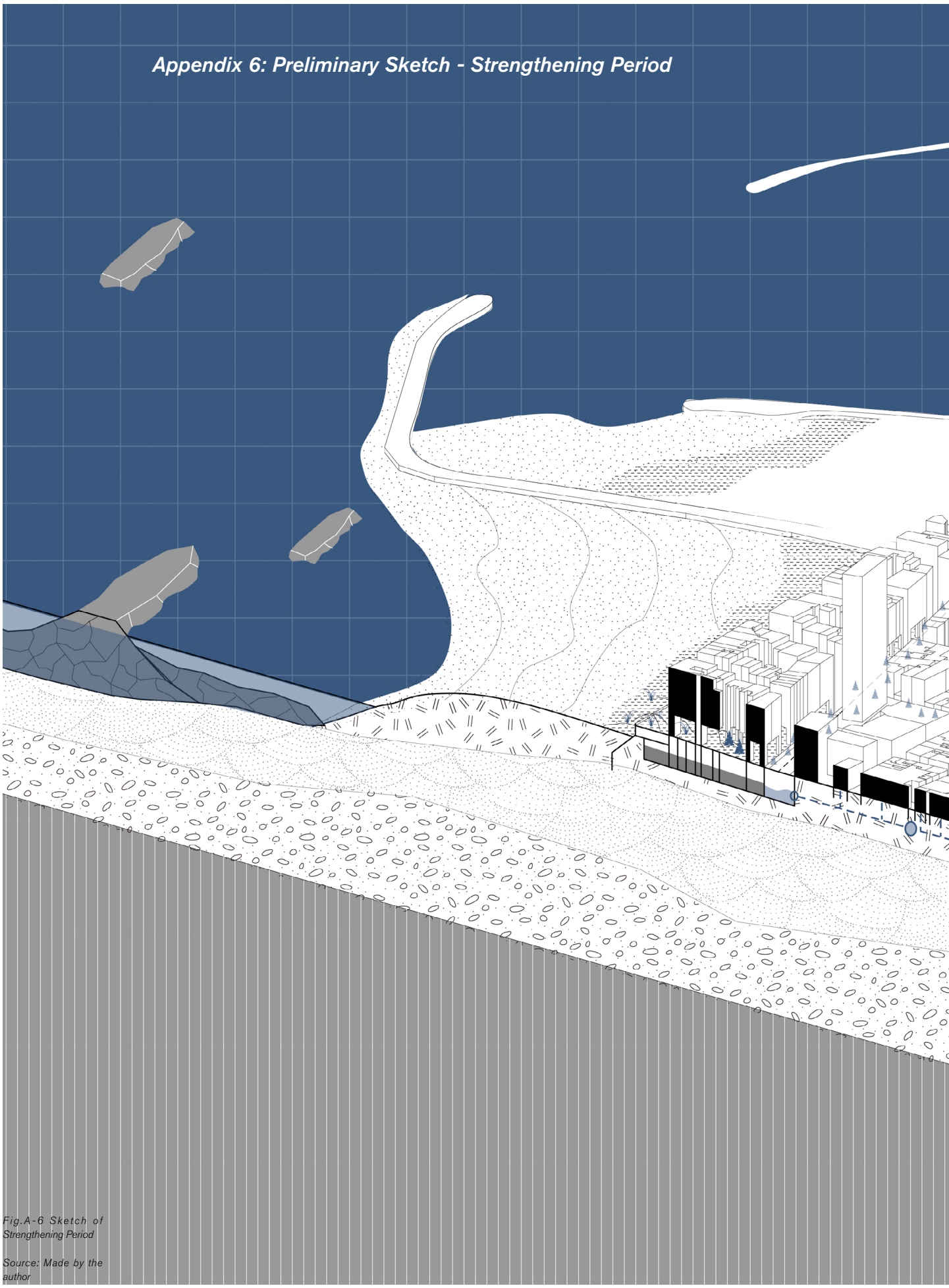
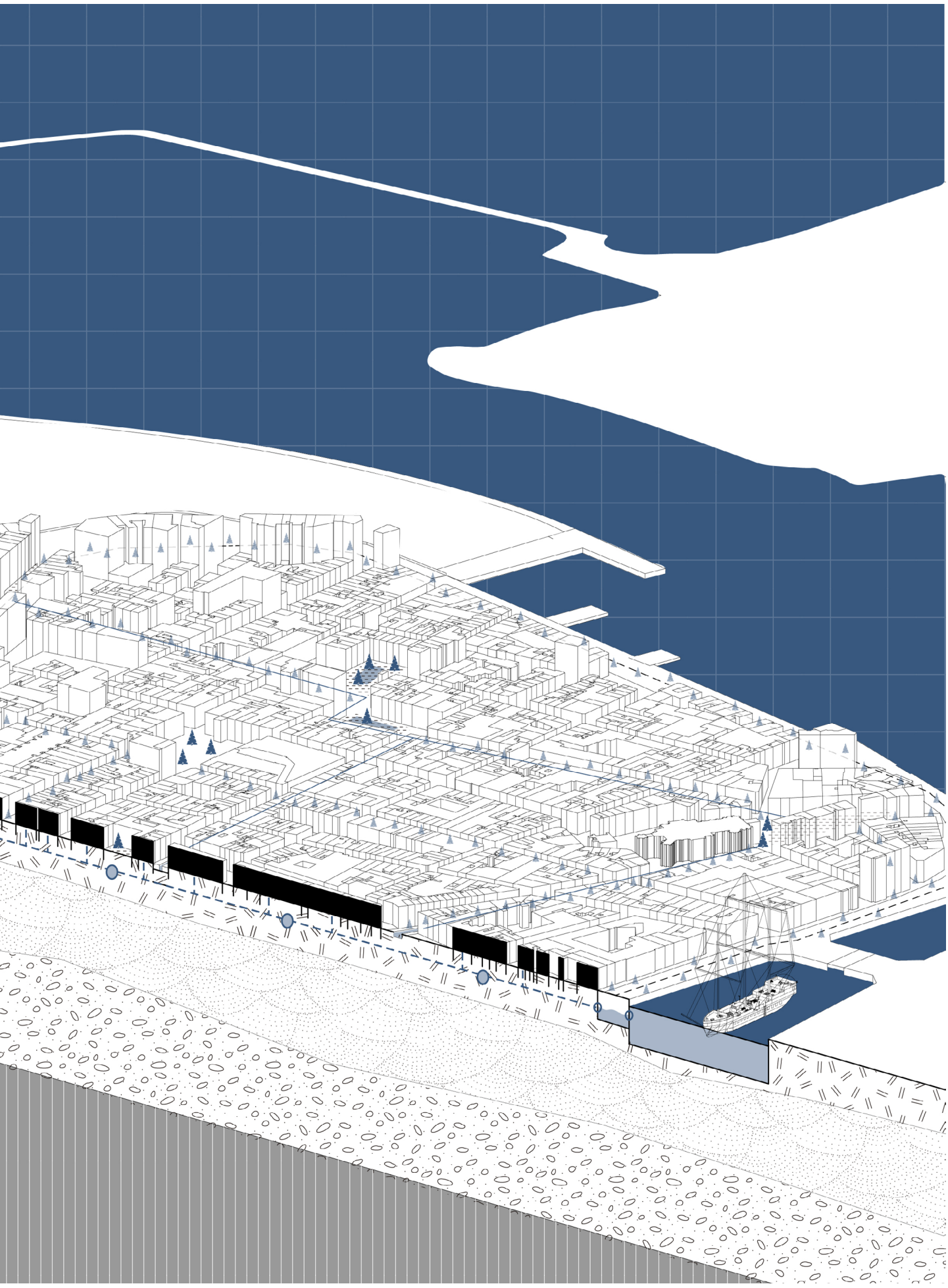


Fig.A-6 Sketch of Strengthening Period

Source: Made by the author



Appendix 6: Preliminary Sketch - Risky Period

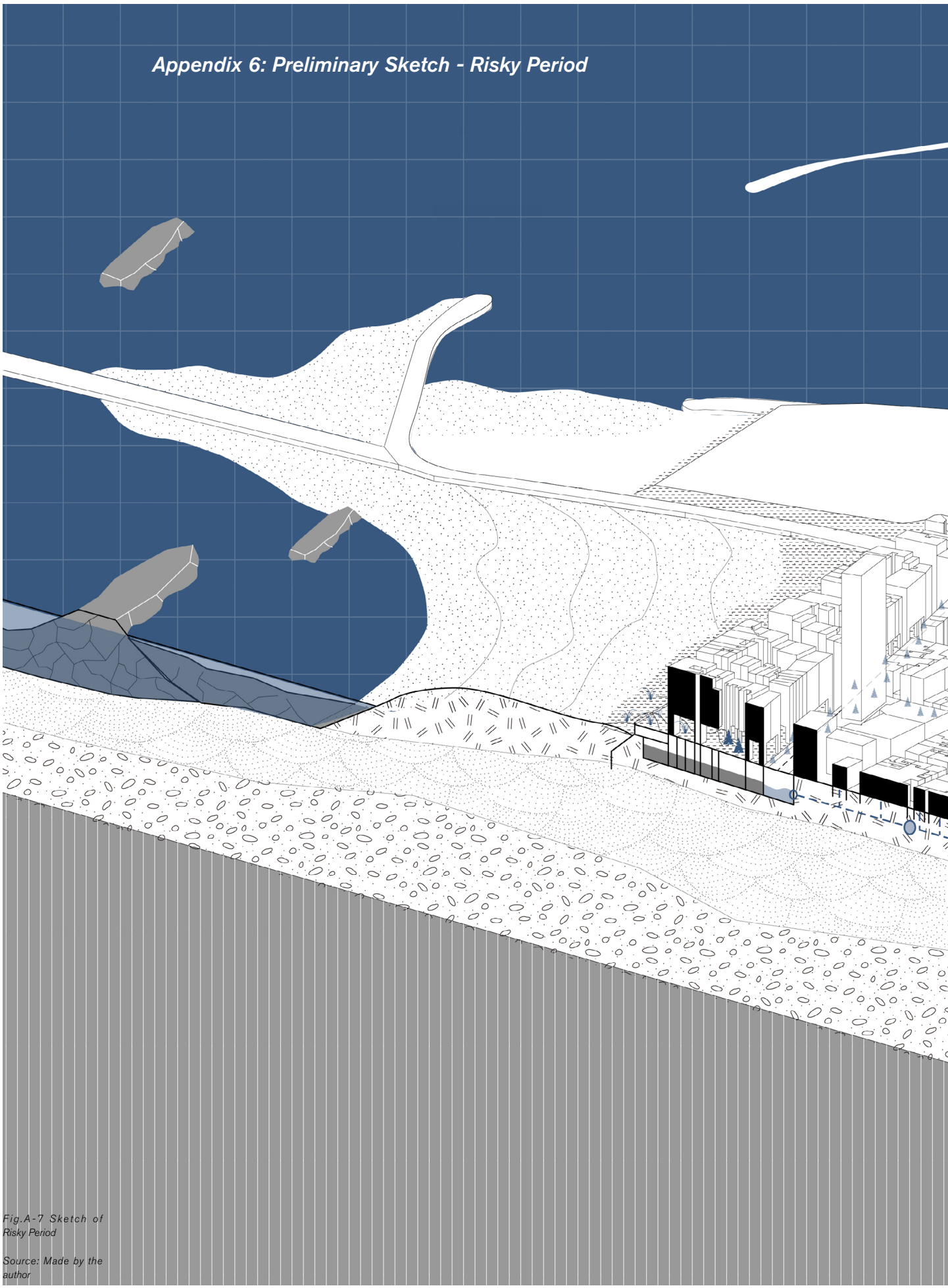
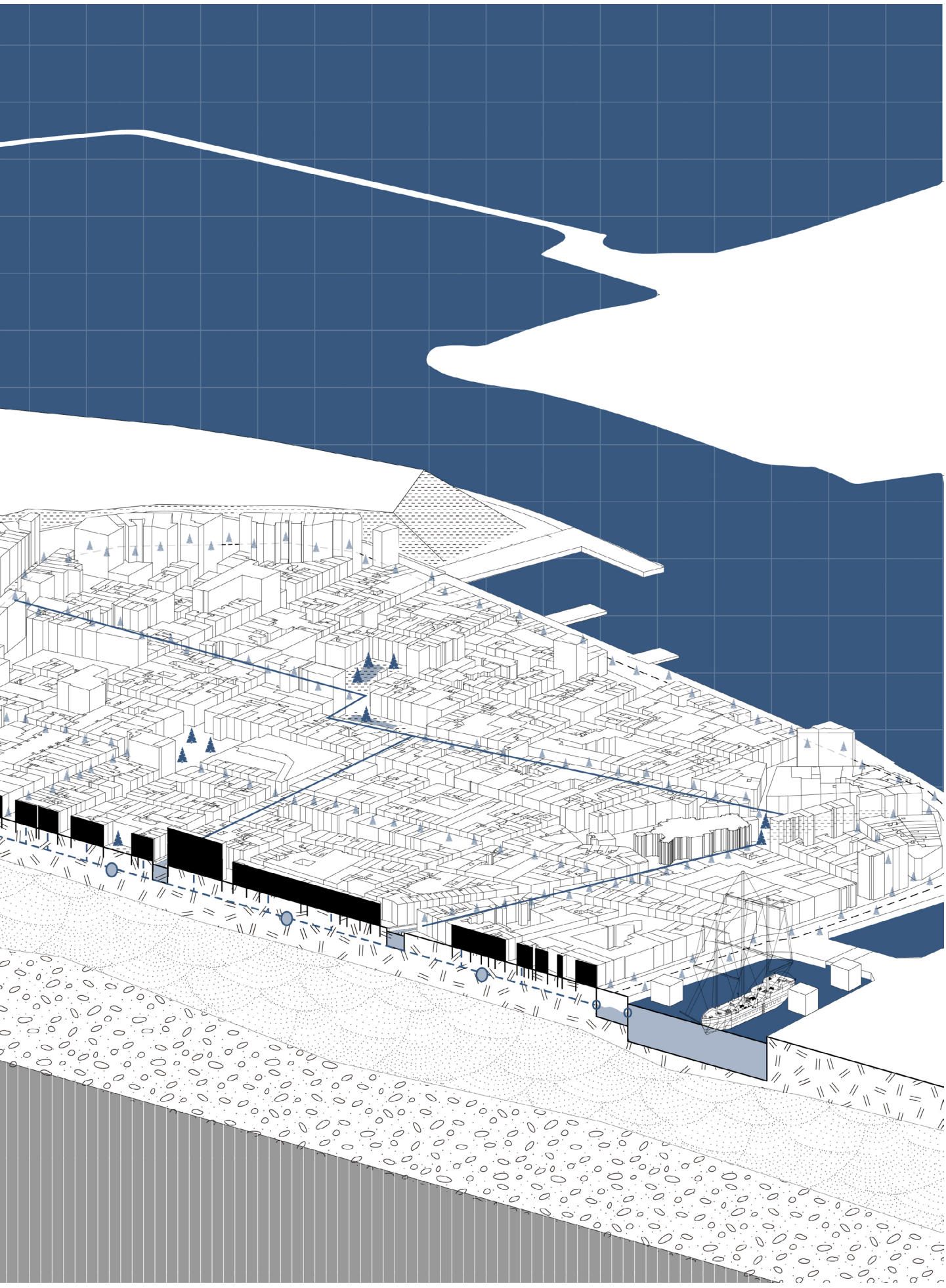


Fig.A-7 Sketch of Risky Period

Source: Made by the author



Appendix 7: Working Schedule

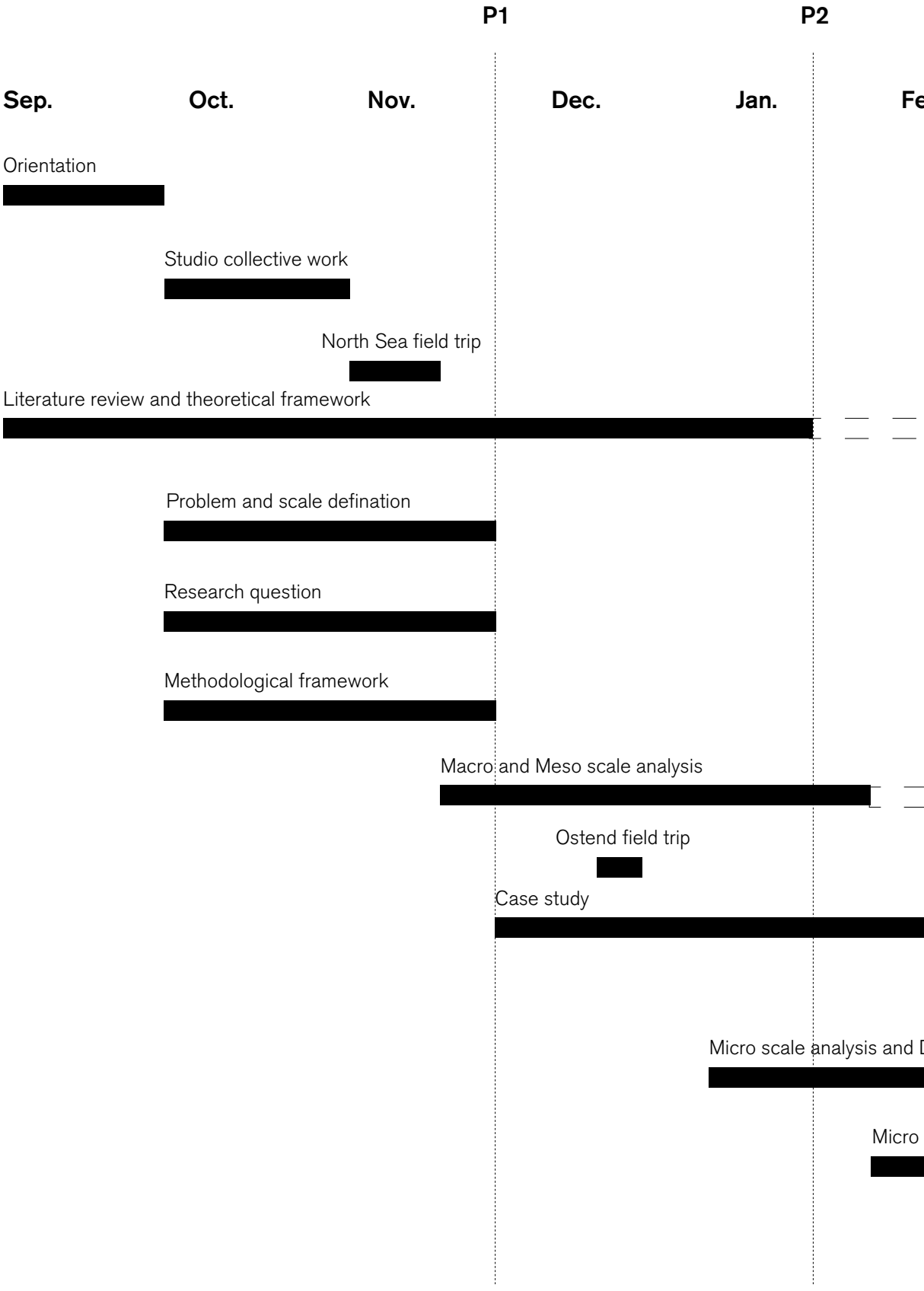


Fig.A-9 Working schedule chart

Source: made by the author


P3
P4
P5
eb.
Mar.
Apr.
May.
Jun.
Jul.
Ostend field trip
Design strategies
scale urban design
Conclusion and reflection
Design by Research

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