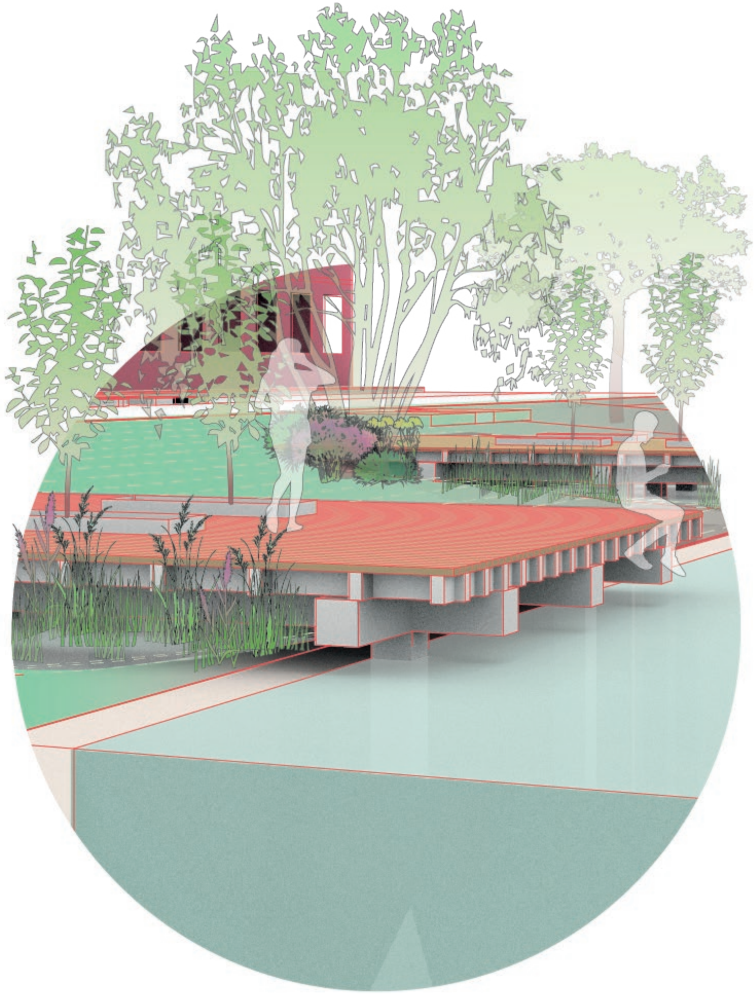
RESILIENCE BY RENOVATION:

Opportunities for nature-based climate change resilience alongside the renovation of Amsterdam's quay wall waterfronts.

Noelle Teh

MSc MADE Thesis | August 2020

This page is intentionally left blank



Nature-based solution for a quay wall waterfront in De Punt, Amsterdam.

Image credit: Noelle Teh

WAGENINGEN UNIVERSITY & RESEARCH

DELFT UNIVERSITY OF TECHNOLOGY

MASTER THESIS

RESILIENCE BY RENOVATION: Opportunities for nature-based climate change resilience alongside the renovation of Amsterdam's quay wall waterfronts.

Author:

Noelle Teh

Supervisors:

Dr.ir. MGAD (Maurice) Harteveld

Faculty of Architecture and the Built Environment

TU Delft

Dr.ir. RJA (Ron) van Lammeren

Department of Environmental Sciences

Wageningen Univeristy & Research

MSc Metropolitan Analysis, Design & Engineering

August 23, 2020

i. Acknowledgements

Over the last two years, I have been living and studying in Amsterdam and have had the opportunity to enjoy the city's web of waterfronts and experience first-hand much of what makes them such important places in this city and its imagination. These experiences would not have been possible without my mother who, with her aquatic-themed words of encouragement, has been a supporter of my wish to embark on further studies. I am also thankful for the unfailing encouragement and optimism of my husband who has picked up his life and moved it here to be with me. For the thesis itself, I would like to thank my two supervisors, Dr. Maurice Harteveld and Dr. Ron van Lammeren, whose perspectives separately and together have given me inspiration and guidance (and sometimes with much needed humour) to keep researching and thinking about how I could improve.

Finally, the process of the thesis has also benefited greatly from the generosity of Dr. Henk Wolfert who in his capacity at the AMS Institute, connected me with researchers and engineers at TU Delft and the Municipality of Amsterdam, respectively. It is from these connections that I gained insight and appreciation for the teams of researchers and practitioners who are all working towards finding ways to protect the waterfront spaces of this city. It is my hope that this thesis can go some way to adding to these efforts.

ii. Abstract

Quay walls are waterfront structures that have a simple, yet important function: separating land from water and in doing so support functions on both land and water. These functions include providing stable land for the construction of buildings, roads, and the safe movement of people on land. On the waterside, quay walls are needed for containing surface water networks, flood management, and transportation functions. Quay walls are therefore an essential infrastructure in waterfront cities with river and canal networks such as Amsterdam, capital city of the Netherlands. The ongoing renovation of 200 kilometres of Amsterdam's quay walls is an example of how age and other urban processes combine, creating a resource intensive challenge for cities to address.

The renovation of Amsterdam's quay walls will change the waterfront spaces that are so ubiquitous in the city and as the renovation continues, it is clear that there is an opportunity to also integrate new functions into the city's waterfront spaces. This thesis proposes that the renovation of quay wall structures in Amsterdam can benefit from being combined with efforts to make urban waterfront spaces more adaptive to climate change. The processes underlying quay wall renovation and climate change are analysed using three spatial scales: the city, the neighbourhood, and the waterfront. These three scales reveal how the city's waterfront spaces contain processes that take place in urban ecosystems and how "Nature-based Solutions" concepts of "Green Infrastructure" and "Ecosystem-based Adaptation" can be used to propose a solutions at the city and waterfront scale.

The results of this are combined into a list of functional requirements that are used to propose ways to improve resilience in Amsterdam's waterfront spaces. With over 90% of Amsterdam's neighbourhoods containing quay wall waterfront spaces, implementing measures to increase climate resilience alongside the walls due for renovation has the potential to reach 448 neighbourhoods and is therefore a promising way to support existing climate adaptation programmes in the city.

To demonstrate this, seven sites in the city are used to visualise how climate adaptation measures can be applied alongside the renovation of Amsterdam's quay walls to increase climate resilience. These scenarios show how measures are adapted to all stages of the quay wall renovation process and can used in a range of urban waterfront spaces in the city. Furthermore, the results show that within the different renovation types, the basic functions of waterfront spaces can be retained while increasing the provision of ecosystem services.

The strategy proposed in this thesis shows that at a minimum there is an opportunity to add 300 square kilometres of climate resilient spaces along the waterfronts of Amsterdam and in doing so increase and improve the social and ecological functions of the city now and in future. The results of this thesis show that the renovation of Amsterdam's quay wall waterfront spaces can be a vehicle for implementing a city-wide climate adaptation programme that serves two long term objectives: making the city more resilient to climate change, and extending the service lifetime of walls already built in the city.

Key words: quay wall renovation, waterfront spaces, climate change resilience, Nature-based Solutions, urban ecosystems.

This page is intentionally left blank

iii. Table of Contents

iv. Table of Figures

v. List of Tables

vi. List of Images

This page is intentionally left blank

1. INTRODUCTION

1.1. RESEARCH DEFINITION & MOTIVATION

1.1.1 Research definition

Structures to separate land and water have been built in Amsterdam since its establishment in the 16th century when it was a village upon the banks of what is now the Amstel river (Feddes & Mader, 2012). Over time, quay wall structures have become a permanent fixture of the city, tracing the city's growth in the intervening centuries to the point where now there are over 600 kilometres (Gemeente Amsterdam, 2019) of quay walls supporting the waterfronts and the functions that they provide to the city at large. This extensiveness is demonstrated in the fact that 441 of Amsterdam's 481 neighbourhoods contain quay wall waterfronts. At present, one third of these quay walls are in urgent need of renovation (Gemeente Amsterdam, 2019) to ensure that they can continue to provide safe and stable waterfronts for the city and its inhabitants. Renovating the quay walls is a resource intensive task for the municipality, requiring significant research and preparation of the affected waterfront areas in addition to the construction works required to replace the quay walls.

Although the municipality has undertaken research into the structural engineering and construction opportunities for the quay wall structure itself, less has been done on the opportunities that arise as a result of the required renovation works. The strategic inclusion of new functions and improvements to the city's waterfront spaces is a recent area of research for the Municipality of Amsterdam – the historic quay walls were built for one function but since then, these functions have multiplied together with the population of the city. This thesis proposes that the renovation is an opportunity to include new functions into the city's waterfronts spaces and specifically those that can address the negative effects of climate change and by doing so, make Amsterdam's waterfront spaces more resilient to climate change. Urban infrastructures – like waterfront spaces and their structures – can be the site of change and transformation in the city, becoming a tool for action that impacts the systems they were built for and beyond (Rutherford, 2020). The change that is being proposed is towards the approach towards the uncertainties and complexities relating to quay wall renovation and climate change in urban waterfronts. Using Amsterdam as a case study, this thesis proposes that the concepts of infrastructural and socio-ecological resilience can offer an alternative for addressing both challenges.

The research and results contained in this thesis are thematically related to current research and innovation programmes that are being developed together with the AMS Institute and TU Delft (refer *Figure 1.1*), adding to research being undertaken for 'Lifespan extension'

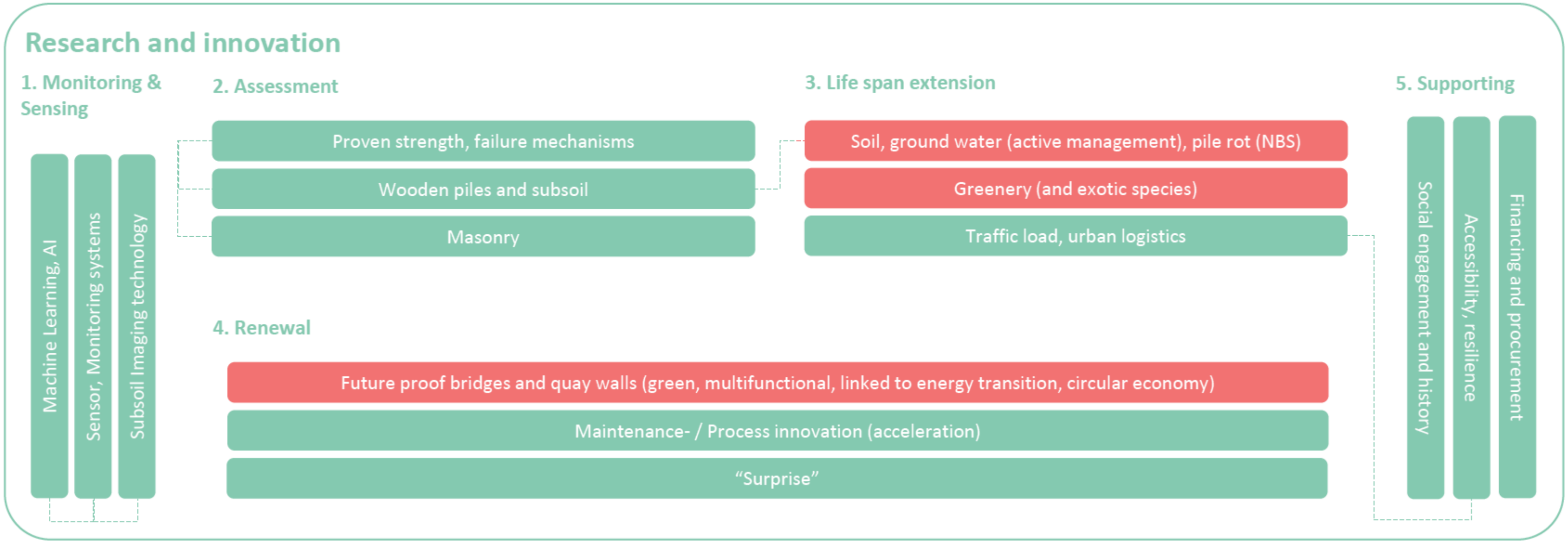


Figure 1.1. Draft research and innovation themes between the AMS Institute and the Municipality of Amsterdam. Image credit: Henk Wolfert, 2020.

and 'Renewal' topics. Within these two research topics are themes relating to this research on the natural processes that occur in quay wall waterfront spaces: soil, groundwater, green spaces, and ways of future-proofing the quay walls together with city-wide sustainability initiatives. These themes set in *Figure 1.1.* show that there is a need for more knowledge into how measures to make waterfront spaces more climate resilient can be a part of - and potentially support - the quay wall renovation process in parallel to existing initiatives by the municipality to address climate change adaptation.

1.1.2 Motivation

Image 1.1 Oudezijds Achterburgwal during renovation of the quay wall sturcture. Image credit: NRC.nl

The principal motivation of this thesis is to research the possibility and opportunity of combining the climate adaptation measures alongside the renovation of quay walls and especially so in cities that are "waterfront cities". Amsterdam is a city that is both waterfront in nature (and culture) and is currently facing the challenge of renovating its quay wall structures alongside allocating resources to address the pronounced local effects of climate change. The reason for choosing these challenges is that upon witnessing the renovation works that have taken place in the city (refer *Images 1.1 & 1.2*) it is clear that the renovation is of the waterfront space as a whole (i.e. from quay wall to building façade) and as such presents an opportunity for urban researchers and practitioners to use this as an opportunity to explore what other urban challenges can be addressed in the city's waterfront spaces.

Image 1.2 Oudezijds Achterburgwal after renovation with new wall, footpath, and trees. Image credit: Noelle Teh.

The second motivation for the research conducted for this thesis is to learn more about "Nature-based Solutions" (NBS) as an approach that contains inter- and transdisciplinary approaches for urban researchers and practitioners to design solutions for urban challenges. Specifically, which NBS concepts and practical precedents can be applied to urban challenges as specific as the renovation of the quay walls and also as complex and general as climate change. As a relatively recent approach, there is a small but growing body of research about NBS concepts, frameworks, and techniques that can be used to reflect upon what, if any, differences there would be to conventional approaches towards the same research topic and these reflections are contained in the discussion.

1.2. RESEARCH OBJECTIVES AND QUESTIONS

The objectives of the research are summarised in *Figure 1.2* which illustrates how the two urban problems – quay wall renovation and climate change effects – can be addressed in one solution that is a product of the shared variables in both problems.

The objectives of the research and their corresponding research questions are as follows:

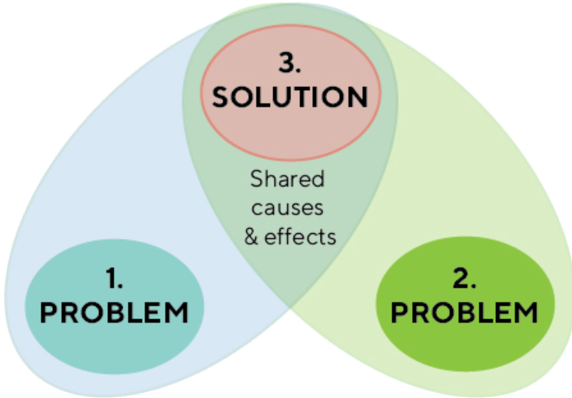


Figure 1.2. Abductive research approach. Image credit: Noelle Teh

Objective 1:	Identify why and how the quay wall renovation affects quay wall waterfront spaces in Amsterdam and how the form and function of waterfront spaces affects the processes that cause the quay walls to be renovated.	**RQ1: Why and how have the quay walls in Amsterdam been renovated and what can be done within waterfront spaces to delay wall replacement?**
Objective 2:	Identify how climate change affects quay wall waterfront spaces in Amsterdam and what opportunities exist to address climate change alongside the renovation of the quay walls.	**RQ2: How does climate change affect Amsterdam's waterfront spaces and how can addressing climate change be combined with the renovation of quay wall waterfront spaces?**
Objective 3:	Explore how a "Nature-based Solutions" approach can be taken to designing measures to make quay wall waterfront spaces resilient to climate change while also reducing the impact of processes that cause quay wall replacement.	**RQ3: What Nature-based Solutions concepts can be applied to increase climate resilience in Amsterdam's quay wall waterfront spaces while also delaying quay wall replacement?**
Objective 4:	Measure and assess the spatial impacts of an NBS approach to climate resilient measures alongside the renovation of quay wall waterfront.	**RQ4: What are the spatial opportunities and limitations of using a Nature-based Solutions approach to increase resilience alongside the renovation of Amsterdam's quay wall waterfront spaces?**

1.3. RESEARCH SCOPE

The scope of this research is as follows:

- The geographic scope is limited to the Municipality of Amsterdam's administrative boundary and the boundaries used by the municipality for neighbourhoods.
- The quay wall waterfronts are limited to those that are registered as wall elements in the *'basisregistratie grootschalige topografie'* (BGT) and that fall within the municipal boundaries of the city.
- Solutions arising from the research do not include structural engineering or similar calculations nor recommendations – structural ideas are architectural in nature and therefore explore concepts of the wall rather than the construction of it in practice.
- Stakeholder analysis not included in the research, but specific stakeholders are mentioned for the purposes of summarising how they affect the processes and functions in quay wall waterfront spaces.
- The timespan for the proposed solutions is limited to the year 2050 and is based on the year limit for climate predictions from the KNMI (2014).

1.4. SOCETIAL RELEVANCE

The results of this research are contemporaneous with the renovation of Amsterdam's quay walls and it is intended that the findings can be used to add to the sharing of knowledge between research institutes and the municipality with respect to the quay wall renovation and strategic benefit of incorporating climate adaptation measures. Additionally, it is hoped that the results of this thesis can add to the growing interest and research being undertaken into "Nature-based Solutions" as a viable approach to typically "engineering-focused" urban challenges - such e.g. renovating of quay wall waterfronts - that could potentially benefit from interdisciplinary perspectives.

The societal relevance of the research topic is evidenced in the proliferation of news articles about the renovation of Amsterdam's quay walls. The topic is inescapable on most local and international news platforms (refer *Image 1.3*) with coverage ranging from the matter-of-fact to opinion pieces – but unified in their concern for the causes and effects of the quay wall renovation on the city.

The design proposals contained in this thesis hope to contribute to discussions on the opportunities arising from renovation. Additionally, the visualisation act as a visual aid for promoting discussions and debate about the strategic benefits that can be had in waterfront spaces alongside the quay wall renovation process.

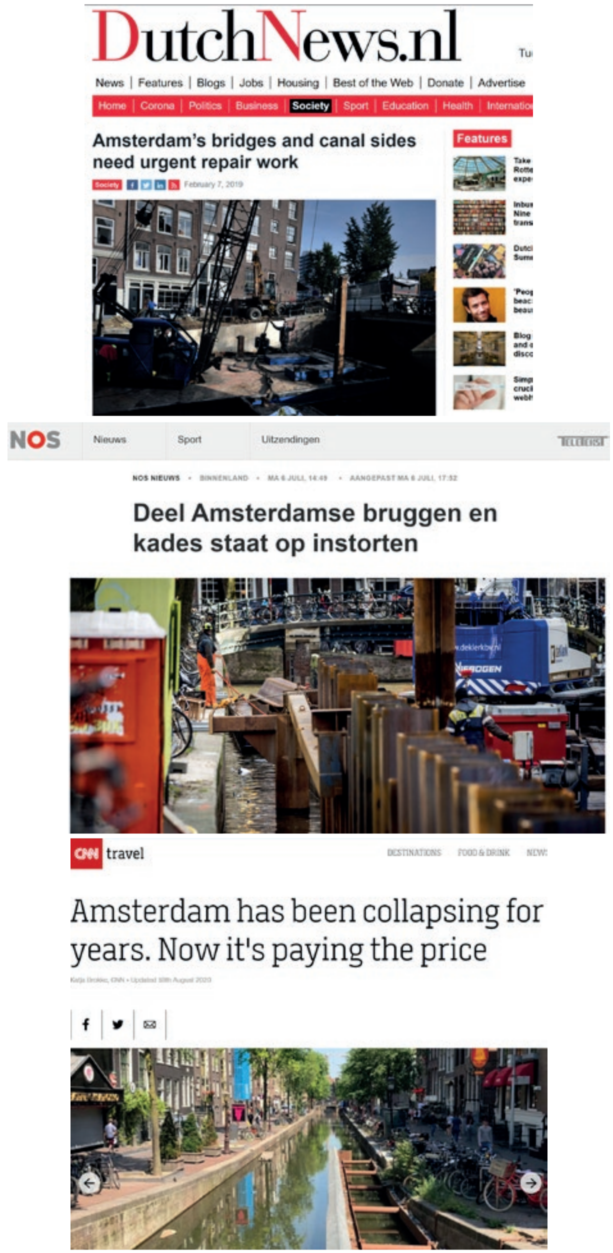


Image 1.3 Local and international news outlets covering the quay wall renovation in Amsterdam. Image credits: Dutchnews.nl, NOS.nl, CNN Travel.

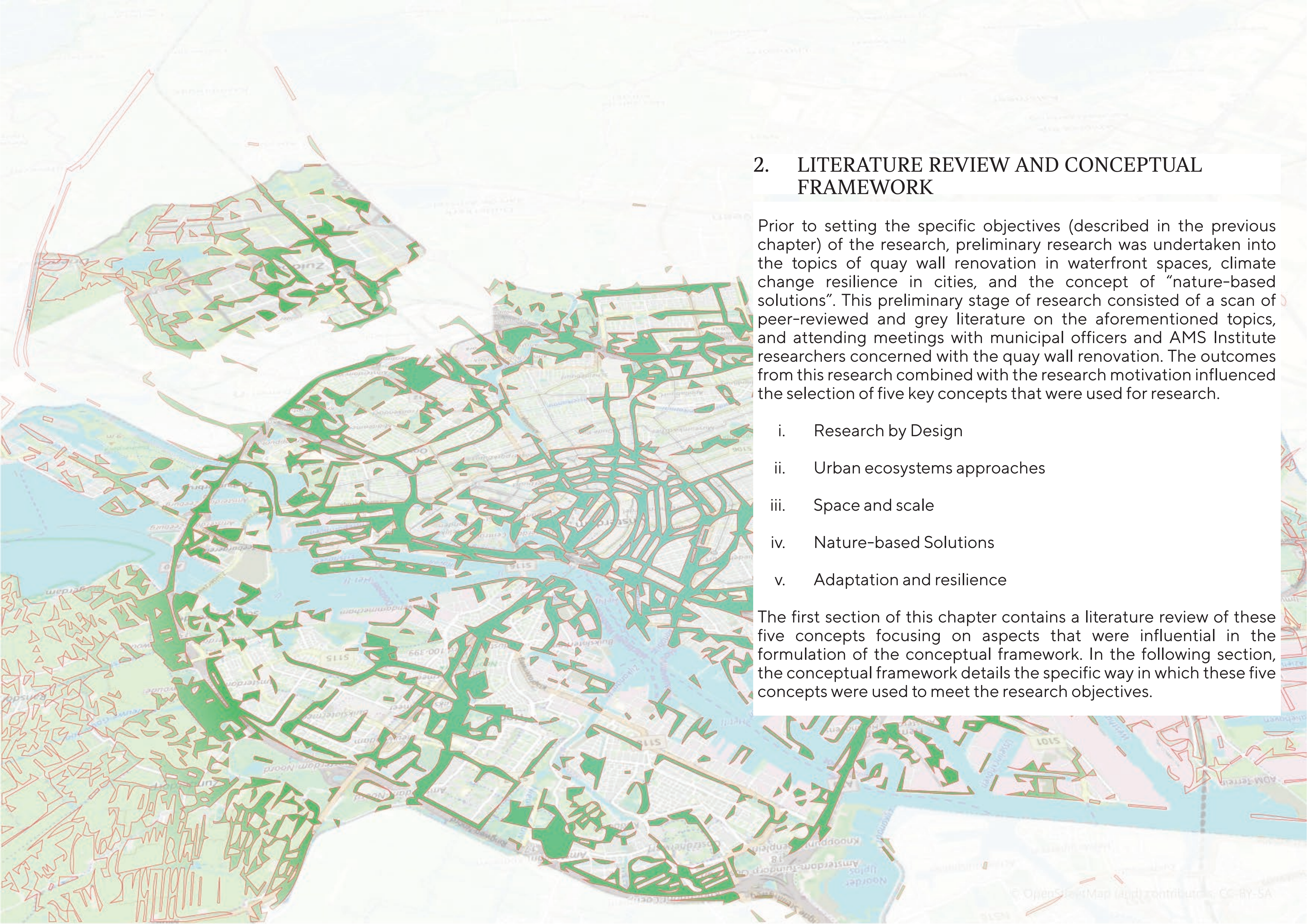
1.5. READING GUIDE

This thesis is conventionally structured with a literature review and conceptual framework (Chapter 2) preceding the materials and methodology (Chapter 3), results (Chapters 4-6), conclusion (Chapter 7), and discussion (Chapter 8) chapters.

In Chapter 2 the key terms and their conceptual background and relationship to existing fields of research are discussed in the literature review. The conceptual framework in the same chapter contains how these terms and concepts have been used specifically for this research. Chapter 3 continues to provide background into the specific materials and methods used for the research and this is done in the sequence of when the research questions are addressed.

Chapters 4 and 5 contain the analysis and synthesis of the two research problems: quay wall renovation and climate change effects, respectively. From the findings and recommendations of Chapters 4 and 5, Chapter 6 contains the solution proposals with further elaboration on the specific NBS concepts that were used and how they apply to the scales of the city and street.

Finally, Chapters 7 and 8 reaffirm the results of the research with respect to the objectives of the thesis followed by a short discussion on limitations and opportunities arising from the research results. The appendix containing relevant materials for the reader follows these chapters and following this are the references for all cited literature.



2. LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

Prior to setting the specific objectives (described in the previous chapter) of the research, preliminary research was undertaken into the topics of quay wall renovation in waterfront spaces, climate change resilience in cities, and the concept of "nature-based solutions". This preliminary stage of research consisted of a scan of peer-reviewed and grey literature on the aforementioned topics, and attending meetings with municipal officers and AMS Institute researchers concerned with the quay wall renovation. The outcomes from this research combined with the research motivation influenced the selection of five key concepts that were used for research.

i. Research by Design

ii. Urban ecosystems approaches

iii. Space and scale

iv. Nature-based Solutions

v. Adaptation and resilience

The first section of this chapter contains a literature review of these five concepts focusing on aspects that were influential in the formulation of the conceptual framework. In the following section, the conceptual framework details the specific way in which these five concepts were used to meet the research objectives.

2.1. LITERATURE REVIEW

2.1.1 Research by design

As stated previously, the research is motivated by the use of a "Nature-based Solutions" approach which preferences a solution- and design-driven approach to the research. As such, this section starts with a brief overview on "research by design" which in itself is not a concept, but as a method of research influences the perspective taken to the concepts used in the research. The main influence being that the research is goal-oriented using processes of abduction to propose possible solutions to the research problem (Brink, Bruns, Tobi, & Bell, 2017; Cross, 2006). As a result, the concepts used in this thesis were selected in a pragmatic way for the identification of possible solution pathways. The literature used for the research predominantly originates from the fields of architecture and design studies where the method itself is a topic of ongoing research and debate – as such, the use of the term in this concept is based on established literature and general terms.

A research by design methodology is a heuristic technique characterised by having a pragmatic approach to problem solving and to do so, explores possible solutions using a variety of methods to reach pragmatic solutions that are defined in "more-or-less" terms (Cross, 2006; Nijhuis, 2020; Roggema, 2016). It is a method that is well suited to complex – or "wicked" – problems such as those found in urban settings where interests, values, and systems overlap and where there is uncertainty and no catch-all solution to be had (Roggema, 2016). In this approach, knowledge is created through the analysis of data, and design methods are used to invent possible solutions which address the objectives of the research (Nijhuis, 2020). The resulting solutions can then be reflected upon or analysed further, possibly generating more research questions as a result.

Research by design is not dissimilar to the empirical research cycle whereby the design task, analysis, generation of schemes, models, and the resulting design are no different to stating a research problem, conducting analysis, generating possible testable answers, and formulation of a hypothesis (Brink et al., 2017, p. 57). Because designing relates to empirical data, the challenge is in producing results that are replicable and especially so when the research is situated in the 'living laboratory' of the city where research conditions cannot be controlled. A way to counteract this is in providing sufficient detail of the materials and methods used for the research so that the same process may be repeated, and results compared.

2.1.2 Ecosystem Approach and Urban Ecosystems

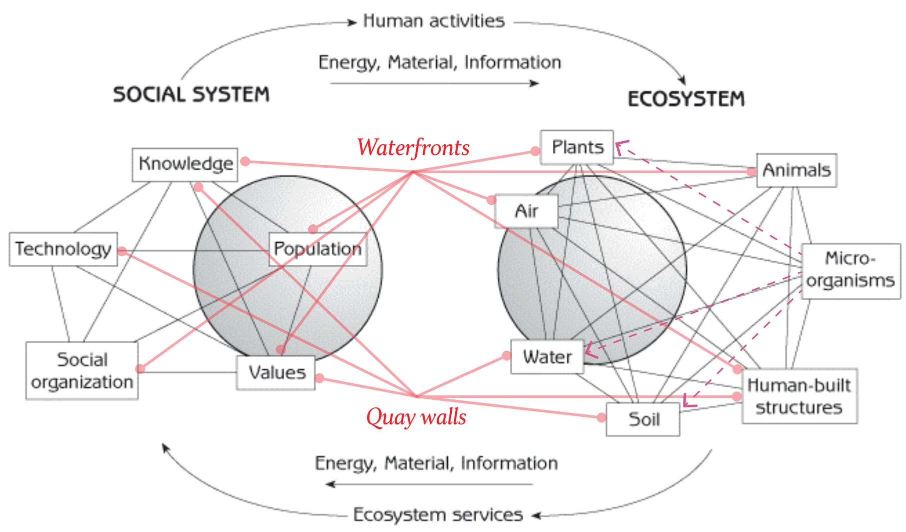
In particular, the urban challenges selected for this design-driven research are inter- and transdisciplinary in nature and are therefore complex or "wicked" as has been mentioned previously. An Ecosystem Approach helps to frame and explain the inter- and transdisciplinarity of the NBS approach which has been selected due to its application to similar urban challenges. Although the Ecosystem Approach originates in the natural sciences rather than engineering or design sciences, the approach has been widely adopted by various fields of research and this is reflected in the literature that was used for this thesis.

The literature used for this thesis was generally the product of interdisciplinary research performed between the fields of natural and earth sciences, urban studies, and innovation studies. Because of the concept's foundations in the natural sciences many of the terms and process descriptions have become similes and is useful for simplifying (at the risk of reductivism) processes in the city.

The Ecosystem Approach is defined by the Convention on Biological Diversity (CBD) as "a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way" (CBD, 2010). As an approach, it is a way to understand (and manipulate) the complexity of cities by conceptualising cities as urban ecosystem in which structures, processes, functions and interactions between organisms in their environment and the role of humans in affecting urban ecosystems (CBD, 2010; Richter, Xu, & Wilcox, 2015).

Using the term "urban" in context to ecosystems requires further definition to provide the specificity that Nilon et al (2003) recommends is needed with respect to the political, social, and economic context that it is being applied to. In the context of this thesis, "urban" is a definition influenced by four variables: administrative status, population and population density, land-use functions, and provision of public infrastructure: the "urban" is a geographically defined administrative unit that contains high numbers and densities of people

Figure 2.1. Cities as a socio-ecological system. Image credit: adapted from Yigitcanlar & Dizdaroglu, 2015.



living in close proximity to diverse land-use functions and intersecting networks of public infrastructures.

In urban areas including the quay wall waterfronts, the interactions between social systems and ecosystems are more visible and can be understood as a continuous loop of energy, material, and information that changes as alongside the changing interactions between people and their natural environment (Davoudi & Sturzaker, 2017; Yigitcanlar & Dizdaroglu, 2015). A socio-ecological approach is used to understand urban ecosystems as a loop of processes and complex interactions that typically take place between the systems rather than being restricted only to one. *Figure 2.1* adapts from Yigitcanlar & Dizdaroglu (2015) and illustrates how, in waterfront spaces, the social system and the ecosystem do not operate independently to each other. Additionally, a socio-ecological approach is characterised by its uncertainty and change (Chapin et al., 2010), which makes it appropriate for analysing urban processes that are also constantly under change and uncertainty, especially in an age of climate change and the depletion of natural resources.

A socio-ecological approach is therefore useful to adopt towards urban ecosystems and the research objectives also has the benefit of limiting the potential for fixating on the properties of individual parts and is beneficial for creating solutions that, according to Keesstra et al (2018) can anticipate effects to the whole system allowing for insight into the possible consequences – good and bad – of a particular action.

However, using an Ecosystem Approaches for the research has its pitfalls and these tend to be related to the concept's broad and interdisciplinary perspective that, as observed by the CBD (2009b) and Richter et al (2015), tend to lack propositions for practical solution instead valuing the rigorous analysis of relations and processes in systems. This risk of "analysis paralysis" is somewhat reduced due to the goal-oriented research objectives and by using the concept of the urban ecosystem which is supported by proponents like Nilon et al (2003) and van Bueren (2012) who recommend it as an effective way to find and organise information that can then be used to solve problems in the city.

2.1.3 Space and scale

Arising from the concept of the city as an urban ecosystem comprised of multiple interactions and parts, are the concepts of "space" and "scale", both of which serve as a conceptual tool for ordering the ideas and processes that take place in urban ecosystems. Space and scale are concepts that appeared in literature originating from the fields of urban studies, engineering and planning. In addition to these fields, the paper from Coenen et al. (2012) was also useful for connecting the concepts of space and scale to the research coming from the fields of innovation and transitions studies.

"Space" and its use in this thesis is a shorthand used to refer to a particular site and when prefixed with terms like "urban" or "waterfront", it denotes the boundaries where different system processes take place and are observed. Space in the urban ecosystem is a telescopic concept, used as a frame to analyse certain processes in the city in context to where they happen spatially and how this affects the form and function of the city for humans.

Additionally, the term "space" adopts a socio-spatial perspective in which the physical site is where social and physical processes take place, affecting each other as a result also affecting the space. The benefit of considering the socio-spatial dynamics of a space, is that it is possible to take an "inside-out"– rather than the conventional "outside-in" (Levin-Keitel, Mölders, Othengrafen, & Ibendorf, 2018) – approach to how changes in space can affect the city and its systems. Additionally, when spaces are considered together with their social meaning it becomes apparent that they are a resource and as such is finite and requires management and planning.

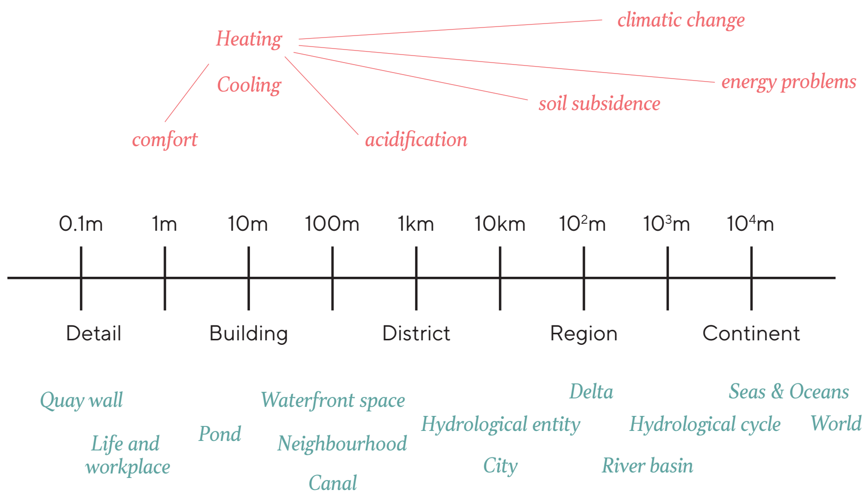


Figure 2.2. Space and scale in understanding urban ecosystems and their processes. Diagram from Duijvestein in van Bueren, 2012.

Next, the concept of "scale" is an important part of analysing the causes and consequences of urban processes because at different scales, processes and problems can be analysed and acted upon very differently depending on the scales that they are being analysed. The importance of scale in the urban context is summarised by van Bueren (2012) who emphasises the necessity of scales as a way to bring order to analysing urban challenges and adding context to the system they occur in. *Figure 2.2.* illustrates how waterfront spaces are comprised of objects and processes that take place at different scales and in relationship to climate-related challenges.

This ordering effect of scale as a concept is also useful for understanding how different scales of space are also subject to different time-scales (Levin-Keitel et al., 2018). Knowing how space is affected by time is also required to analyse how different urban processes interact with each other – e.g. diurnal heat release in cities or the slow process of subsidence.

The need to define concepts of space and scale is due to the multiple meanings that these terms can have depending on the educational background of the reader. Space and scale as combined concepts are necessary for the process and product of this research because the scale of the analysis takes place at the same scale as the solution (van Bueren, 2012; Yigitcanlar & Dizdaroglu, 2015). This reinforces the importance of their inclusion to avoid the "spatial blindness" that has been identified by Coenen et al (2012) and Levin-Keitel et al (2018) who observe that the relevance of space to climate adaptation measures and other sustainability-focused innovations tends to be overlooked.

2.1.4 Nature-based Solutions

The objectives of the research are met by using a "Nature-based Solutions" approach which is applied to the spaces and scales of the quay wall waterfront and by the Ecosystem Approach that has been adopted. By taking this approach it allows for the exploration of solutions which also address climate change alongside the renovation of Amsterdam's quay wall waterfront spaces.

"Nature-based Solutions" (NBS) is a concept and approach that has been created and researched as a solution-focused concept under the conceptual umbrella of the Ecosystem Approach (Cohen-Shacham et al., 2019). It is a comparatively recent concept with most of the peer-reviewed literature pertaining to it dating back to the mid-2010s when it first appeared in reports by the EU Commission and the International Union for the Conservation of Nature (IUCN). Since then, most of the literature about NBS as an approach has been generated from the research fields of environmental research, conservation, geography, transitions, urban studies, and transitions and is focused predominantly on aspects of implementation and assessment of the NBS approach as a way to critically analyse the concept and its utility to researchers and practitioners. It is notable that most of the literature appears to come from Europe despite the claims to global application from its proponents.

Nature-based solutions (NBS) is a solution-focused approach that promotes the use of inter- and transdisciplinary methods and approaches for integrating nature and natural processes in the planning, design, and execution of actions to address societal challenges (Kabisch, Korn, Stadler, & Bonn, 2017).Nature-based solutions (NBS) is a concept used in environmental management and research and conceptually is a solution focused extension of the Ecosystem Approach (Nesshöver et al., 2017; Raymond et al., 2017). There are two main definitions of NBS referred to in the literature used for this thesis. The first is the definition (IUCN, 2016, p. xii) by the International Union for the Conservation of Nature (IUCN) is:

"...actions to protect, sustain, manage, and restore natural or modified ecosystems, which address societal challenges effectively and adaptively while simultaneously providing human well-being and biodiversity benefits"

And secondly the definition (EU Commission, 2015, p. 4) offered and adopted by the EU Commission:

"...solutions that are effective and resource efficient and offer a flexible approach to sustainable and inclusive economic growth while improving human health and natural environments while addressing societal challenges."

The two definitions differ in emphasis – the IUCN definition focuses on the conservation and protection of ecosystems and omits mention of the potential economic benefits and resource efficiencies that the EU Commission emphasises. Both definitions however emphasise the benefits gained by humans in the form of ecosystem services and the improvement of the natural ecosystems that we depend upon. NBS and the increasing use of its concepts are representative of the increased appeal of concepts that seek to use natural processes to address societal challenges (Kabisch et al., 2017). It has also been noted that the concept's wide appeal also signifies a more anthropocentric approach to the promotion of conservation and sustainability-related actions (Cohen-Shacham et al., 2019; Nesshöver et al., 2017).

Figure 2.3 summarises the relationship between NBS and the Ecosystem Approach and the societal challenges which NBS as an approach seeks to address. The five ecosystem-based approaches which it covers contain concepts (some of which predate the NBS concept) that can be used individually or in concert to address the ten societal challenges that have so far been identified in the literature (Cohen-Shacham et al., 2019). In addition to addressing societal challenges, NBS projects to date have been able to provide ecosystem services and produce co-benefits that can assist in addressing more than one societal challenge (Faivre, Fritz, Freitas, de Boissezon, & Vandewoestijne, 2017).

In the context of this thesis it is necessary to define what is meant by ecosystem services in the context of NBS and its reported benefits. The term originates from the field of ecological engineering (Bohemen, 2012) and is used to describe the interactions between species with each other in the physical environment (ecosystem) and how these interactions support the well-being of humans in the form of four overall categories: provisioning, regulating, cultural, and supporting (CBD, 2012). Although ecosystem services are referred to in a positive light, they can also cause disbenefits to people in the form of ecosystem disservices. Ecosystem disservices are defined as the nuisances and harm that can be caused by increasing the presence of natural or ecological processes and includes increased allergens in the air or pests (Haase et al., 2017). In recent years more attention has been paid to the ecosystem disservices and consideration of the effects of increasing the amount of nature in urban areas (Kronenberg, 2015).

For urban challenges like those facing Amsterdam's quay wall waterfronts an NBS approach is an opportunity to research and adapt the growing body of evidence that shows NBS approaches can produce viable solutions to urban challenges associated to climate change adaptation, urban degeneration, and aging infrastructures (Frantzeskaki, 2019). This is detailed in the conceptual framework and Chapter 6 where the specific concepts of "Green Infrastructure" (GI) and "Ecosystem-based Adaptation" (EBA) are elaborated upon and applied to the research objectives, respectively.

Limitations of the NBS concept and its approaches include the lack of consistent evidence to support some of its claims of being able to address societal challenges like social justice and inclusion or creation

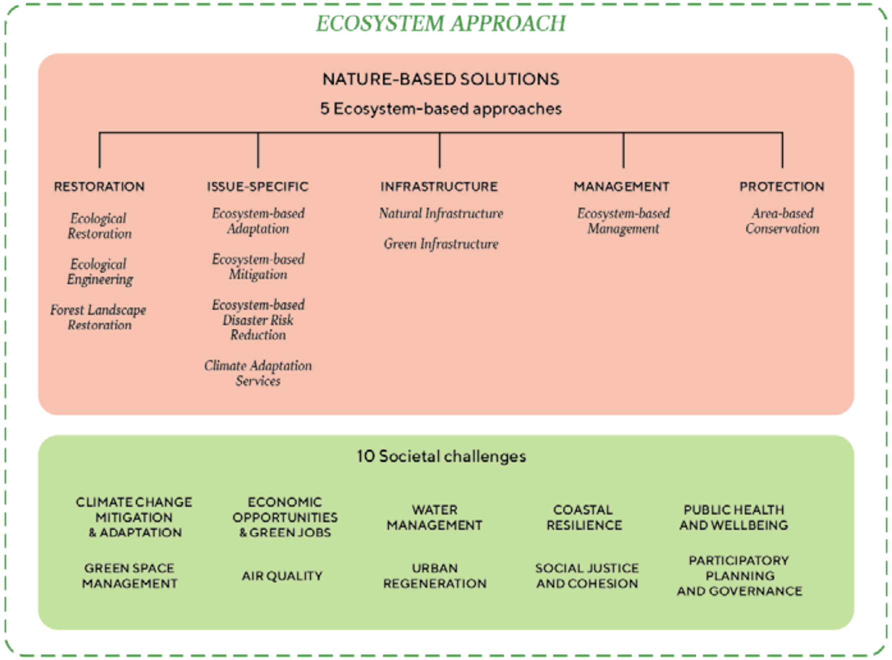


Figure 2.3. Nature-based Solutions as nested concepts and the societal challenges which are addressed. Diagram adapted from Cohen-Shacham et al, 2019 and Raymond et al, 2017.

of economic opportunities (Faivre et al., 2017; Frantzeskaki, 2019; Kabisch et al., 2016). This could be in part attributable to the lack of knowledge exchange (Cohen-Shacham et al., 2019) between the practice, policy, and research activities that have been occurring in parallel. This is also evidenced in the scarcity of academic research into quantifying the benefits of NBS projects – a gap which the literature of Somarakis et al (2019) and Frantzeskaki (2019) attempts to bridge. Even if scarce, the literature and evidence contained therein for the success of NBS approaches in addressing climate change-related issues in urban areas does exist, some of which is in the material used for undertaking the NBS case studies for this research (refer Appendix F).

2.1.5 Adaptation by increasing resilience

The concepts discussed so far pertain mainly to the analysis and approaches used for meeting the objectives of the research. Climate change adaptation and the specific approach to adaptation is driven by the concepts of infrastructural and socio-ecological resilience. As with the previous concepts, the literature on these two subjects comes from a broad range of fields given that these terms have been widely adopted in research relating to climate change and transitions. For this thesis, the literature used to define these concepts originated predominantly from the fields of spatial planning, urban studies, transitions, and geography.

First, it is necessary to define what is meant by climate change adaptation in comparison with mitigation. Mitigation and adaptation are two approaches that can be taken towards climate change. Locatelli (2011) summarises the difference between the two approaches according to which aspect of climate change they address, at what spatial scale, and over what time scale:

- Mitigation: addresses the causes of climate change at the global scale and has long-term effects.
- Adaptation: addresses the effects of climate change at a local scale and tends towards short-term reduction of vulnerability.

Additionally, climate change adaptation is defined as the process of making structural and functional changes to respond to the negative effects of climate change to reduce the susceptibility and vulnerability of people in their living environments (Commissioner, 2019; Rijksoverheid, 2016; van Bohemen, 2012). The purpose of the research is therefore to identify ways in which the effects of climate change are addressed at the scale of the city and the waterfront with the aim of achieving short to medium term reduction in vulnerability. In this thesis, climate adaptation is a strategy for the design and management of solutions.

As climate change adaptation refers to the strategy to address climate change, the concept of resilience describes how adaptation measures perform in urban ecosystems. Resilience as a concept is defined as the ability of a system to absorb shocks and after a period of recovery to reorganise without fundamental changes to its essential characteristics and functional relationships (Andersson, Borgström, & McPhearson, 2017; Bohemen, 2012). Resilience is a concept that is frequently used in the literature regarding more liveable cities (Romero-Lankao, Gnatz, Wilhelmi, & Hayden, 2016), however because of term's broad use by multiple disciplines it is important to clarify what kind of resilience is being sought in this thesis (Deppisch, 2017). As such, there are two additional definitions provided for what is meant by resilience in this thesis: socio-ecological resilience, and infrastructure resilience.

First, "socio-ecological resilience" is a term that emphasises the ability for ecosystems to retain their characteristics and functions after a period of recovery from a natural or anthropogenic disturbance and in addition to this have the capacity to continually learn and adapt to continued change (van Bohemen, 2012). This is relevant to the renovation of Amsterdam's waterfront spaces because of the time-scale and the spatial scale that the renovations have: technical innovations that are integrated today should be able to be monitored and adapted to changes that will happen in the future.

The concept of socio-ecological resilience is a necessary elaboration given that the research has been undertaken with an over-arching concept that includes socio-ecological approaches which already take what Levin-Keitel et al (2018) refer to as a biological and nature-conservation perspective that includes the concept of resilience alongside other concepts like planetary boundaries.

In addition to learning and adapting to change, "infrastructure resilience" refers to how infrastructures that incorporate change in their design can become dynamic and foster sustainable social practices that help with broader goals relating to climate change adaptation and mitigation (Schäfer & Scheele, 2017).

Lastly, vulnerability as a concept is also applicable to climate change resilience and adaptation. Climate change adaptation measures that are designed to be resilient can reduce vulnerability, but it does not completely eliminate it. Climate adaptation measures do not necessarily reduce the occurrence of the effect, they reduce the exposure to the negative aspects of climate change effects. Vulnerability in the context of climate change and disturbances to urban areas does not mean the opposite of resilience, rather it is defined as the susceptibility and exposure of individuals, groups, or structures towards damages and risks (Andersson et al., 2017; Deppisch, 2017). Vulnerability is a part of the uncertainty that exists in socio-ecological systems like cities. Ways to reduce vulnerability therefore rely on social systems to, for example, raise awareness of the public to the risks of climate change and build capacity within society to implement adaptation and mitigation measures (Deppisch, 2017). Resilience is therefore a way to reduce vulnerability because it makes space for risk and in case of disturbance reduces the damages caused.

2.2. CONCEPTUAL FRAMEWORK

The concepts discussed in the previous section form the main structure for the conceptual framework that underpins the research. The specific objectives of the research contribute to achieving an overall goal for the research: to analyse how the renovation of Amsterdam's quay wall waterfronts is an opportunity to implement climate adaptation measures throughout the city in a material way. Materiality in this case uses the definition provided by Rutherford (2020) who, in the context of rematerializing research describes materiality as the "tangible, evident artefacts, forms and processes of cities". Knowing that the results of the research would have outcomes affecting the materiality of the city is also related to the research by design approach and so again, the idea of design approaches as a method of research underlies conceptual framework and how the concepts are arranged to support the research questions.

The first assertion is that the city is an urban ecosystem comprising of social and ecological systems that interact in unique ways at different scales and spaces. Three spatial scales are proposed for the research into the renovation of Amsterdam's quay wall waterfronts and the effects of climate change in the city's waterfront locations. *Figure 2.4* illustrates how the research stages and corresponding questions relate to the three spatial scales. The three scales are telescopic where the large scale refers to the city and the small scale to the waterfront or street. The neighbourhood is the scale in between that spatially embodies a socio-ecological approach. The relevance of the neighbourhood scale is that it is a space and place where people can exert spatial and social control (van Dorst, 2012) – it is a tangible scale in which the urban system can be appreciated better in the street or waterfront scale. The street scale is where the solutions in research questions 3 and 4 are materialised in the waterfront spaces and from the street scale an evaluation of local impacts to the space can be generalised to gain insight into further research opportunities. In the neighbourhood scale, the waterways become oriented to the socio-ecological systems in the city, situating the renovation of the quay walls and giving relevance to the placement of the proposed solutions along the waterways that define Amsterdam as a city.

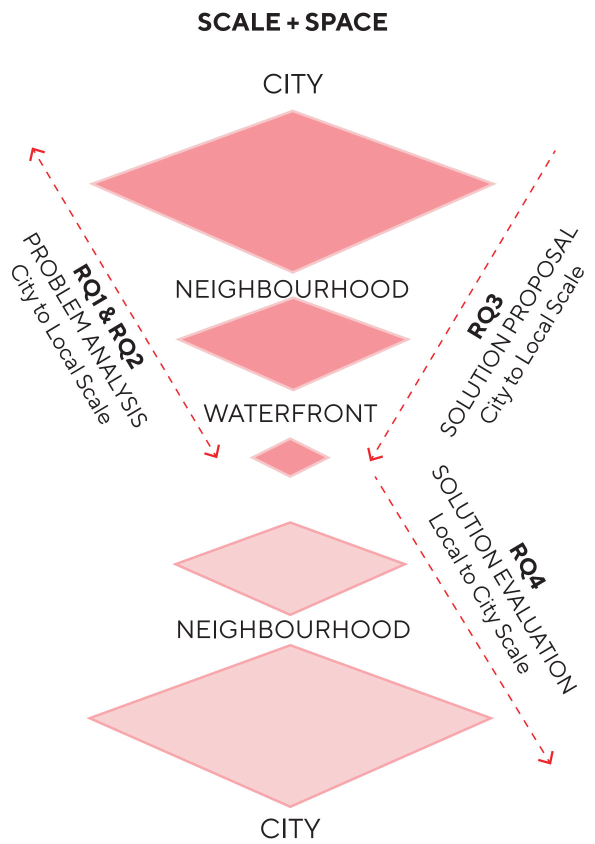
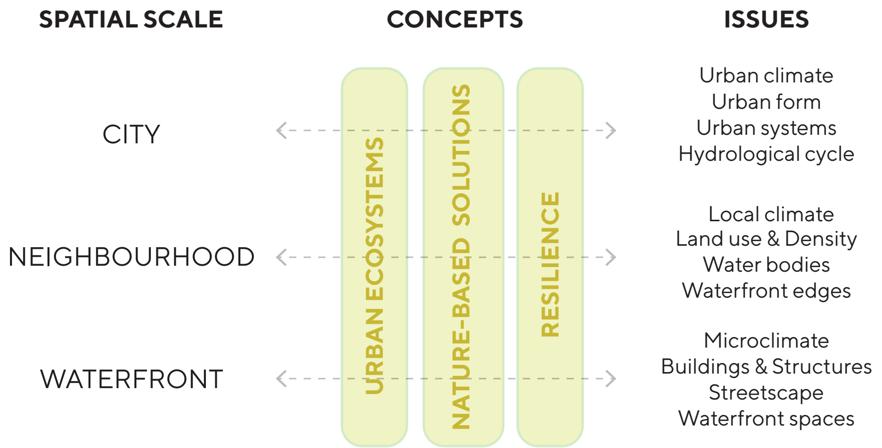


Figure 2.4.Conceptual Framework illustrating the relationship between scales and research questions. Image credit: Noelle Teh

Figure 2.5.Conceptual Framework illustrating the relationship between scales, spaces, and issues. Image credit: Noelle Teh



Within these three spatial scales of city, neighbourhood, and street the concepts of the city as urban ecosystem, infrastructural and socio-ecological resilience, and nature-based solutions as an umbrella concept for solutions to societal challenges are applied. Doing so focuses the research on specific issues that relate to the research questions and objectives. *Figure 2.5* illustrates this relationship between the spatial scales, concepts, and issues that arise as a result. The concepts are a lens through which the research objectives can be met.

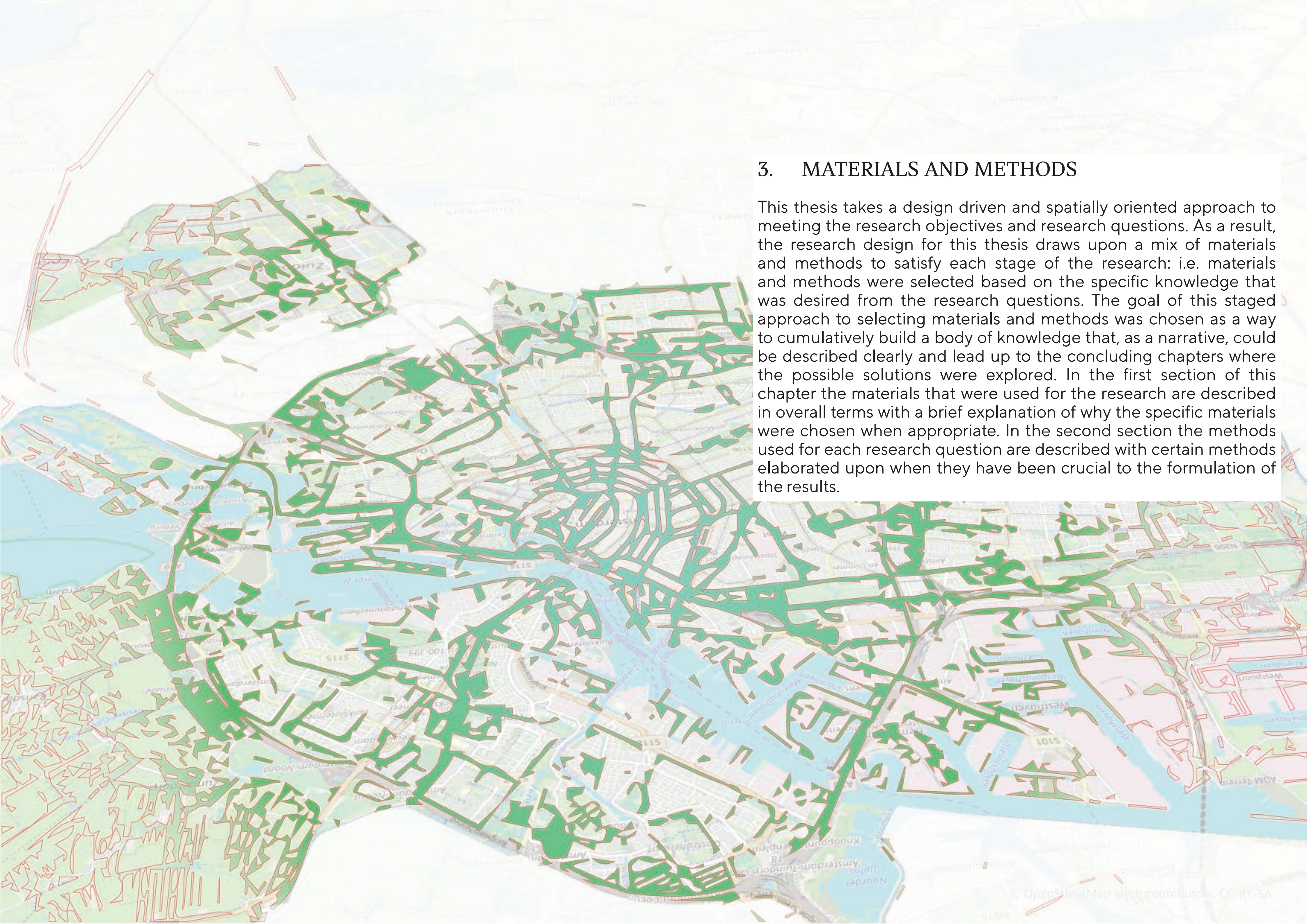
In the first two objectives and their corresponding research questions it is necessary to move between spatial scales when researching the two problems as they do not immediately share the same causes or consequences – it is through analysing these problems in set spatial scales that the shared drivers and consequences can be identified. Once the specific challenges and problems are framed in a scalar and spatial way it becomes a way to propose solutions that address the problem in a holistic way – or at least within the boundary of the urban ecosystem.

To adapt from van Bueren (2012), the scale of the solution is proposed in the scale of analysis of the problem and in the context the research objectives this results in a spatial strategy at the city and street scale. The reason for this relates to the concepts of adaptation and resilience and the specific NBS concepts of "Green Infrastructure" (GI) and "Ecosystem-based Adaptation" (EBA) that are used to make Amsterdam's quay wall waterfronts resilient to climate change while also delaying quay wall replacement. These concepts are applied at different scales within the city where they are used to address socio-ecological processes that occur in those scales and in doing so create a feedback loop that supports this transition towards climate resilience.

Finally, to complete the results the solutions are evaluated from the street scale from which recommendations can be made towards the potential for waterfront-scale interventions to have a significant impact at the neighbourhood and city scale what the potential changes are to the city as an ecosystem.

3. MATERIALS AND METHODS

This thesis takes a design driven and spatially oriented approach to meeting the research objectives and research questions. As a result, the research design for this thesis draws upon a mix of materials and methods to satisfy each stage of the research: i.e. materials and methods were selected based on the specific knowledge that was desired from the research questions. The goal of this staged approach to selecting materials and methods was chosen as a way to cumulatively build a body of knowledge that, as a narrative, could be described clearly and lead up to the concluding chapters where the possible solutions were explored. In the first section of this chapter the materials that were used for the research are described in overall terms with a brief explanation of why the specific materials were chosen when appropriate. In the second section the methods used for each research question are described with certain methods elaborated upon when they have been crucial to the formulation of the results.



3.1. MATERIALS

Materials used included literature, images, construction documents, notes from self-conducted semi-structured interviews and attended symposium, geospatial data, census data, and observations made from visits to sites where quay wall renovation is currently taking place. This mix of qualitative, quantitative, and empirical data and materials was comprised specifically of:

- Peer-reviewed academic papers and grey literature obtained from the online library catalogues Wageningen University and TU Delft.
- Government reports from local and national levels of government in the Netherlands.
- Books and literature prepared by private companies or quasi-public agencies.
- Archival images and construction drawings obtained from the search engine or by request from the online catalogue of the city archives of Amsterdam.
- Population and geospatial (GIS) data and obtained from the open data platform of the Municipality of Amsterdam, Dutch government geodatabases, and the Climate Effect Atlas from the Climate Adaptation Services Foundation (2020).
- Notes taken during meetings or semi-structured interviews conducted with municipal officers and researchers involved with research on the quay walls of Amsterdam.
- Notes and photographs taken during visits to site where the quay walls are being renovated.
- ArcGIS Pro GIS software.
- Graphics and illustration programs including Adobe Illustrator and Photoshop.
- 3d modelling CAD software (Rhinoceros).
- Microsoft Office Word and Excel for word processing and spreadsheet creation, respectively.

The Appendices contains the data schedules, interview and meeting lists, interview questions and notes from semi-structured interviews, site visit photos and observations, case study projects, and subsurface and groundwater level data used for the landscape scenarios in chapter 6. Given the objectives and scope of the research the participants of the research mainly consisted of the interviewees from the municipality.

The decision to use certain materials was based on their applicability to the three spatial scales used to order the research and the issues that arise within each scale. *Figure 3.1* illustrates how the three scales and their corresponding issues were researched using the types of materials listed above. In the following chapter the specifics of the materials and methods used to respond to each research questions are detailed.

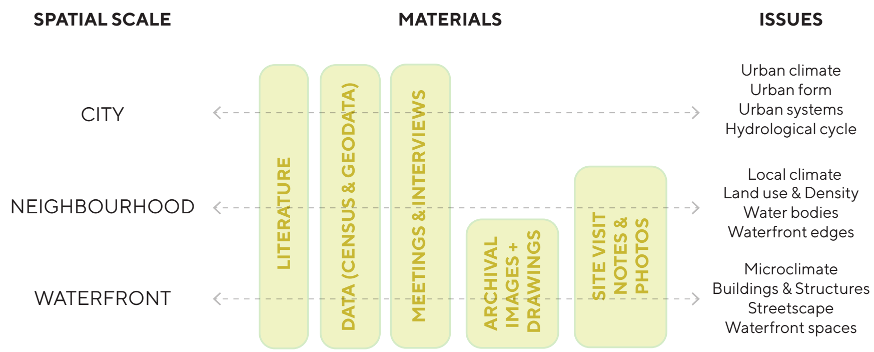


Figure 3.1. Relationship between spatial scales of research and materials selected for the corresponding range of issues. Image credit: Noelle Teh

3.2. METHODS

The decision to use certain methods during the analysis and design stages of the research was driven by a methodological process that tended to produce then revisit – and if necessary revise – the methods and results, each time refining the problems and solutions related to the research objectives. However, the process generally followed the process illustrated in *Figure 3.2.* The research methods used for each research question are elaborated upon in the following subsections.

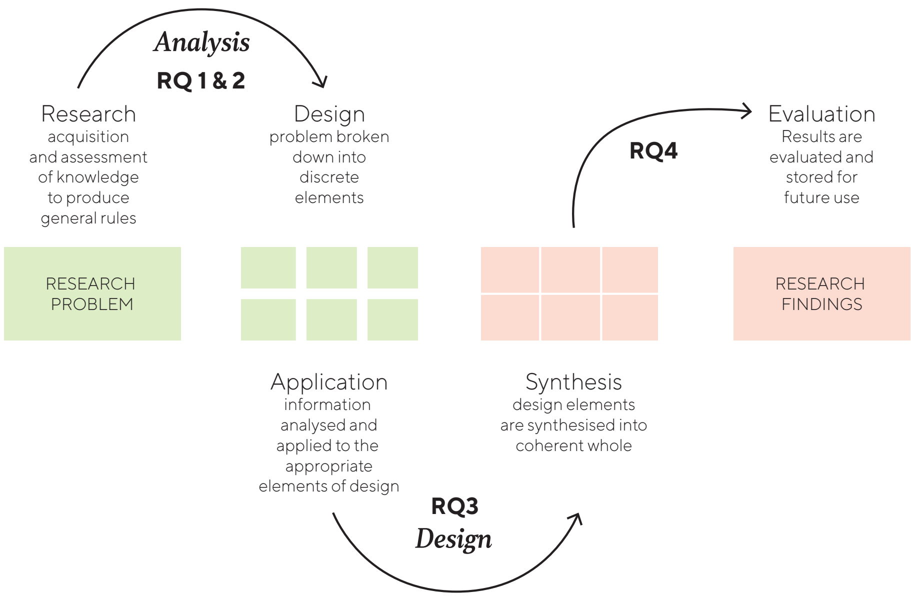


Figure 3.2. Stages of research in the analysis-synthesis model for research by design. Adapted from Milburn & Brown, 2003, pp. 51–52.

3.2.1 Methods for RQ1

Methods used to respond to the first research question mainly related to the acquisition of data to analyse the social and ecological processes involved in the quay wall renovation and the associated waterfronts in Amsterdam. The methods used during this stage included:

- Spatial analysis with GIS software:
    - Using geodata and GIS software to establish the spatial extent of quay wall waterfronts in the city.
    - Using population data, geodata, and GIS software to propose a "quay wall impact score" to make an assumption on the rate of renovation based on the age of buildings within a neighbourhood to visualise the spatial extent of renovation in the city.
- Reviewing literature, archival data, and conducting semi-structured interviews to:
    - determine the functions within Amsterdam's quay walls and waterfronts currently and in the past.
    - determine the overall causes and processes leading to the renovation of a quay wall.
    - gain knowledge into the current process of renovation with emphasis on the types of renovation methods used and their impact (temporary and long term) to waterfront spaces.
    - gain knowledge into additional measures and research that are being undertaken alongside the renovation.
- Performing site visits to observe and collect empirical data on how the renovation process has affected and changed the city.
- Attending presentations about the quay wall renovation organised by the AMS Institute and the Municipality of Amsterdam.
- Modelling the basic components of waterfront spaces in 3d computer-aided design (CAD) software based on data collected to appreciate the spatial composition of typical waterfront spaces in Amsterdam.
- Operationalising results into a list of functional requirements that to create general rules for the possible design solutions.

Elaboration on specific materials and methods:

Spatial analysis of the assumed rate of quay wall renovation within Amsterdam:

To make an assumption on the quay walls that are most likely to be renovated first – and therefore sooner to affect people and processes in the city – data from the *'Basisreistratie Adressen en Gebouwen'* or 'Basic Registration of Addresses and Buildings' (BAG) was used. The precise age of the quay wall structures is not known, nor is the method in which they were constructed. Using the BAG data, an assumption was made that the higher the number of buildings from a particular period of time within a neighbourhood the likelier it is that the quay wall structures belong to the same time period as the walls would have been built or re-built to make it possible to construct the buildings. Buildings were selected by attribute in ArcGIS Pro to create groups by 50 year intervals dating backwards from 2020. This 50 year interval is based on the literature pertaining to industrial quay walls by de Gijt (2010) although this is a very conservative estimate of the actual service lifetime of a wall. All neighbourhoods assigned with an age beyond 100 years old (the upper limit stated by the municipality (2019)) were eventually classified together as these are understood to all require urgent attention and it is a matter of when and not if they will be renovated in the next 20 years. The results of this analysis and classification became the basis for the spatial distribution of renovation types described in Chapter 4 and 6.

GIS to create a "quay wall impact score":

To locate and visualise the impacts of renovating the city's quay walls on the scale of the city, open data from the municipality and other government bodies (refer Appendix A for all used data sources and types) was used. First, the data was converted into a GIS-compatible format to identify neighbourhoods that contain quay walls and use this information to calculate then compare which neighbourhoods contain the most amount of quay walls as a percentage of its total area and therefore are assumed to contain the highest potential area of change. The area of the quay wall waterfront is measured by the top surface of the quay wall as a geodata object and is based on the assumption that the BGT data is accurate and all walls are the same width. This is separate to the analysis on the width of the waterfront itself which varies greatly and is briefly described in Section 3.2.3. To determine the population density, municipal population data – also at a neighbourhood scale – current to January 2020 was joined to the spatial data tables to calculate the population density (measured as persons/km2). Using the 'symbology' tool in ArcGIS Pro the two maps were classified into tertile groups with the groups used to form the quay wall impact score.

The quay wall impact score is made from three variables: i) the age of a neighbourhood as indicator for the age of all quay walls within a neighbourhood, ii) quay wall area as percentage of total neighbourhood area, iii) population density per neighbourhood. Using these three variables the assignment of renovation method was based on the assumed age of the wall and a "quay wall impact score" comprised of the addition of scores given to the tertile ranks of the percentage of quay wall area and population density where the higher the rank the lower the number score.

This resulted in the neighbourhoods containing waterfronts can be classified into four groups based on the options for different renovation methods:

Renovation method	Quay wall neighbourhood age and impact score
Replace	• More than 100 years old and impact score of up to 2
Reinforce	• More than 100 years old and impact score of up to 4 but more than 2. • Walls built between 1920 and 1970 and with impact score of up to 2
Reduce	• More than 100 years old and impact score of more than 4. • Between 1920 and 1970 and with impact score of more than 2. • Walls built after 1970 and with impact score of up to 4.
Renovate later	• Walls built after 1970 and with impact score of more than 4.

Table 3.2. Proposed variables for assigning quay wall renovation method.

The results of the quay wall impact score and recommended renovation methods are detailed in Chapter 4 and are used again in Chapter 6 for site selection.

Meetings and Semi-structured interviews:

In addition to the literature from De Gijt (2010) and Cork & Chamberlain (2015), a basic understanding of the technical requirements of the wall was obtained by using informal meetings with quay wall researchers from the AMS Institute and semi-structured interviews with municipal officers from the quay wall and bridge programme at the Municipality of Amsterdam (refer to Appendix B for dates and persons). The meetings were used to identify recurring themes which in turn informed the analysis of the quay wall renovation process. Semi-structured interviews were also used to gain current insight into the renovation process and to be aware of the changes and lessons that are being learned real-time in the municipality. An example of this is what was learned about the additional strategic works and research efforts occurring at the same time. The outcomes of these meetings were used to form the functional requirements at the end of Chapters 4 and 5.

Site visits:

Site visits to quay wall waterfronts in Amsterdam were undertaken to observe what types of structures the municipality has been using for the renovation and how they have been used in different contexts of the city. Sites for visiting were identified using the municipality's quay wall and bridge information website (https://www.amsterdam.nl/projecten/kademuren). During site walks, photos were taken of the different renovation types and how they related to the existing waterfront that they were located in. For active construction sites it was sometimes challenging to see what was being installed but for this research it was sufficient to see relative dimensions of structural elements and construction materials used. Sites were visited over a duration of six months, making it possible to see the finished construction of some renovated waterfront areas. The site photos were grouped according to site and annotations made post-walk for future use as empirical evidence in the research. The site photos can be found in Appendix D.

Operationalisation of research findings:

Using the knowledge gained from the research activities for the research question, a list of functional requirements was created in response to the query of "...what can be done to delay wall replacement?" at the end of the research question. These functional requirements are based on the concept of resilience as a goal for the design and function of quay wall waterfront spaces. The precise design and function of which is proposed in later chapters but at this stage of the research the purpose of these functional requirements is to provide an operational aspect to the findings from the research in this chapter. These functional requirements relating to the wall and waterfront are combined with similar functional requirements created from the results of research question 2.

3.2.2 Methods for RQ2

Methods used to respond to the second research question build upon the results of the first research question and are mainly related to the analysis of geospatial data and literature review regarding the specific effects of climate change (heat, flood, and drought) in waterfronts areas and neighbourhoods in Amsterdam. The methods used during this stage of the analysis were:

- Literature review for selection of climate scenario regarding the current and predicted effects of climate change in the Netherlands and Amsterdam.
- Literature review of the overall causes and effects of climate change (with respect to heat, flood, and drought) and how they are measured.
- Spatial analysis with GIS software:
    - Using geodata and GIS software to analyse the spatial distribution of climate change effects within the boundary of the city and with respect to the population density of neighbourhoods containing waterfront spaces;
    - Attributing and reclassifying climate change effect data at the neighbourhood scale to rank neighbourhoods according to vulnerability to climate change effects.
- Operationalising results into a list of functional requirements that to create general rules for the possible design solutions.

Elaboration on specific materials and methods:

Spatial analysis of climate change effects and classification for "climate change impact score"

Geospatial data from Climate Adaptation Services' (CAS) (2020) 'Climate Effect Atlas' (KEA) was requested for analysis and processing. First the spatial distribution of climate change effects was undertaken for data that was directly related to heat, flood, and drought and had corresponding data for the 2050WH scenario. This was so that trends over space and time could be analysed and form part of the "climate change impact score" that was created to be combined with the "quay wall impact score" so that specific neighbourhoods could be selected as landscape scenarios. To do this, the geodata was summarised within the previously identified "waterfront neighbourhoods" and reclassified according to the intervals and corresponding impact scores detailed in Appendix E.

To make ordinal ranges that form the basis of the climate impact score, the literature and data sources were used. In the case where ranges varied across the literature an assumption needed to be made. An example of this is in the mapping of flood impacted areas in Amsterdam, the depth measurement used to determine risk of flooding varied across the literature and the data however 200mm was identified as a common depth threshold for indicating damages to society. This depth was taken from the literature (Stone, Duinen, Veerbeek, & Dopp, 2011) and the GIS data (Klimaateffectatlas, 2020).

A limiting factor to the final "climate change impact score" was the coverage of the geodata used – for some climate change effects the data was not available or at the necessary resolution. This was part of the reasoning behind using the score to guide the types of design techniques used rather than guiding the priority of renovation.

Operationalisation of research findings:

Using the knowledge gained from the research activities for the research question, a list of functional requirements was created using the concept of resilience towards climate change as a goal for the design and function of quay wall waterfront spaces. The purpose of these functional requirements is to provide an operational aspect to the findings from the research in this chapter and these were subsequently combined with the requirements from the first research question and chapter to be taken forward into Chapter 3.

3.2.3 Methods for RQ3

Methods used to respond to the third research question (Chapter 6) at this point differ as the research stage transitions from analysis into synthesis and design. Methods used during this stage were:

- Case studies for the identification of design characteristics and techniques of NBS approach.
- Operationalisation of case study outcomes to create design characteristics.
- Modelling scalable "typical" components of resilient NBS measures in 3d computer-aided design (CAD) software.
- Establishment of evaluation criteria for landscape scenario sites.
- GIS functions to determine spatial strategy for implementing resilient NBS measures alongside the renovation of quay wall waterfronts.
- GIS functions for classifying waterfront site widths.
- Site selection for landscape scenarios.

Elaboration on specific materials and methods:

NBS case studies for design characteristics

A cross-section of NBS projects were selected for additional study as case studies. The purpose of the case studies was to identify what, if any, similar characteristics exist between the NBS projects at a city and street scale. The scope of projects was limited to those that were referenced in the literature and had stated aims towards climate regulation and water flow regulation – two categories of NBS benefits with accompanying intervention types as classified by the EU Commission (2015). The results of the case study are in Appendix F and are organised according to the spatial scale that they relate to (city and street). The case studies form a collection of "project sheets" which serve as empirical evidence to the list of design characteristics that are used to steer the proposals that form part of the response to the research question.

Evaluation criteria for landscape scenario sites

The evaluation criteria for the landscape scenario sites is a result of the combined functional requirements produced at the conclusion of research questions two. The landscape scenario sites are lengths of waterfront spaces located within the Municipality of Amsterdam and as 3d CAD models are sites of experimentation on the possible design solutions to meet the functional requirements arising from the research so far. The functional requirements are combined with the design characteristics to create a range of "typical" design techniques that can be implemented into the waterfront spaces. These design techniques are an exploration of possible design solutions and are part of the determination of indicators to measure the functional requirements and the extent to which they are met or present within the landscape site scenarios.

GIS functions for classifying waterfront site widths

Using the "Euclidean Distance" function in ArcGIS Pro, the waterfront widths within the Centrum district of Amsterdam are visually appraised so that waterfronts where there is less than eight meters can be

Figure 3.3. GIS Buffer analysis of Amsterdam's waterfronts in the Centrum district (top) and example of narrow waterfronts on Groenburgwal, near Amstel 1 (bottom). Data credit: BGT, 2020 and Noelle Teh.

classified and used as a further refinement to the range of landscape scenario sites that will be used to demonstrate possible solutions to the research problem. A dimension of less than eight metres indicates a "narrow" waterfront as this number is derived from the knowledge that six metres is the nominal minimum clear width required for emergency vehicles in a street – an additional two metres width would not be sufficient for large street trees. Although there are conditions where this is currently not the case in the city, it is assumed that during the replacement works the streets will need to be compliant to current-day standards. *Figure 3.3* shows the result of this operation and provides an example of how some waterfronts are barely 6 metres wide and cases like these need to be considered in the landscape scenario sites.

GIS functions for implementation strategy and landscape scenario site selection

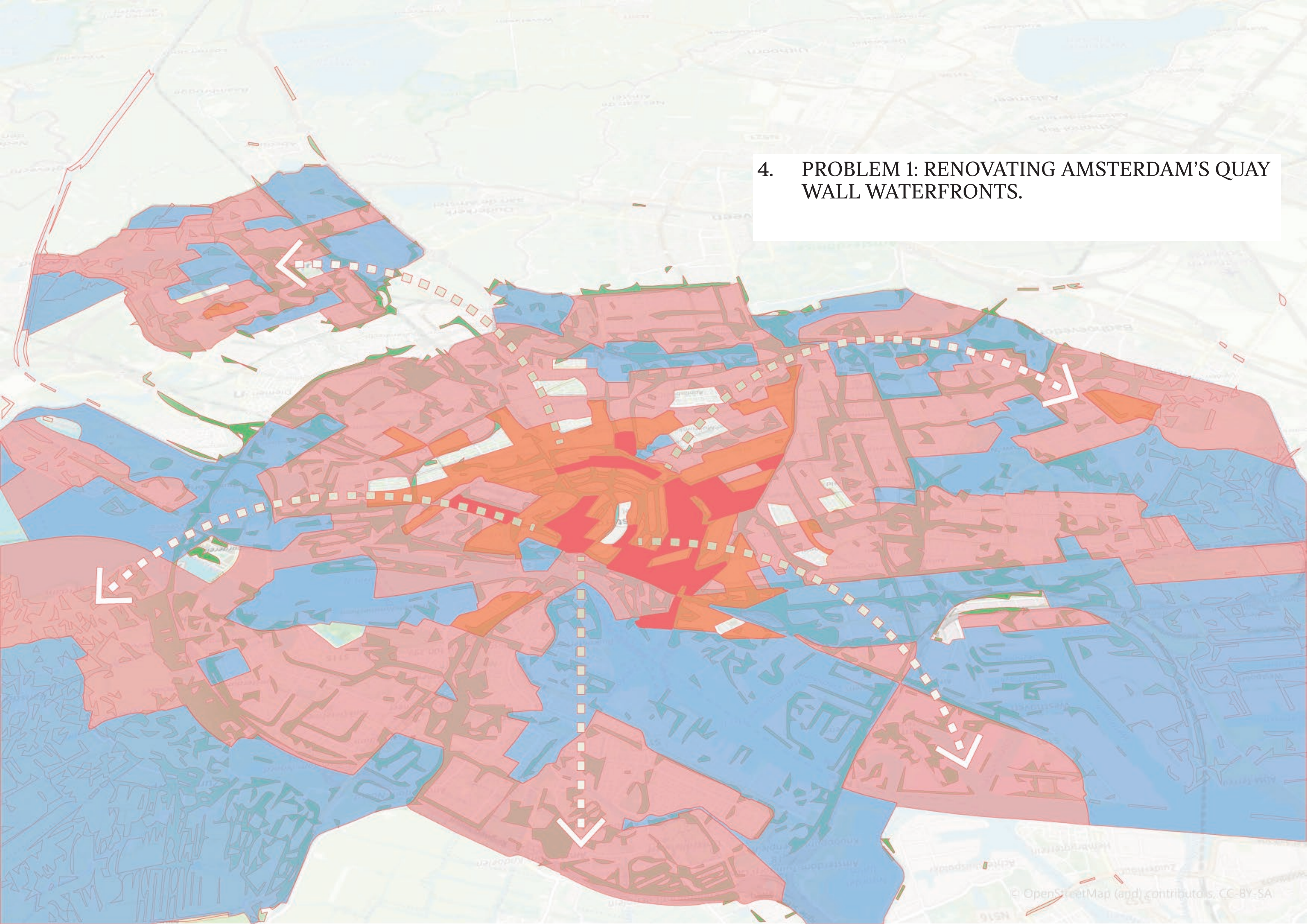
GIS software is used to demonstrate how the impact scores created in previous stages of the research are calculated to create a city scale implementation strategy for the proposed solution. To do this, the tables of impact scores are joined together according to neighbourhood codes and the sum of their scores added and classified renovation types according age and quay wall impact score with the climate change impact score determining the vulnerability of a neighbourhood and the types of design techniques that are required. Additional detail on the method and results are detailed in Chapter 6.

3.2.4 Methods for RQ4

As the last research question, this question serves as a reflection and evaluation question prior to the conclusion and discussion. As a result, only the method of evaluation remains. The method of evaluation is based on measuring the 3d modelled landscape site scenarios in the 3d CAD software that it was created in. Measurements taken relate to the variables defined in the evaluation criteria (e.g.: change in metre square of permeable surfaces). These measurements are then used to make generalisations about the relative benefits of the design proposals over a "do nothing" scenario.

This page is intentionally left blank

4. PROBLEM 1: RENOVATING AMSTERDAM'S QUAY WALL WATERFRONTS.



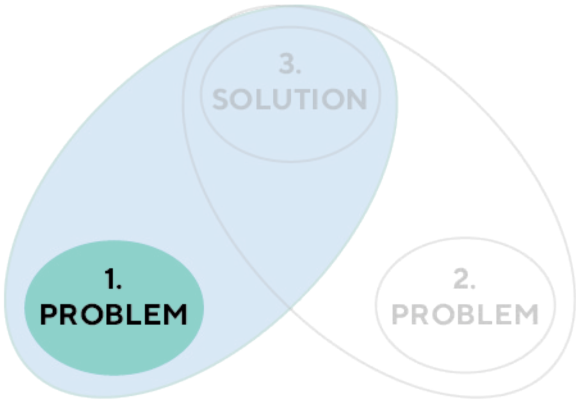


Figure 4.1. Chapter content with respect to theoretical framework. Image credit: Noelle Teh.

Amsterdam is a city with a built form as much defined by water as it is in defiance of water. The quay walls together with the waterfront spaces of the city are the physical manifestation of this complex relationship between the city, its inhabitants, and the natural environment. The quay walls and their waterfronts are an essential infrastructure that represents multiple interdependencies between different actors and processes in the city.

Because the quay wall waterfronts are so ubiquitous it is possible to overlook the importance of what these spaces and structures do from the scale of the city to the street. It is when they are damaged and in need of replacement or additional support that their integral role in the city becomes apparent. This is especially so in the Centrum district of Amsterdam where renovation has already begun on the myriad of canals that form the 17th Century "Canal Ring" that is the principal component to the city's listing as a UNESCO World Heritage site (ICOMOS, 2009). The challenge of renovating the city's quay walls is not restricted to the Centrum. 448 of the city's 481 neighbourhoods contain quay wall waterfronts which will likely require renovation in the coming 50 years.

The renovation is a resource intensive task for the municipality that, as the responsible party for most of the quay walls, must take measures to ensure that the quay wall waterfronts can continue to provide a safe and stable terrain for the various urban functions that take place along the city's waterfronts. According to the Municipality of Amsterdam, there are over 600 kilometres of quay wall in the city of which 200 kilometres are in need of renovation, and from 2020-2023 it is expected that only 4.5 kilometres will be replaced (Gemeente Amsterdam, 2019). For the remaining 195.5 kilometres, additional research is required into what can be done to delay the processes that leads to replacement and – as is the case of this thesis – do so in ways that provide co-benefits for the city.

In this chapter, the research question:

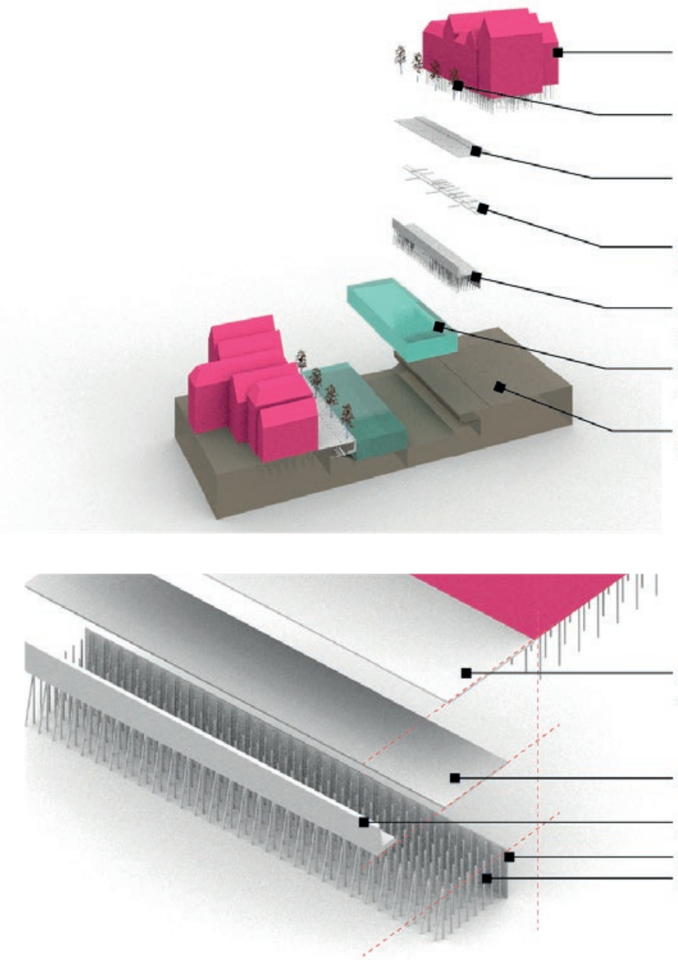
"Why and how have the quay walls in Amsterdam been renovated and what can be done within waterfront spaces to delay wall replacement?"

is being addressed and the results from this question are used to establish the variables relating to the causes and methods of renovation of quay wall waterfronts.

4.1. QUAY WALL WATERFRONTS – AN ESSENTIAL INFRASTRUCTURE IN AMSTERDAM

4.1.1 *Functions of quay wall waterfronts*

Figure 4.2. Components of a typical urban quay wall waterfront. Image credit: Noelle Teh.



The main function of a quay wall is to provide a rigid barrier between land and water and in doing so protecting and elevating the land behind it from the water in front of the wall. The waterfront lands that are created by the quay wall are valuable for human settlement evidenced in the profusion and persistence of waterfront cities and towns throughout history. From this perspective, a quay wall is more than a retaining wall – it is an essential infrastructure for human settlements to flourish and benefit from close proximity to the water. The origins of quay wall waterfronts in the Netherlands – and then later Amsterdam – can be traced back to the first appearance of waterfront structures that have been documented in the 9th century the town of Dorestad (near what is now Wijk bij Duurstade in the Dutch province of Utrecht) which had become an important trade hub and, despite Dorestad's decline in influence by the 10th century, trade continued to flourish in The Netherlands reaching its peak in the 16th and 17th centuries (Gijt, 2010). It is during this time that Amsterdam's iconic canals were constructed, setting the precedent for its growth as a city on water. Since then, maritime trade has shifted out of the city centre and the waterfronts that were once used for handling shipped goods have been converted into leisure spaces or co-opted into city scale urban mobility networks.

Figure 4.2 illustrates the components found in a typical quay wall waterfront in the city. The components are separated from one another to show how each component relates to another and the multiple functions and processes that are happening within the space.

At the scale of the city, the quay wall waterfront space network is as much a public good in and of itself as it is a route for goods to be distributed throughout the city. As an infrastructure, the height of the water and the speed of the current in the canals is influenced by the location of the quay walls. Changes to the quay walls at the street or neighbourhood level have ramifications throughout the city's water network therefore requiring the involvement of Waternet (the water authority covering Amsterdam). The canals also serve as a city-wide flood management tool that can be used to temporarily store excess water after heavy rainfalls and in doing so protecting the functions and assets on land. At the scale of the city there are also benefits to be had to live or work near the water – in the Municipality of Amsterdam's (2016) 'Water Vision 2016-2040' the city's waterfront networks are emphasised as assets to the city as a whole, setting Amsterdam apart from other cities because of the waterfront life that is offered. The waterfront space network is symbolic of Amsterdam and is actively managed and integrated into planning for the future.

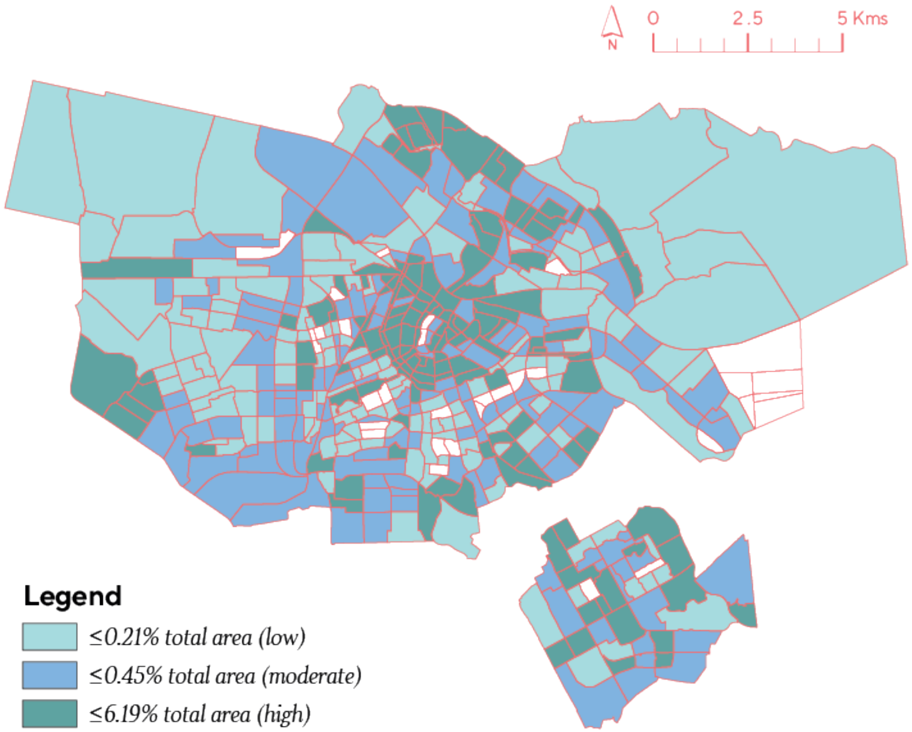
It is at the scale of the neighbourhood that the city-wide functions become more apparent with some neighbourhoods benefiting from the value of the quay wall waterfronts that they contain. Examples of this are the "Canal Ring" of the Centrum district or the new waterfront neighbourhoods of IJburg and Sluisbuurt. The quay wall waterfronts are a part of everyday life and they become places where people gather during hot days to seek respite either in or on the water. When this happens, waterfront spaces in neighbourhoods become hubs for social activities. At this scale the waterfront spaces offer another mode of transport in addition to the road network – mostly for leisure but also for moving heavy goods or even providing emergency services.

At the scale of the waterfront, the specific distribution of functions becomes apparent. Typically, there is a distance between the edge of the waterfront wall and the façade of the buildings – this is the specific space of the quay wall waterfront and is comprised of components and functions above and below ground (refer *Figure 4.2*). Below the quay wall waterfronts are the pile foundations used to give structural support to the quay walls and the ground plane and buildings adjacent to them. Embedded in the soil below the street are the myriad of cables and pipes that supply and remove energy, water, and waste from the buildings, street, and houseboats. These essential services need a stable environment and ground movement in any direction can cause disruptions to services or risks to public safety (e.g. gas pipe leak). On the ground the functions vary in dominance but typically include space for pedestrians, bicycles, cars, and parking for both modes of transport. Occasionally, there are tracts of green space with plants and trees, but the amount of vegetation can also be limited to a single row of widely spaced trees. On the water side, houseboats must by law be connected to sewage at a minimum and this is done through discrete points along the quay wall edge. Boats of the moving variety are also moored along the quay wall edge. The quay wall waterfront spaces are therefore largely transitionary and support the movement of people and services across both land and water.

Waterfront spaces contain interconnected functions and a way to understand the interaction between functions across scales and systems is provided in the table below where a list of functions is categorised according to the scale which they occur in. The list of functions is not exhaustive and is informed by Hijdra et al (2014) and Cork & Chamberlain (2015) and observation taken during site visits (Appendix D). It is acknowledged that some functions could also be categorised as part of the other system but this forced distinction is also useful for highlighting the hybridity of these functions in later sections.

Table 4.1. Table of general functions supported in Amsterdam's quay wall waterfronts.

Scale	Function	System
City	• Elevating and separating land for human settlement. • Water flow regulation and buffering on land and in water. • Intra-city transportation functions including the leisure and tourist boats transporting passengers and cargo boats transporting bulky or heavy goods like construction materials.	Ecosystem Ecosystem Social
Neighbourhood	• Water management functions by collecting stormwater prior to it reaching the water. • Emergency service access providing space for emergency vehicles to access and attend to emergencies in the buildings and spaces along the water. • Recreational and social functions leisure boats, swimming, kayaking, etc. • Emergency service access providing space for emergency vehicles to access and attend to emergencies in the buildings and spaces along the water.	Ecosystem Social Social Social
Waterfront (water side)	• Climate control functions in some areas where the water provides a cooling effect to neighbourhoods.	Ecosystem
Waterfront (land side)	• Erosion control functions as the wall prevents soil to be washed away by the currents of the water. • Space for vegetation on land and water side both ornamental and biodiversity enhancing. • Street functions including car and bicycle parking, carriageways, pedestrian footpaths, street lighting, and street trees. • Residential functions for docked houseboats including provision points for services and informal garden spaces on the street. • Recreational and social functions like informal and formal seating areas sometimes in combination with more explicit recreational functions like small platforms extending into the water for swimming.	Ecosystem Ecosystem Social Social Social



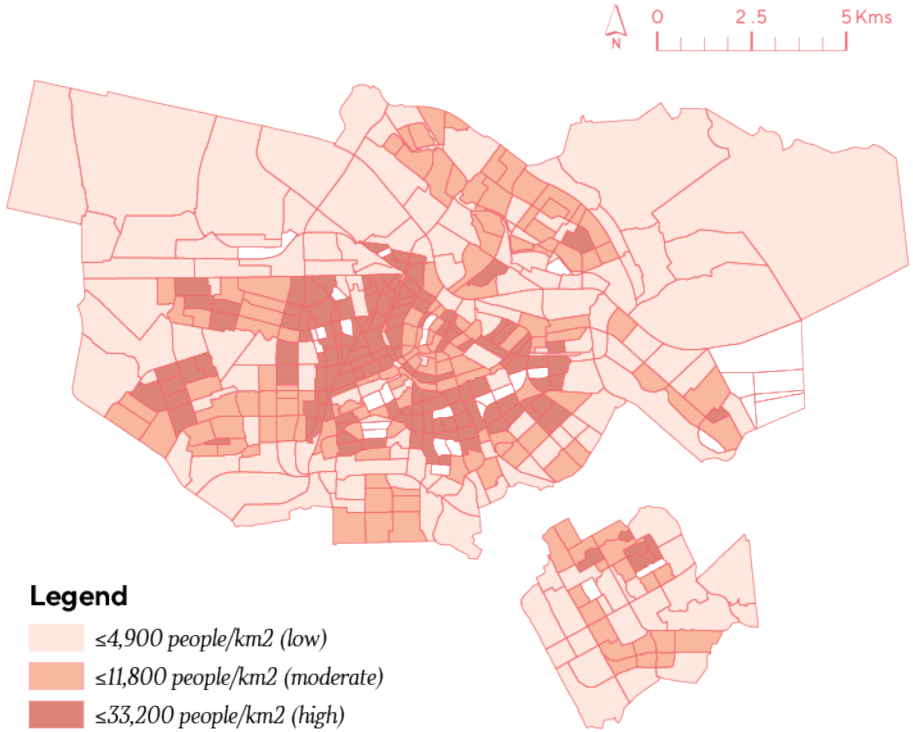


Figure 4.3. (Left) Map of Amsterdam's waterfront neighbourhoods classified according to area of quay wall as a percentage of neighbourhood area. Data credit: Gemeente Amsterdam and BGT, 2020

Figure 4.4. (Right) Map of Amsterdam's waterfront neighbourhoods classified according to population density as people per square kilometre. Data credit: Gemeente Amsterdam and BGT, 2020

Table 4.1 (previous page) demonstrates how socio-ecological functions are embedded into quay wall waterfront spaces and how the renovation of the quay wall is more than a civil engineering exercise – it is a socio-ecological exercise in which the spaces allocated for certain functions has impacts at the scale of the street and the city. There are also "intangible" functions – defined as functions or benefits that are not monetised and sometimes omitted from analysis (Stone et al., 2011) – that the quay wall waterfronts perform with respect to cultural heritage and contributing to the landscape and aesthetics of the city. These intangible functions are actively planned (as in the case of the city's 'Water Vision') and part of an economy of urban spaces which makes waterfronts highly prized areas for urban inhabitants (Prominski, 2012). Although these are not included in the table above, they contribute to the relevance of waterfront spaces to the social systems of the city.

4.1.2 Extent and impact of quay wall waterfronts

Quay wall waterfront spaces provide many functions across many scales in the city. But as a spatial typology, they are not evenly distributed throughout the city and therefore the services (and disservices) that they provide are not evenly distributed throughout society. This is also compounded by the fact that the city is not uniformly settled – there are some neighbourhoods with over 33,000 inhabitants per square kilometre and others with less than 4,700. Understanding how these uneven distributions intersect is necessary to gain an overall understanding into which neighbourhoods have the most quay wall waterfront areas and how densely populated they are. This is so the potential impact of quay wall waterfront renovation can be appreciated in terms of the impact to the space as an area measurement and the impact towards an amount of people living within that neighbourhood.

Figures 4.3 and 4.4 contain maps where the aforementioned spatial statistics are attributed to neighbourhoods which are then classified into tertiles. This provides insight into which neighbourhoods are likely to have larger areas disturbed by the waterfront renovation and in turn the density of people who would be affected by this. These maps also show where these neighbourhoods are in relationship to one another which also sheds light on potential disturbances at a district level. Tables containing the data for individual neighbourhoods is located in Appendix E.

At the scale of the city, there is no discernible spatial pattern connecting the amount of quay wall waterfront spaces within a neighbourhood and its population density. However, it is visible that there are a number of neighbourhoods that have both comparatively high population densities and quay wall areas (e.g. neighbourhoods in the inner-west of the city). At the scale of the city, the population densities shown in *Figure 4.3* make it possible to elucidate the development of the city in previous years based on where the densest neighbourhoods are located.

Also significant is that of the 481 neighbourhoods in the Municipality of Amsterdam, 449 – or 93% – of the neighbourhoods contain quay wall waterfronts – the renovation of the quay walls over time will have an impact on almost every neighbourhood in the city. When classified into tertiles, the neighbourhoods can be compared between each other in terms of "more" or "less" however it is also necessary to consider that neighbourhoods with the highest rank in terms of quay wall area have more than six times the amount than the neighbourhoods in the middle rank. Likewise, for population density the lowest ranking neighbourhoods have up to ~4,900 people/km2 with the next highest rank having ~11,800 people/km2. Nevertheless, the ranking of the data is necessary to gain an overall impression of the difference between neighbourhoods so that a preliminary appraisal can be made about the challenges and possible solutions.

At the scale of the waterfront the resolution of the maps for analysis can be used for an indication only, as it is not possible to map exactly where the concentration of households and people are at a street level using open data. Despite this, the maps are useful for considering how the location of a waterfront space together with the population density can potentially impact the types of waterfront functions available and how many people it will serve.

Quay wall impact score

A "Quay wall impact score" was made from the classifications to the percentage of quay wall area and population density (refer *Figures 4.3 and 4.4*). This impact score is based on a tertile classification where the upper tertile is counted with a score of 1, middle tertile with a score of 2, and lowest tertile with a score of 3. By calculating the sum of these two scores per neighbourhood the findings can be used in future stages to propose city to street scale strategies that prioritise neighbourhoods which have high amounts of waterfront areas and high population densities. The reasoning behind this is based on Schafer & Scheele (2017) who observed that the more dense an infrastructure is, the more disruption – and potential for change – is caused when it fails. In the context of the quay wall waterfronts of Amsterdam, the disturbance caused by quay wall renovation can also serve to improve aspects of the waterfront spaces that could in turn increase the benefits provided to a higher number of people. The impact scores for each neighbourhood are in Appendix E and will be revisited in later sections of the thesis.

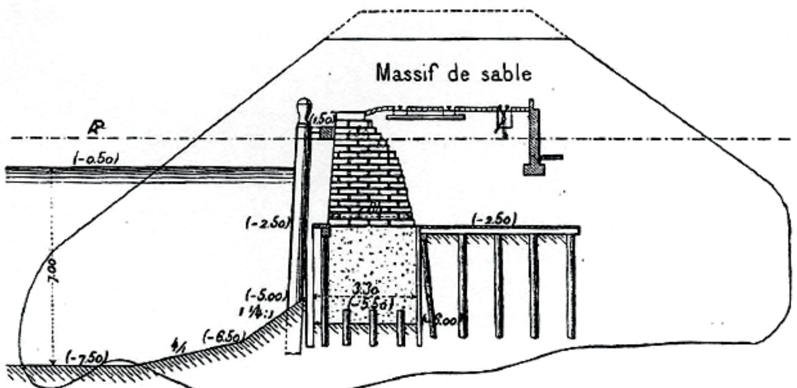


Image 4.1 Quay wall construction in Amsterdam from 1850s. Image credits: de Gijt 2020

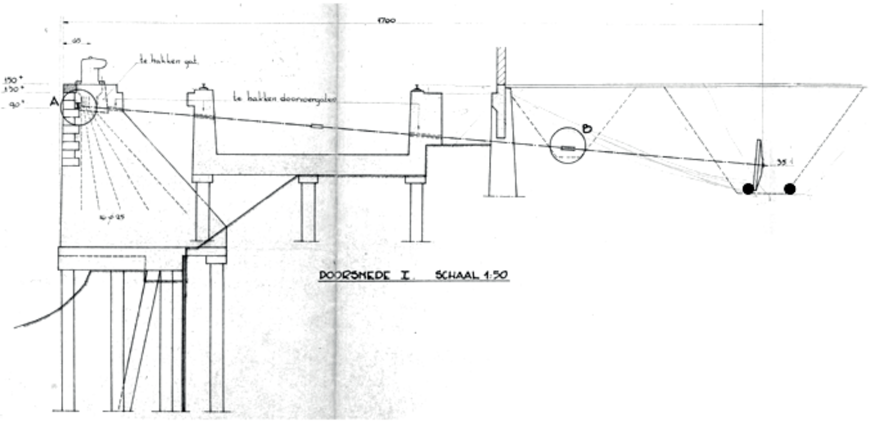


Image 4.2 Quay wall construction in Amsterdam's Coenamerikahaven from 1954. Image credits: Stadsarchief, 2020

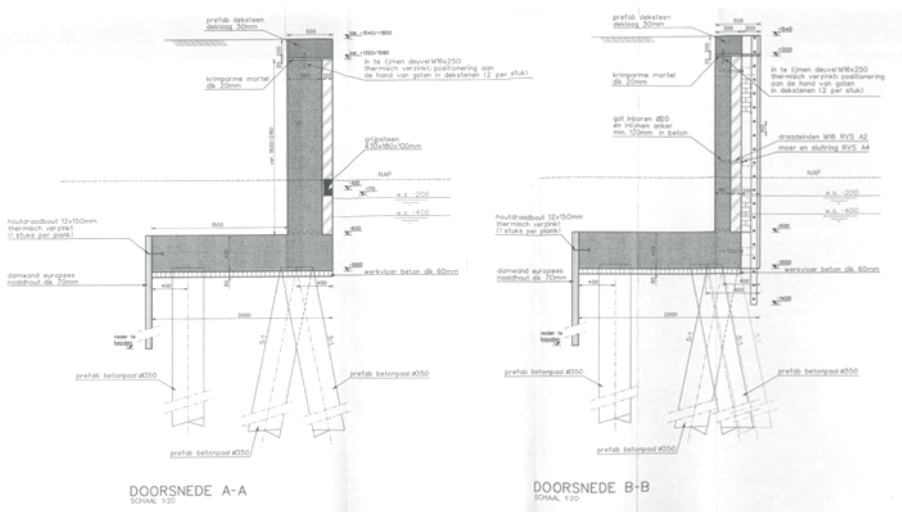


Image 4.3 Quay wall construction in IJburg dated 2002. Image credits: Stadsarchief, 2020

4.2. RENOVATION OF QUAY WALL WATERFRONTS IN AMSTERDAM

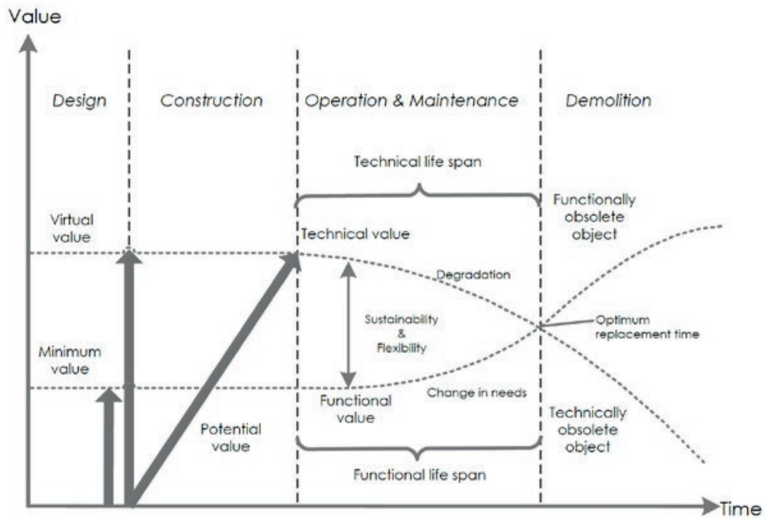
4.2.3 *Causes of quay wall renovation*

The quay wall waterfronts of Amsterdam are multi-functional spaces that form a city-wide network of waterfront spaces that provide and distribute essential services to the city's inhabitants. The quay wall structures that support them were built in progression as the city's population grew and expanded outwards, each time reclaiming and retaining land from the water and using different iterations of quay wall construction methods to do so. *Images 4.1-4.3* show quay wall construction drawings dating between 1850 and 2002 and using the 1850 wall as an example, the technology used 150 years ago to build the quay wall may not have changed in principle, but the society and environment around it has. Although some quay walls can function for up to 300 years (de Gijt, 2020) despite societal and environmental changes, the walls still require monitoring especially given the increased uncertainties caused by climate change and trends towards increasing urban populations (CBS Netherlands, 2017).

Age is the principal factor in quay wall renovation and the speed and severity of degradation to the structure are dependent on local factors like how the quay wall waterfront is used by people and exposure to environmental processes. The accumulation of time in combination with these processes results in the quay wall structure losing its ability to meet public safety requirements while meeting its functional purpose. *Figure 4.5* (page over) by Goldbohm et al (2018) illustrates how the processes of degradation relates to the different stages of a quay wall structure's lifespan where in any case the wall will eventually be demolished because it is either unable to perform structurally or functionally. In the case of the latter, it is it interesting to note that in *Figure 4.5* the function (and social) changes have as much bearing on renovation as the technical changes to the quay wall.

The assessment framework used by the municipality follows this lifespan model. The *'Toetsingskader Amsterdamse Kademuren'* (TAK) model is used to evaluate the strength and loading of the structures over time and is based on two variables: strength and design loading of the structure. From this assessment the walls are categorised as either in need of urgent replacement, reinforcement or reduction measures, or not in need of action. Of the 200 kilometres that are known to be at risk, 135 kilometres (67.5%) of the at-risk walls do not comply with regulations for safety and durability (Gemeente Amsterdam, 2019, p. 13). Safety and compliance define the need for quay wall renovation and

Figure 4.5. Development and decline of technical and function lifespan over time. Image credit: Goldbohm et al 2018.



the causes of wall degradation are analysed based on how they affect the ability for the wall to continue to comply with safety requirements.

Firstly, the changing type of economic activity and functions in Amsterdam have also had impacts on the quay wall structure. In parts of the city that were built during the height of maritime trade, the waterfront spaces were used for handling and moving goods to and from the waterfront buildings to boats in the canals. Now, heavy goods are also transported along on the waterfronts streets in vehicles that are heavier than what was assumed in the original designs. To date, the municipality has already had to restrict the access of heavy vehicles into the historic centre to limit further degradation to the already vulnerable quay walls (Gemeente Amsterdam, 2019).

Quay wall structures are particularly vulnerable to dynamic processes such as those from by the water system, temperature, and living organisms. At the scale of the city processes that cause the quay wall structures to weaken relate mostly to city-wide changes that are not easily perceived in the waterfront scale. For example, the falling groundwater table level combined with subsidence poses a serious risk to the timber pile footings of quay walls (and other structures in the city) by exposing them to oxygen which promotes rotting (Klimaateffectatlas, 2020). Changing water levels on both sides of the wall also affects the hydraulic pressure on the wall which can result in seepage which destabilises the wall. The changing chemistry of the water is also a risk as saltwater borers (insects) that attack timber piles can migrate into the city's canals if the water becomes brackish due to saltwater intrusion. Furthermore, changes in temperature at all scales is another cause of wall degradation and as the temperatures continue to increase due to climate change, some walls will become vulnerable to excessive movement in the structure. This is especially true for old quay wall constructions where a mix of materials were used, all of which have different reactions to temperature changes (Cork & Chamberlain, 2015).

Recreational functions that waterfront spaces offer in some neighbourhoods also contribute to the degradation of the quay wall structure. Increased boat traffic increases the incidence of scouring from boat propellers which results in erosion of the canal bed which exposes the wall structure (Cork & Chamberlain, 2015).

Changes over time with respect to transportation methods and modes is an important consideration at the waterfront scale. The weight and number of cars parked and driving over the streets on top also degrades the wall structure and in some places in the city car parking has been removed (and heavy objects like trees) to reduce the load on walls that have been identified as at-risk. *Image 4.4* shows where trees have been removed at a waterfront in the Centrum to prevent further movement to the structure and waterfront.

As mentioned earlier, living organisms pose a threat to the integrity of some quay wall structures because vegetation with invasive root systems (e.g. the invasive Japanese knotweed *Fallopia japonica*), burrowing animals, insects, and even bacteria can break down the materials the wall was constructed from (Cork & Chamberlain, 2015). In particular, woody vegetation like trees can compromise joints in the wall and are prone to "wind rock" which adds live loads to the wall (Cork & Chamberlain, 2015).

Image 4.4 The waterfront of Nieuwe Herengracht where trees have been cut down to relieve pressure on the quay wall. Image credit: Noelle Teh

4.2.4 *Current approach to renovation*

The Municipality of Amsterdam approaches the renovation of the quay wall waterfronts in stages and is based on what action is required for a particular length of wall. These stages are referred to as:

i. Assessment
ii. Life span extension
iii. Supporting
iv. Replacement
v. Monitoring and sensing

The stages of life span extension, supporting, and replacement are the focus of this research. From the perspective of changes to waterfront spaces caused by renovation of the quay walls, the three aforementioned stages can also be understood as measures to "reduce", "replace", and "reinforce", respectively. The difference between them are illustrated in *Figure 4.6*.

The "reduce" measure is used when the presence of heavy loads on the land side of the quay wall pose the most risk to the stability of the wall. To reduce the loads placed on the wall the materials and functions in waterfront spaces are limited so as to reduce as much weight as possible in balance with retaining basic functions like vehicular and pedestrian access. From site visits and interviews with municipal engineers (Appendices C and D) the reduction of weight is achieved by removing car parking functions and removing paving units and replacing these areas with extensive planting of small shrubs to hold the exposed soil in place. In some places this also includes removing street trees. These changes can present a nuisance to local residents who use the car parking areas or want to have direct access to the waterfront. In the sites visited where the reduce measure was taken there were no boats nor houseboats seen moored against the affected section of the wall.

The "reinforcement" measure is used when the quay wall structure can or should be supported from the water side. Reinforcement measures are combined with measures to reduce the loads on land. To reinforce the waterfront, a temporary platform is constructed from steel sheet pile – a structural element more commonly seen in industrial areas – and backfilled with sand. This protrusion into the water reduces the volume of water within the canals, changing the water flow and capacity of the canal. Where volume is removed from the canal, the reinforcement platform can be backfilled so that the sand is lower than the water's surface, effectively creating an overflow area for the water if needed. The platforms are wide – usually more than two metres – and they have the double function of reinforcing the wall at present and being used as a working platform for the replacement of the wall. In the time between their installation and replacement the platforms can become informal garden areas, injecting areas of green into some of the densest areas of the city. In other areas of the city, the platforms have also been adopted as a front yard space for house boats.

The "replace" measure is used when the quay wall and its associated waterfront are no longer safe and must be removed and replaced with a new wall structure and streetscape behind. This measure causes disruptions to the street and neighbourhood include the prohibition of car access, limiting pedestrian access, and preventing all access to the affected waterfront – the waterfront space becomes a construction

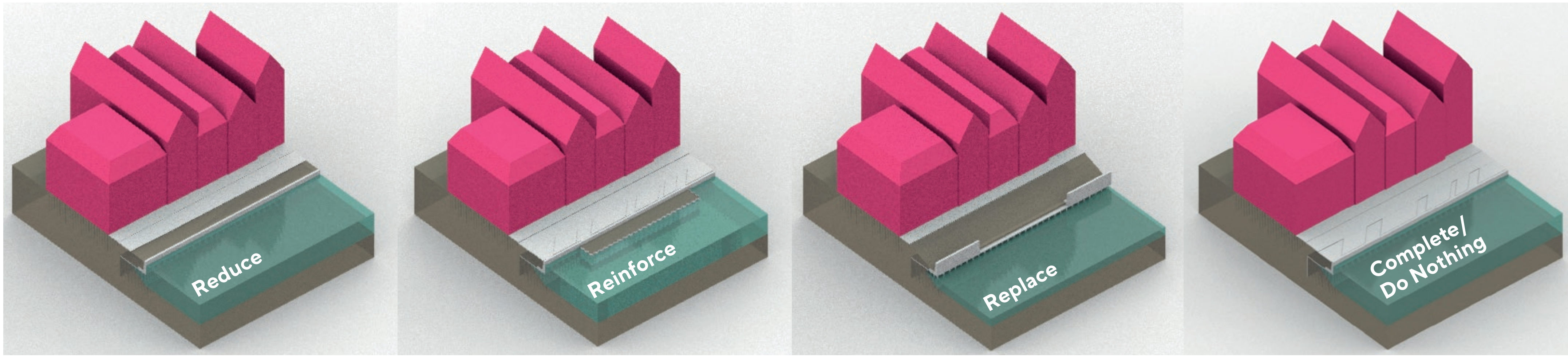


Figure 4.6. Renovation method types. Image credit: Noelle Teh

site. During this stage of renovation there is an upheaval of the entire waterfront space meaning that it becomes possible to make changes to underground services and the design and function of the waterfront spaces. For the quay walls that have been replaced in the city centre there have been few changes made to the basic functions and design of the waterfront and this is partly due to heritage restrictions but also the lack of space available between the buildings and water. To date, the replace measure appears as an exercise in maintaining the city scale functions of the waterfront in combination with improvements to the appearance of previous functions in the waterfront.

The renovation of Amsterdam's quay walls is a process that is also determined by the stakeholders present in the scales that the renovation process affects. The diversity of functions that waterfront spaces in the city provide are supported by an intersection of stakeholders with different roles and interests in the safety and continued function of waterfront spaces. Although the Municipality of Amsterdam is tasked with the renovation of the quay walls, within the municipality unilateral decisions are not made by a specific department and stakeholders from outside the municipality are also required. Once a section of waterfront has been identified for renovation, input is needed from a range of stakeholders so that they are aware of what needs to be done and how it is being done in a way that meets their interests. For example, the department of traffic and open space is responsible for the waterfront spaces on land, the engineer's office is concerned with the quay wall structure in context to its installed location, energy suppliers like Liander are concerned with maintaining their underground pipes and cables, and Waternet covers both land and water and approval from them is needed to proceed with the renovation. Rigorous and comprehensive as the process is, the specificity of the municipal departments and stakeholders tends to steer discussions about the renovation towards mainly technical concerns. Indeed, the technical aspects must be attended to but the renovated waterfront spaces must also be considered as a social act and product.

As such, the renovation of Amsterdam's quay walls is a social process with the outcomes of the renovation as much steered by technical requirements as the social requirements placed upon waterfront spaces. In interviews with municipal officers (Appendix C) it is understood that there are three "key performance indicators" (KPIs) used to steer the outcomes of renovation (in addition to safety) and are listed in terms of expressed priority:

1. **Cost** – measured as cost per metre square
2. **Benefit to people** – measured as affected persons per metre square
3. **Strategic benefit** – measured as number of strategic benefits per metre square (e.g. installing cabling for electric cars).

These KPIs reflect how the process of renovation has been steered inside the municipality and highlights the relevance of stakeholder's and citizens' input into the renovation process. Other than achieving public safety, there is clearly an interest – and opportunity – to explore further what and how benefits can be included alongside the renovation process. The types of co-benefits that are possible alongside the renovation of the quay wall are largely determined by the interests of the person or group proposing them and what time horizon these co-benefits are targeted towards.

At present the focus within the municipality has been towards researching the co-benefits that are possible during the replacement stage, some of which are visible from the newly replaced quay wall waterfronts (*Image 4.5*). Co-benefits in these locations include an increase of green areas and the installation of drainage solutions that improve the ability for water to infiltrate through to the ground below. Other strategic benefits that have been identified are installing car-charging points, decommissioning natural gas networks, and climate change in the city – all of which reflect long-term transitions that are taking place in society. This thesis proposes that in all three types of measures there are opportunities to test and propose co-benefits to the renovation of the quay wall structure.

Biodiversity planting in Singel. Image credit: Anne Bruggen

4.3. "FLATTEN" AND "SPREAD" THE CURVE OF RENOVATION

As replacement is inevitable, the two transitionary stages prior to it – lifespan extension and support – are important stages in the process of "flattening the curve" (Wolfert, 2020): i.e. increasing the time between when a quay wall is identified as a risk and when the structure is replaced (*Figure 4.7*). At present the municipality appears to have adopted this approach and waterfront spaces that have received "reduce" and "reinforce" measures will likely retain those measures in the medium term. An example of this is that for some reinforcement platforms, they are being constructed designed with a service lifespan of 10 – 20 years (Appendix C) – temporary as they may be in the time scale of the city, they are generational in the time scale of humans.

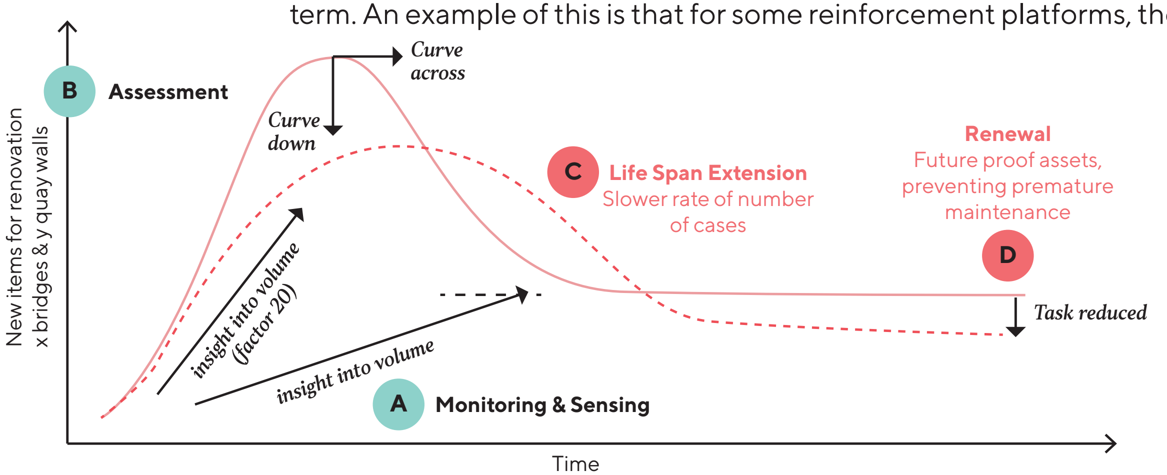


Figure 4.7. Strategy diagram to "flatten the curve" of wall replacement with relevant areas of research highlighted in red. Adapted from Henk Wolfert, 2020

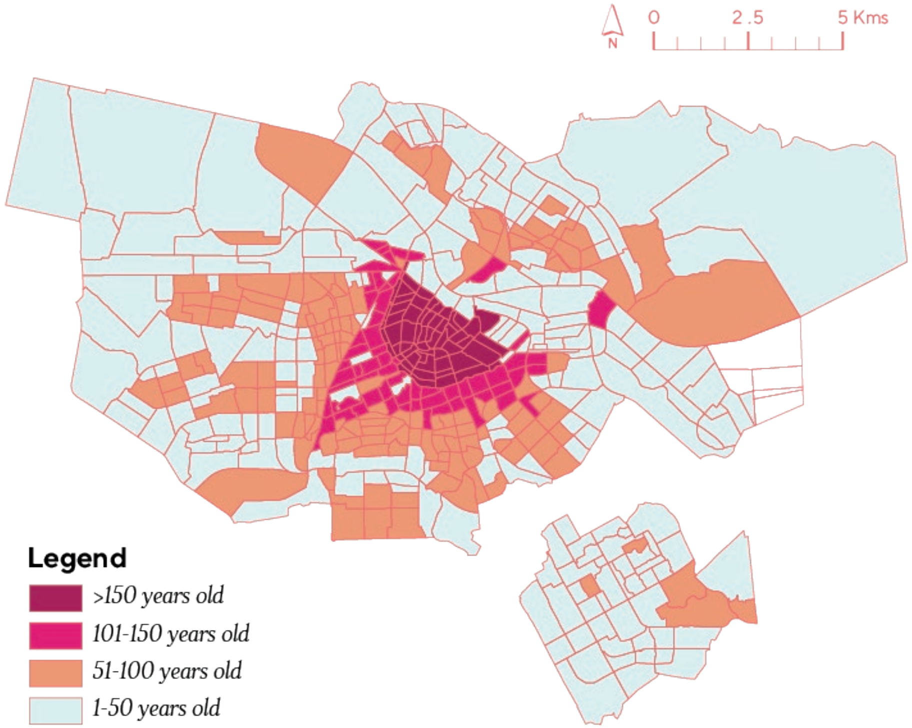


Figure 4.8. Progression of quay wall renovation based on assumed neighbourhood age. Data credit: BAG, BGT, Gemeente Amsterdam 2020.

The motivation for delaying the renovation of the quay walls becomes more apparent when the spatial scale of the task is analysed. To visualise the renovation's effects at the scale of the city, an analysis was undertaken on the anticipated progression of the renovation based on the assumed age of the quay walls in the neighbourhood (refer to methodology for details). The map in *Figure 4.8* shows the anticipated progression of renovation throughout the city's waterfront neighbourhoods in intervals of 50 years. Using the assumption that quay wall structures require renovation after 100 years it can be seen in the map that there are currently 109 neighbourhoods that contain quay wall waterfronts in need of renovation. Delaying the renovation of the quay walls is necessary so that the works can occur in balance with the operation of the city and its functions. The scale of the task becomes greater when the coming decades are considered. In the map (*Figure 4.8*) it can be assumed that an additional 32 neighbourhoods will be added to the 109 that are currently within range for renovation. This shows that the spatial planning of the renovation program also needs to look beyond what needs to be renovated now and take preventative action to also delay the degradation processes that are taking place around quay walls that in the coming decades will also be more than 100 years old, of which some will be in need of urgent replacement.

This can be done by extending the "reduce" and "reinforce" measures to waterfronts not yet in need of immediate attention and to do this in a way that also addresses the causes of quay wall degradation. The proposed strategy is comprised of two parts: identifying which neighbourhoods should have measures taken pre-emptively, and creating a list of functional requirements that detail which degradation processes should be limited as much as possible.

4.3.5 Impact as a variable for delaying quay wall replacement

In previous sections the "quay wall impact score" was described and is used presently as an important part of a city-wide strategy to delay the replacement of quay wall waterfronts in Amsterdam. The purpose of this is to extend the service lifetime of the quay wall structures so that replacement can take place at a later date. *Figures 4.9–4.10* illustrate the difference between what is understood to be the current approach to renovation and the proposal being made to extend the "reduce" and "reinforce" measures to delay the need for replacement in the long-term. *Figure 4.11* illustrates the proposed "spreading" of measures over Amsterdam's waterfront neighbourhoods in comparison to the current scope (*Figure 4.12*).

This is a proactive approach to the renovation of the quay wall waterfronts – "proactivity" being a principle ascribed to by the renovation programme (Gemeente Amsterdam, 2019) – but means that the spatial coverage of measures will need to increase. While this presents an additional expenditure in the short term, the long term benefits would be to alleviate the struggle to keep up with renovation of the quay wall waterfronts.

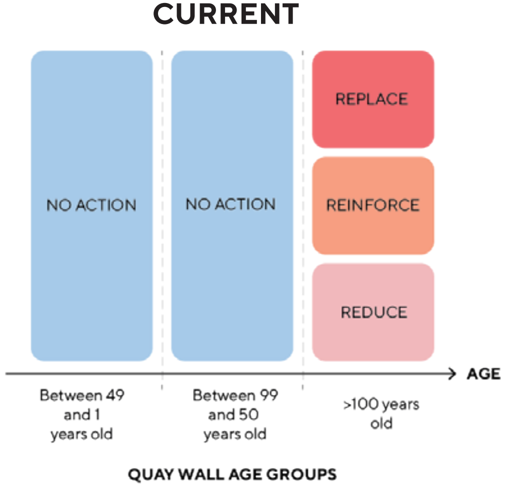


Figure 4.9. Current approach to types of quay wall renovation (top left). Image credit: Noelle Teh

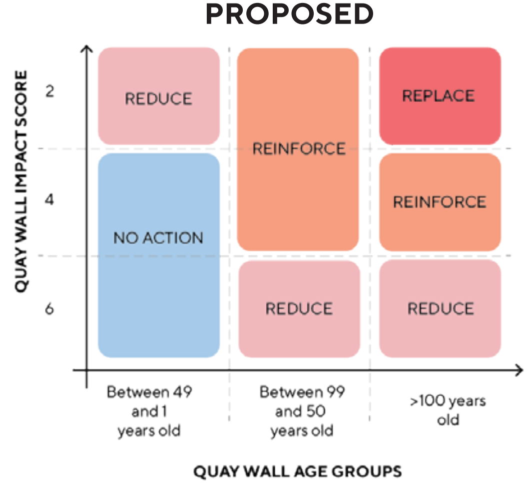


Figure 4.10. Proposed approach to types of quay wall renovation (top right). Image credit: Noelle Teh

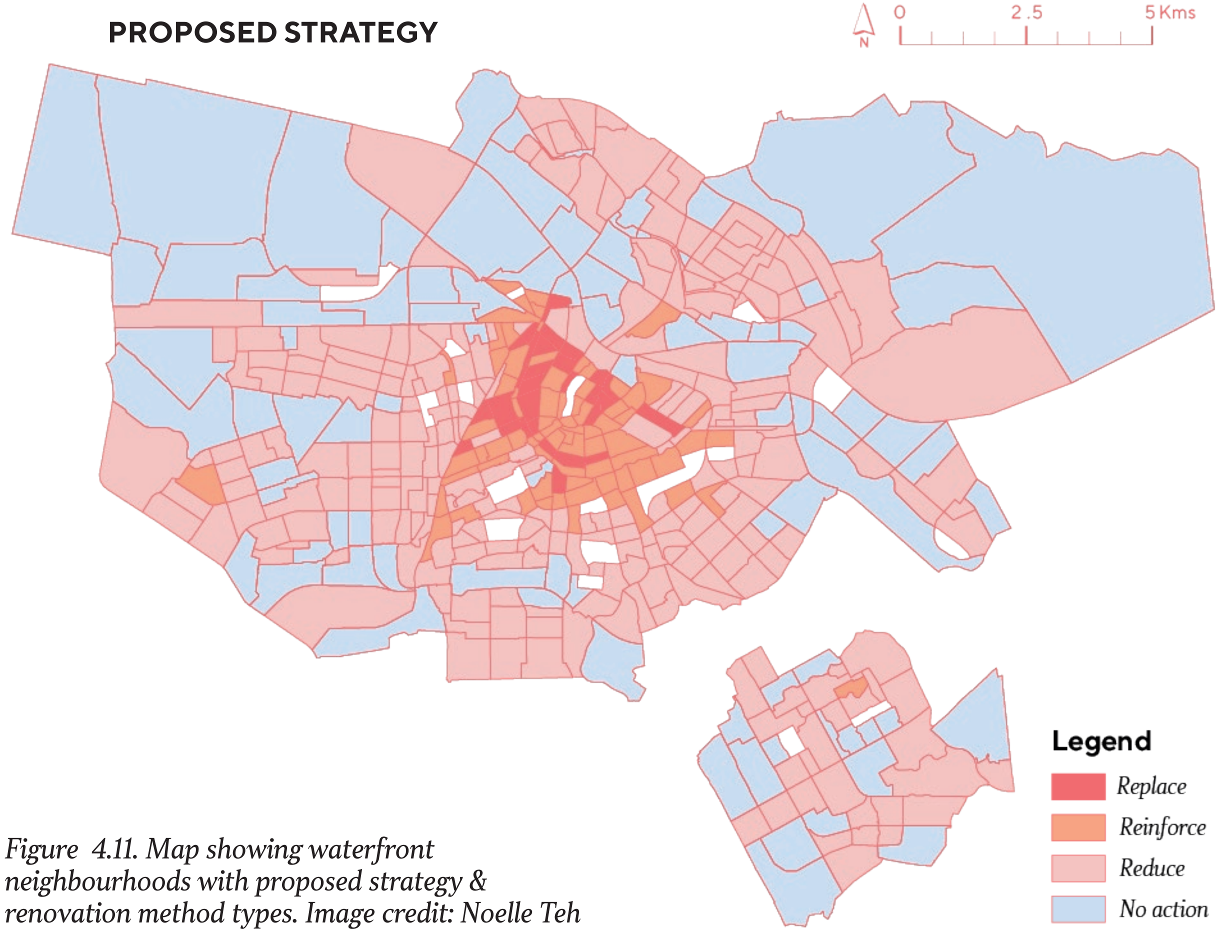


Figure 4.11. Map showing waterfront neighbourhoods with proposed strategy & renovation method types. Image credit: Noelle Teh

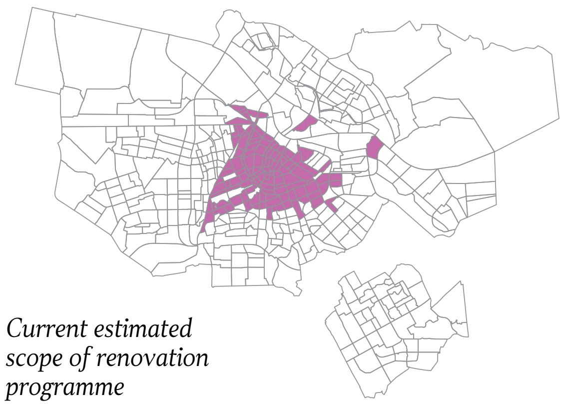


Figure 4.12. Reference key map showing current scope of renovation of walls more than 100 years old (based on age analysis). Image credit: Noelle Teh

4.3.6 *Functional requirements to delay quay wall replacement*

The second part of the proposed strategy is to reduce the impacts of the processes that cause degradation of the quay wall structures and in doing so further delay the time to replacement. Below, a list of functional requirements is proposed and forms the basis of how the "reduce" and "reinforce" measures are designed:

Functional requirements	Solution indicator
Reduce heavy loads next to the wall	Removal of materials or functions which involve the use of heavy machinery or objects behind the wall on land side.
Reduce fluctuations in groundwater table level	Increase infiltration of water through the soil to recharge ground water table.
Regulate temperatures around the quay wall structure	Decrease exposure of wall components and improve cooling abilities of the structure and surfaces adjacent to it.
Protect canal bed from erosion	Decrease exposure of canal bed to scouring forces caused by water traffic.
Reduce live loads next to the wall	Stabilisation of trees next to quay walls. Relocation of vehicular traffic away from the wall's edge.

Because the renovation measures occur at the scale of the waterfront, the processes that occur at a city scale and neighbourhood scale need to be translated into actions that can be taken at a street scale. It should be noted that although the delaying of quay wall replacement is the goal, measures like removing all woody vegetation (as recommended by Cork & Chamberlain (2015)) have not been adopted because although a measure may be practical, in reality it may not be desirable nor necessary given the technical solutions to limit damage.

4.4. CONCLUSION

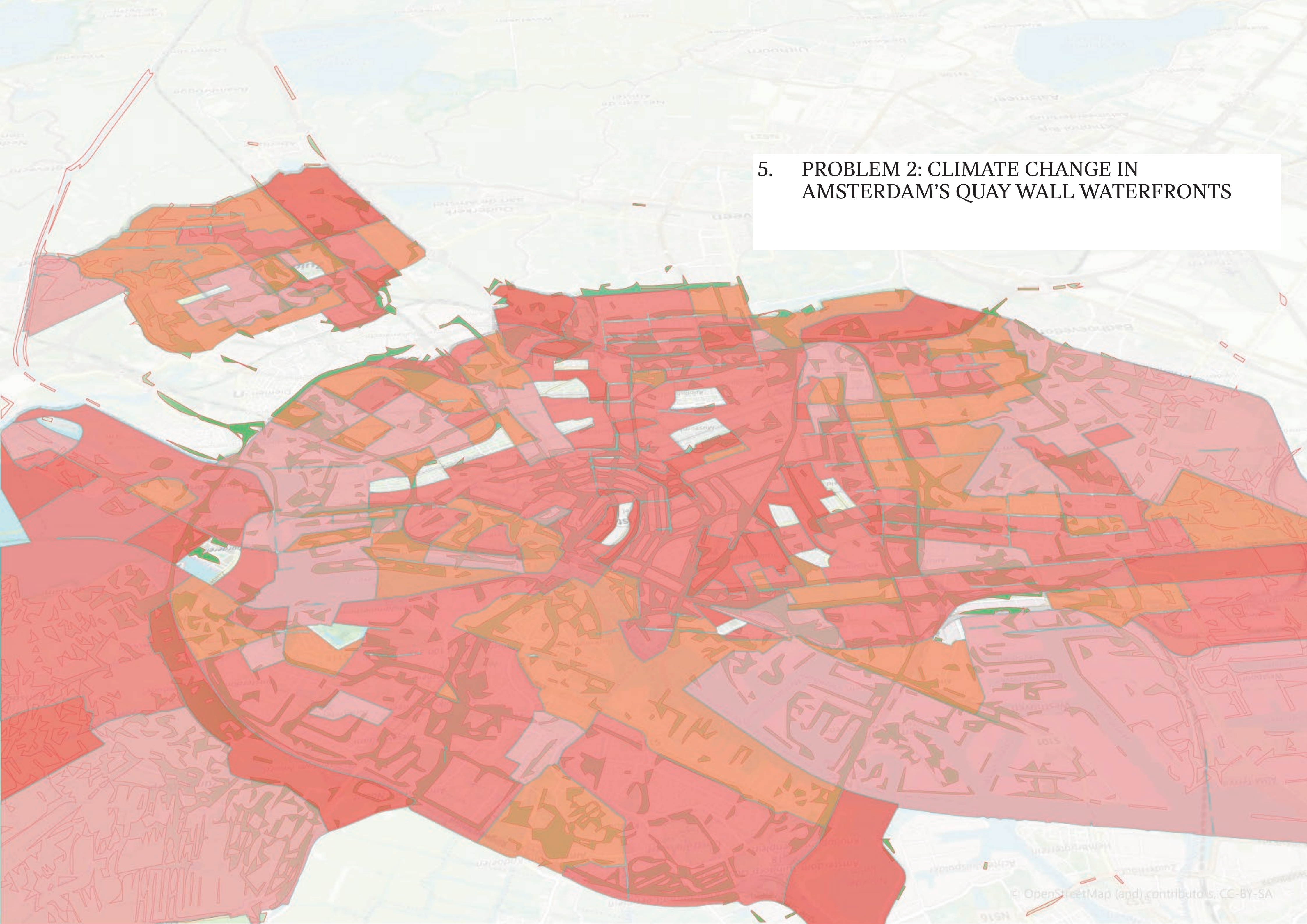
In this chapter the importance of the quay walls was described in the context of its extent throughout the city and the multi-scalar functions it provides in the city. The renovation of Amsterdam's quay walls is a technical and social process that stands to change the form and function of the city's waterfront spaces for decades to come. Due to the number of quay wall waterfronts that require renovation it is necessary to find ways to prolong the lifespan of newer quay wall structures in the city so that more time can be given to the replacement efforts currently underway while ensuring that city functions can continue in a safe and efficient way.

This chapter concludes by proposing a strategy for delaying the renovation of the quay walls using the principles of the "reduce" and "reinforce" methods and in doing so potentially assist in limiting the underlying causes for quay wall replacement. By "spreading" the renovation methods to more waterfront neighbourhoods there is also an opportunity to spread more of the co-benefits that can be created by the renovation process. This is already evidenced in current renovation sites (refer *Image 4.6*)where changes have been made that support long-term changes to make Amsterdam a more sustainable city. In the next chapter, the challenge of climate change adaptation is offered as a co-benefit that can be combined with the renovation of Amsterdam's quay wall waterfronts.

Image 4.5 Before (left) and after (right) image of replaced quay wall waterfront at Rechts Boomssloot. Image credit: Noelle Teh

This page is intentionally left blank

5. PROBLEM 2: CLIMATE CHANGE IN AMSTERDAM'S QUAY WALL WATERFRONTS



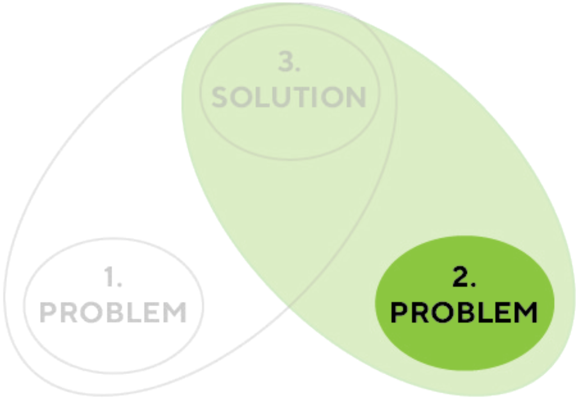


Figure 5.1.Chapter content with respect to theoretical framework. Image credit: Noelle Teh

Amsterdam, like the rest of the Netherlands, is vulnerable to the effects of climate change: increasing temperatures and unseasonal changes in precipitation that cause flood and drought at different times of the year (Ivens, 2020; KNMI, 2014). These, in addition to sea level rise, pose a serious threat to the city and greater Amsterdam area.

Urban waterfront spaces are uniquely affected by changes in the climate and these changes go beyond affecting the social and ecosystem functions that waterfront spaces offer because they also change the processes that cause the quay wall structure to degrade. Therefore, the changing climate is also of concern to the renovation of the city's quay wall waterfronts because there are already enough challenges at present that need attention (e.g. keeping construction pace with the number walls that need to be replaced now). Despite climate change presenting another complication to the renovation process, this chapter summarises the causes and effects of climate change – specifically drought, flood, and heat – and how they affect the quay wall waterfronts of Amsterdam.

The purpose of this inquiry is to identify climate change processes that affect the city's inhabitants and also the quay wall waterfronts that people use and enjoy. Once these processes are identified a list of functional requirements is proposed that address quay wall degradation alongside creating climate resilient waterfront spaces for the city's inhabitants.

In this chapter, the research question:

"How does climate change affect Amsterdam's waterfront spaces and how can addressing climate change be combined with the renovation of quay wall waterfront spaces?"

is being addressed and the results from this question are used to establish the variables relating to the causes and effects of climate change on waterfront spaces in the city.

5.1. "NEW NORMAL": CLIMATE CHANGE IN AMSTERDAM

In February 2020, the Municipality of Amsterdam published their climate adaptation strategy (Ivens, 2020) in which the specific approaches taken by the municipality regarding climate adaptation were described. These approaches included promoting research and innovation and working together with public and private bodies to make the city resilient and "climate proof" (Ivens, 2020). Examples of working together with other public bodies included research that has been done together with the *'Geneeskundige en Gezondheidsdienst Amsterdam'* (GGD) on the impacts of increased temperatures on human health, and the stormwater projects completed with Waternet under the 'Rainproof Amsterdam' initiative.

The strategy's aims to "climate proof" the city are promoted as a way to protect and enhance the liveability and the social, economic, and physical value of the city despite the effects of climate change. The effects of climate change in this perspective are something to be adapted to as a "new normal" (Ivens, 2020, p. 2) way of life in the city. In addition to the climate adaptation strategy the municipality is undertaking various programmes that are targeted towards climate mitigation–e.g. "Carbon neutral Amsterdam" and "Circular Amsterdam". Where the adaptation strategy seeks to make changes to the form and functions of the city, the mitigation strategies predominantly target the behaviours and processes in the city.

The "new normal" that is being proposed is further supported by the prediction that the effects of climate change will continue (Locatelli, 2011) irrespective of the current adaptation and mitigation strategies in place: there is no known end point for when adaptation and mitigation

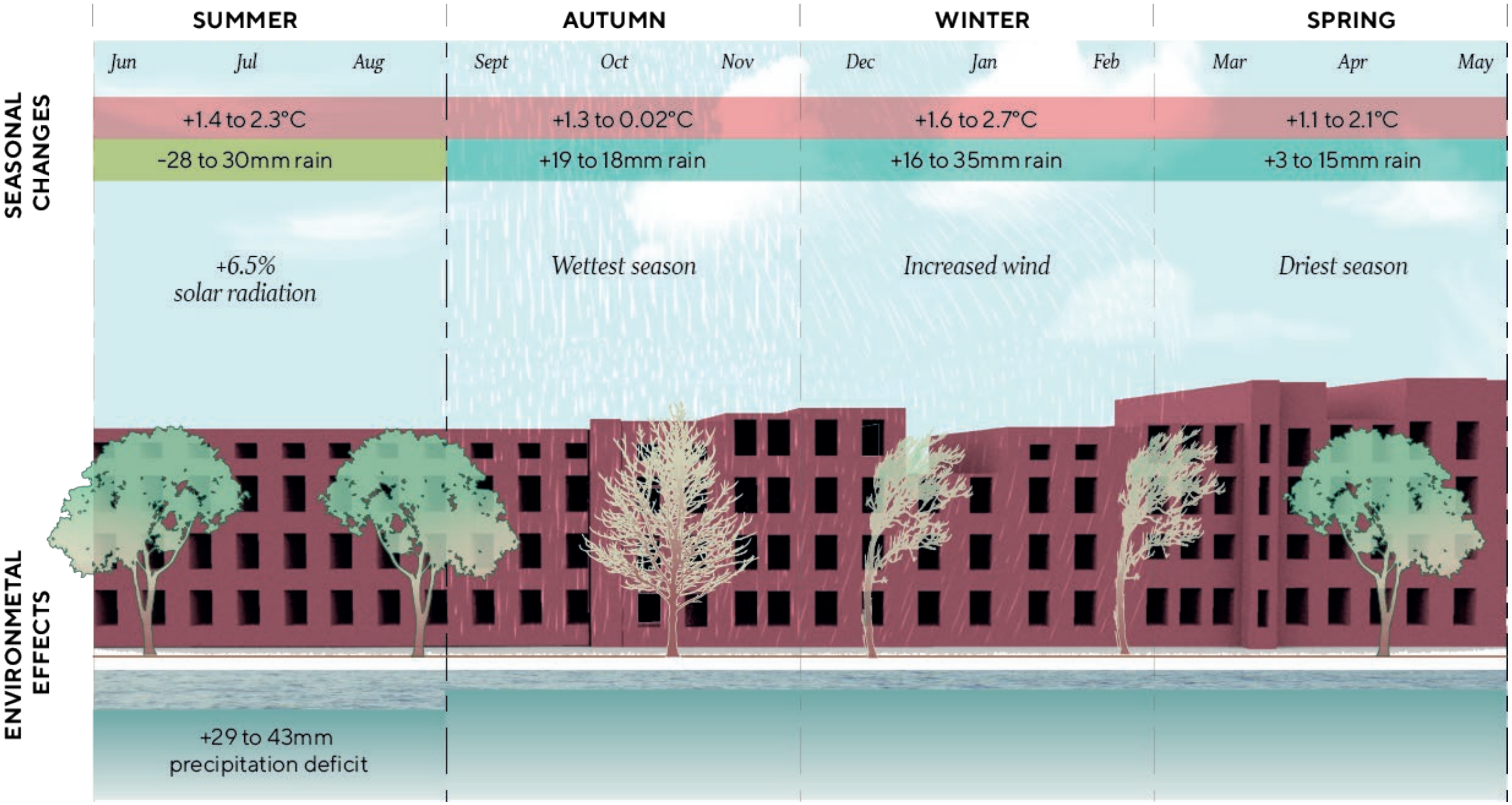


Figure 5.2. Anticipated effects of climate change, current and 2050WH scenario visualised in context to urban waterfronts. Data credit: KNMI, 2014

measures are needed. The data and predictions from the Dutch meteorological institute (KNMI) reflect this "new normal" as changes to the climate are differentiated only in magnitude of change.

In 2014, the KNMI published a revised report on the anticipated effects of climate change in the Netherlands and outlined what the consequences could be for people and the natural environment in the Netherlands. These anticipated effects were presented as scenarios based on changes to wind patterns and global temperatures with the resulting four scenarios commonly referred to as the "KNMI '14 scenarios" that predict changes in two time horizons: 2050 and 2085 (KNMI, 2014).

For this thesis it was decided to use the scenario "WH" until the year 2050 (2050WH) that represents the most change to wind patterns and global temperature rise. Unless otherwise stated, predicted changes described in this section refer to changes between 2020 and 2050 under the KNMI's "2050WH" scenario. In the 2050WH scenario, the effects of climate change will affect all four seasons of the year and includes increases in temperatures, incidences of drought, increased rainfall and risk of flooding, and increased wind speeds. *Figure 5.2* summarises how these differences in climate will affect Amsterdam's urban waterfronts throughout the year and these differences can be categorised into three climate challenges: drought, flood, and heat.

5.2. THE EFFECTS OF DROUGHT, FLOOD, AND HEAT IN AMSTERDAM'S WATERFRONTS

5.2.1 Drought

Drought is the first effect to be described and is already occurring in Amsterdam which has had an ongoing precipitation deficit (an indicator of drought) in recent years (Ivens, 2020). There are two kinds of drought: meteorological and hydrological (Grant, 2016). The former being associated to a lack of precipitation – e.g. rainfall or snow, and the latter associated to the disruption of soil water processes in the ground, rivers, and lakes. In urban areas, the anthropogenic drivers of both forms of drought include population growth causing increased consumption, urbanisation causing increased land take and soil sealing, and climate change causing irregular weather patterns. Drought processes are exacerbated by urbanisation which disrupts the hydrological cycle at the neighbourhood and waterfront scale and also because cities create a microclimate which alters the rainfall patterns that provide drought relief. The challenge with drought is that it is a time-dependent process - although there may be rain, drought is a phenomenon that relates to the availability of water in sufficient quantities and at the right time.

The presence and severity of drought in Amsterdam is measured as the total amount of precipitation minus the total amount of evaporation between the months of April and September (Klimaateffectatlas, 2020; KNMI, 2014). For Amsterdam it is anticipated that over the next thirty years the deficit in precipitation will increase, affecting the inner west, north, and southeast neighbourhoods of the city in particular (refer to *Figure 5.3*). In the coming years leading to 2050, the data from the KNMI(2014) and CAS (2020) indicates a trend towards a greater precipitation deficit.

The way that drought affects the city is experienced across the three scales and although at the city scale the damages may be limited to failing greenery in the city's parks and gardens, it can also affect waterfront structures that are placed under stress from the changing hydraulic pressures on either side of the wall. With respect to the loss of greenery in the city, this can also have a negative impact on the quay wall waterfronts as unhealthy trees can become unstable, causing the "wind rock" described in the previous chapter. If the tree is left unattended then in period of high wind the tree can easily fall over and in the process damage the wall and the surrounding waterfront space as its root ball lifts large amounts of soil with it.

Prolonged periods of drought characterised by limited local water availability are also referred to as "bottlenecks" (Mens, 2015) and occur at the scale of the district and neighbourhood creating challenges for the people who live in these areas because one of the effects of drought is a lowered groundwater table which exacerbates subsidence. Subsidence – together with a falling groundwater table – are a risk to building foundations including those of the quay walls and their waterfronts. Currently, a dry summer can cause the groundwater table can drop to as much as eight metres within Amsterdam (Klimaateffectatlas, 2020). It is fluctuations like these which increase the risk of the quay wall structures degrading faster than anticipated.

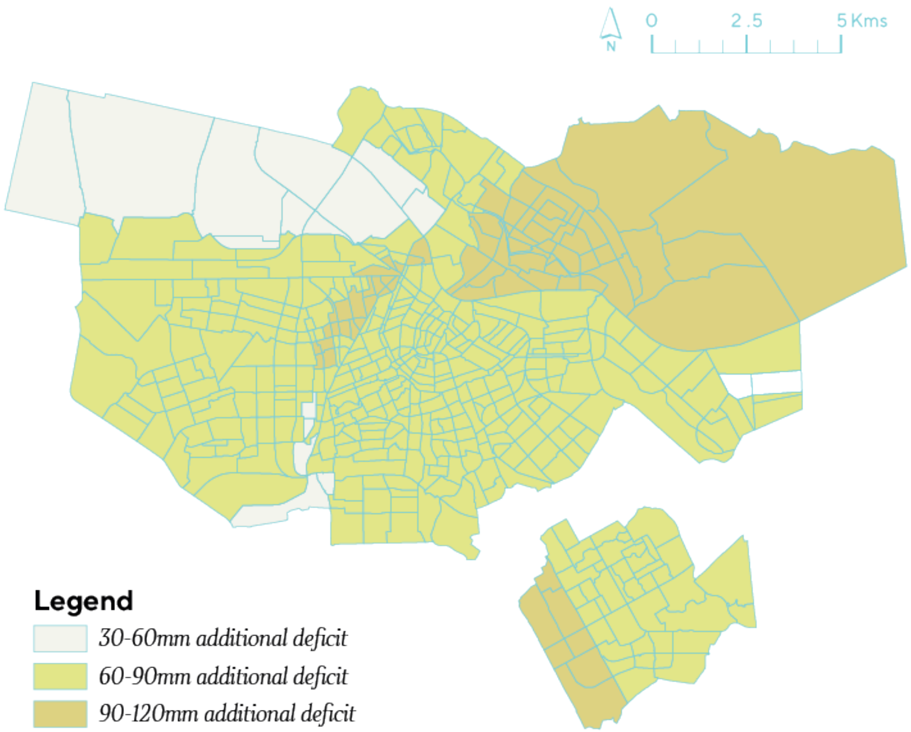


Figure 5.3. Additional precipitation deficit anticipated from now to 2050. Data credit: KEA 2020

Addressing "bottlenecks" at the neighbourhood level is possible for water-related issued as evidenced by Rainproof Amsterdam's many initiatives (Naafs, 2018). In addition to demonstrating what measures can be taken at a neighbourhood scale, the Rainproof initiatives provide insight into the potential for acting on a local scale for city-scale challenges – an approach which Woltjer & Al (2008) have recommended in the context of the Netherlands where local measures are an attractive alternative with respect to cost and benefit in comparison with large scale infrastructure measures (Woltjer & Al, 2008).

By connecting neighbourhood and city scale considerations to the design of waterfront scale measures it is possible to improve conditions locally. Measures will ultimately depend on the available space, type of soil, and height of the groundwater table but the principles employed to reduce the impacts of drought can be adopted in waterfront spaces and likely elsewhere in the neighbourhood.

The first effect of drought that can be addressed is maximising the amount of water that can infiltrate the soil when there is rain. This is done by reducing the imperviousness of surfaces in waterfront areas by removing sections of paving, for example, or using swales and raingardens to collect surface water for distribution in the soil profile below. This can assist with regulating the groundwater table therefore reducing the risk of subsidence.

The benefit of reducing paved areas are that water can better infiltrate through to the soil and that the weight from the paving is removed from the wall - a measure currently in use by the municipality. As a result of removing the pavers the ground surface will need to be covered to prevent additional moisture leaving the ground via evaporation. Plants – and those which are drought tolerant – are best for this function and through the addition of organic matter increases the amount of moisture in the soil.

5.2.2 Flood

In addition to prolonged and severe periods of drought, Amsterdam is also vulnerable to a higher risk of flooding due to climate change. According to the KNMI (2014) the amount and intensity of rainfall will continue to increase in the coming decades, placing additional pressure on the capacity of the soil and stormwater infrastructure network to effectively collect and discharge stormwater. There are two types of flooding that effects the city and its waterfronts (Rosenzweig et al., 2018):

1. Fluvial: flooding when water bodies overflow and inundate adjacent areas
2. Pluvial: flooding when the rate of precipitation exceeds the capacity of the water to infiltrate through the soil or drain through stormwater infrastructure causing ponding and overland flow.

Like drought, the anthropogenic drivers of flood are population growth, urbanisation, and climate change. Urban areas are also more prone to heavy rainfall events and this is in a large part due to the urban heat island (UHI) effect as heat increases turbulence in the air triggering precipitation (Grant, 2016; Richards & Edwards, 2018).

Across the city the effects of flooding vary between neighbourhoods and is influenced by the presence of a high groundwater table (meaning that the soil is quickly saturated) and/or being located in a low point in the landscape (e.g. Oosterpark in Amsterdam's east). For waterfront neighbourhoods the risk of flooding from the canals is smaller than flooding from rainfall because the canal is actively managed by Waternet in coordination with other water boards and authorities – the height of the water in canals is managed so that the water level maintains the range of approximately 0.30 – 0.40 NAP in the inner city(Appendix C). Flooding is an effect of climate change that highlights the complex networks of stakeholders involved with water management in Amsterdam and The Netherlands a whole. This is also reflected in the diverse range of water bodies and approaches to them found within the city – the quay wall waterfronts being one part of a greater whole.

When flooding occurs, it is measured and classified according to its effects on human health and property. Using the literature by Moftakhari et al (2018), Stone et al (2011), and Rovers et al (2014), ***Figure 5.4*** shows the depths of flood water alongside the impacts to urban infrastructure and activities. This figure reinforcing again the complexities of the waterfront spaces and also the role of water in revealing the essential

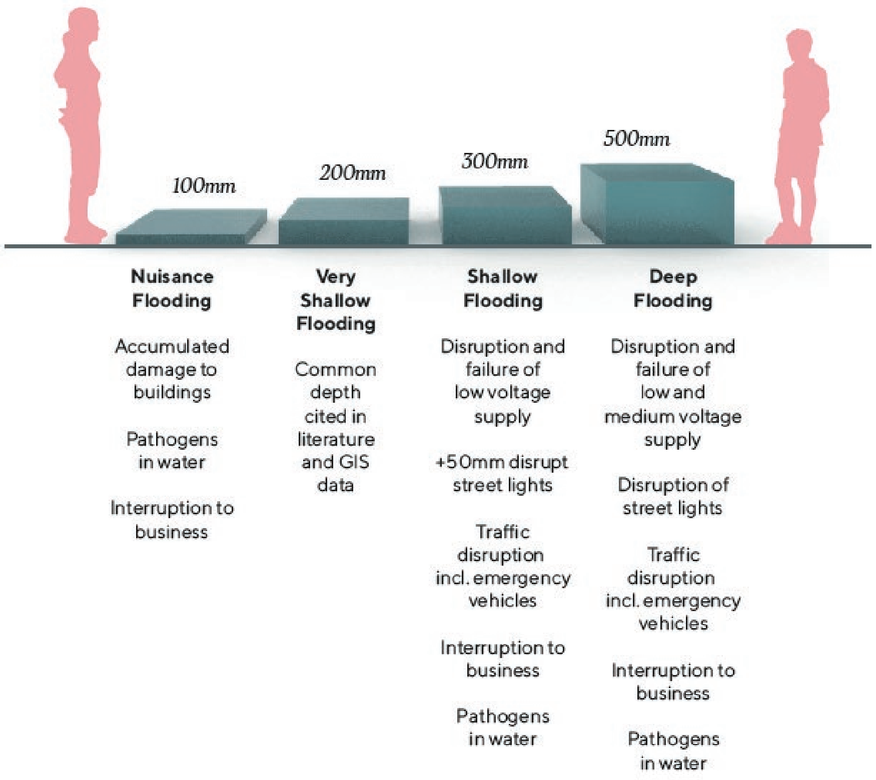


Figure 5.4. Effects of flooding at different depths in urban areas. Data credit: Moftakhari et al., 2018; Rovers et al., 2014; Stone et al., 2011

services contained within them. Although the effects of nuisance flooding are not immediately apparent, they can have severe impacts in the long term because the damages caused accumulate resulting in long-term property damage and threats to health from the build-up of contaminants from vehicles and waste on the streets (Moftakhari et al., 2018). When a mixed stormwater and sewer system overflows the result is an increase of pathogens in the surface water and this poses a risk to human health on land and when it enters the surface water network. Similarly, in heavy rainfall events chemicals and heavy metals on the road's surface runs off the waterfront edges and into the canals posing additional health risks especially in summer when many recreation activities take place in the water.

At the scale of the neighbourhood the effects of flooding are related to effects caused by drought. For example, a fluctuating groundwater table height also entails a rising groundwater which for waterfront spaces is also problematic because it changes the hydraulic pressure around waterfront structures (refer to *Figure 5.5*). The other consequence of this is that the fluctuations also reduces the strength of the pile footings that support the buildings between the canals (de Gijt, 2020). The initiatives to address flooding at the scale of the neighbourhood include creating temporary inundation areas (water features, swales, raingardens, etc) that can detain water for discharge at a later time and adding surfaces that are more permeable and able to slow the rate of water entering the stormwater system.

These measures are planned at the level of the neighbourhood to address the flood-related "bottlenecks" but are implemented at the scale of the street and waterfront. In addition to measures mentioned above, reducing the amount of impervious surfaces can also help with reducing the amount of water that enters the stormwater network, instead the water can infiltrate through to the soil and take advantage of the soil's water buffering functions. This can be assisted by plants that have root systems that increase the water holding capacity of the soil, designing floating structures, using cellular structural systems in constructions to reduce compaction to the soil. Above ground it is also possible to use green roofs (extensive and intensive) for stormwater attenuation however these are dependent on the building location and ability to bear additional loading.

These measures can be described as being part of a "controlled drainage" approach that is characterised by first utilising the soil's ability store water (buffering) while also increasing capacity in the drainage system and enabling controlled discharge of stormwater (Ritzema & Van Loon-Steensma, 2018). Measures that are taken for flooding also overlap with those for drought: increasing permeability by removing paving, creating areas for water to be stored for reuse and/or discharge, and using plants to retain moisture in the soil.

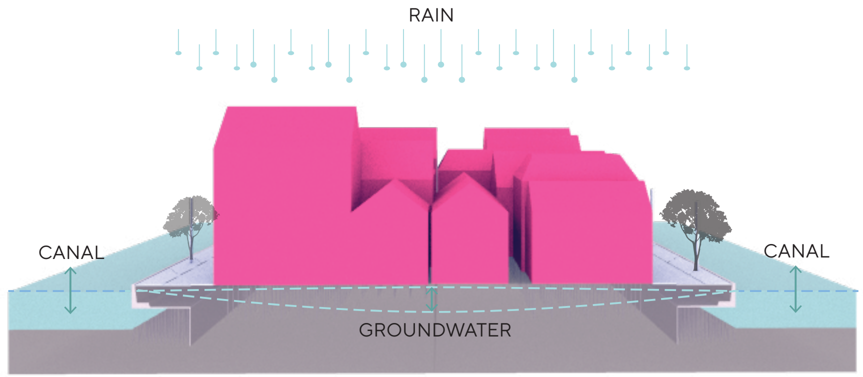


Figure 5.5. Groundwater fluctuation impacts to waterfront areas. Adapted from: de Gijt, 2020.

5.2.3 Heat

Related to precipitation and drought is the increasing temperatures (heat) resulting from climate change. Increasing temperatures are particularly problematic for urban inhabitants because increased temperatures exacerbates the urban heat island (UHI) effect. The UHI effect is defined as the temperature difference between urban and rural areas with urban areas having higher temperatures than their peri-urban and rural surroundings (Heaviside, Macintyre, & Vardoulakis, 2017; Li et al., 2019). The UHI effect takes place over a diurnal cycle expressed by the way that temperatures drop at night but the potential cooling benefit is diminished by the release of solar energy stored as heat in building materials and water bodies (Steeneveld, Koopmans, Heusinkveld, van Hove, & Holtslag, 2011).

Anthropogenic heat sources include cars and industrial machinery, as well as the materials that cities are built with, characterised by dryness and low albedo that affects how heat is stored and released. The UHI effect is also exacerbated by the altered airflow patterns caused by the geometry of the city (Heaviside et al., 2017; Stone et al., 2011). In the years between now and 2050 it is expected that temperatures will continue to rise due to climate change increasing the severity and extent of the UHI effect and its negative effects on public health and public spaces like the quay wall waterfronts of Amsterdam.

Increased temperatures and their persistence throughout the day and night is a risk to public health, especially those who are elderly or have pre-existing conditions that make them vulnerable to heat (Heaviside et al., 2017; RIVM, 2019). For the Netherlands, heat stress becomes a health issue at a Physiologically Experienced Temperature (PET) of 23C and upwards (refer table *Table 5.1*).

Figure 5.6 shows the current distribution of high and extreme heat stress in Amsterdam's waterfront neighbourhoods. This map should also be read with the knowledge that temperatures will increase in the coming years to 2050.

Although waterfront spaces contribute to the UHI effect, they can also provide respite by providing access to the water for swimming or recreational activities like rowing during the warmer months. This is another instance of "intangible" benefits that waterfronts offer to the inhabitants of Amsterdam. However, the buildings that flank the waterfront spaces are the greatest contributor of heat by surface area, and the vertical face of the quay walls can also contribute to the amount heat. The walls form a part of what is referred to as the urban canyon –

PET (°C)	Perception	Physiological stress level
0-4	Very cold	Extreme cold stress
4-8	Cold	Strong cold stress
8-13	Cool	Moderate cold stress
13-18	Fresh	Light cold stress
18-23	Comfortable	No issues
23-29	Slightly Warm	Light heat stress
29-35	Warm	Moderate heat stress
35-41	Hot	High heat stress
>41	Very Hot	Extreme heat stress

Table 5.1.Physiological Equivalent Temperature (PET) classification for the Netherlands. RIVM (2019, p. 23).

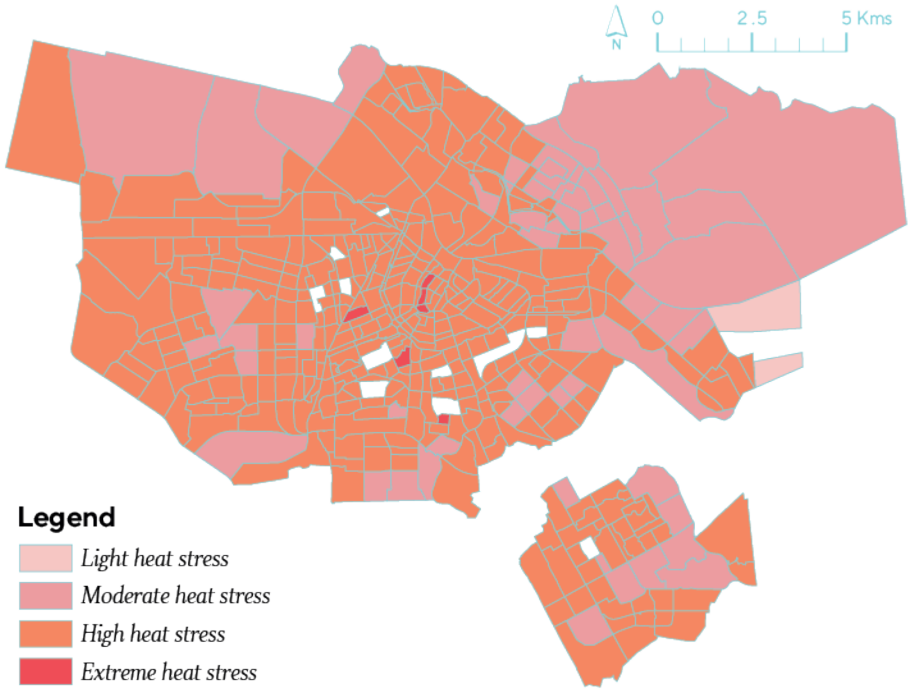


Figure 5.6. Waterfront neighbourhoods and their current vulnerability to heat stress (left). Data credit: KEA 2020, BGT 2020.

the canyon formed by buildings on either side of a road or in this case canal and road – and the further apart walls are the more chance there is of heat being transported away by air (Shishegar, 2013).

The presence of water is another factor in the UHI effect because although it transports heat away quickly, depending on the size and movement of the water, it can also be a heat source. This is because when the surface temperature of the water is greater than the surrounding air temperature, heat continues to warm the heat above it (Jacobs et al., 2020). As a result, measures that aim to change the airflow in waterfront areas may not be successful in cooling waterfront areas – especially those in an urban canyon – because increase airflow does not necessarily result in the heat being transported away (Li et al., 2019). *Figure 5.7* shows which quay wall waterfronts currently are likely to release heat and for a continuous stretch of days. As it is at the scale of the waterfront that impacts of heat are experienced by humans it is therefore at this scale that the following analysis is focused.

The measures that can be used to reduce the UHI effect in the city's urban waterfront spaces include reducing the amount of area sealed with hard paving materials, changing surface materials to have a higher reflectivity (albedo), shading the water's surface, and increasing areas with shrubs and trees that cool the air via evapotranspiration. City inhabitants can also decrease the amount of heat sources in urban waterfronts by reducing car usage and the use air-conditioning units that generate more heat in external spaces. Relating to the quay wall structure, reducing car usage during warmer months in waterfront areas would also assist with preserving the wall structure.

With respect to plants, it should be noted that during high temperatures there is an increase in transpiration activity by plants which increases their consumption of water and in times of drought this may pose a risk to maintaining the groundwater levels needed to protect the pile foundations under buildings and structures. As with concerns regarding increased evapotranspiration, it is also necessary to evaluate the cooling effect of plants during the cooler seasons as having more heat in colder months is also a health benefit (Heaviside et al., 2017).

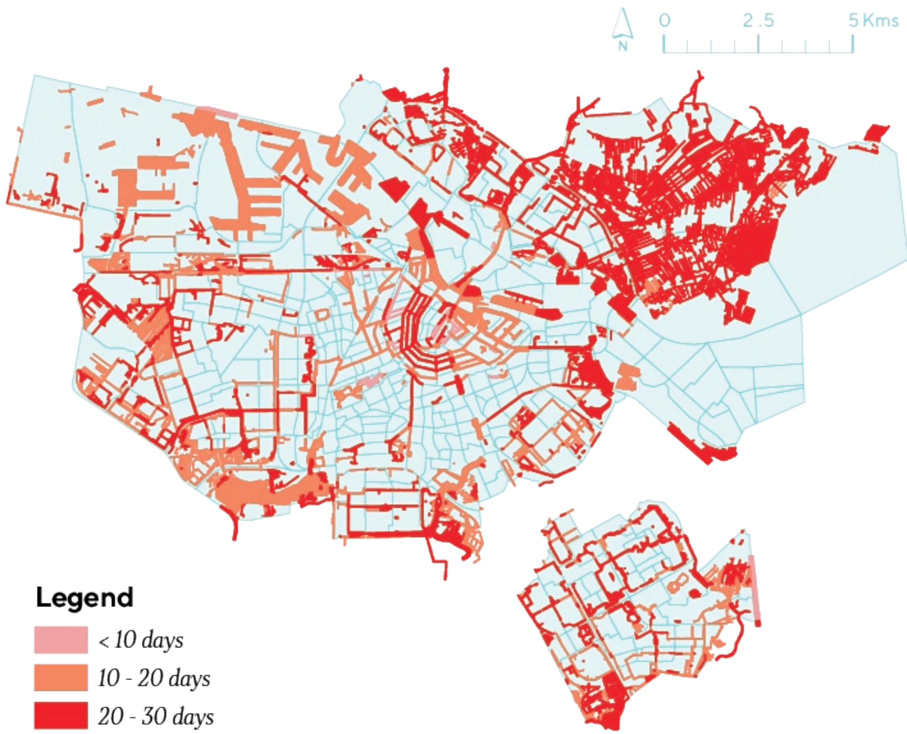


Figure 5.7. Number of continuous days that Amsterdam's surface water bodies are likely to release heat. Data credit: KEA 2020, BGT 2020.

5.2.4 *Climate change impact score*

The maps shown in previous sections of this chapter show how the effects of climate change are present in all waterfront neighbourhoods and the varied way in which they are affected by climate change. This is due to the variations in aspect, topography, hydrology, and geometry causing some neighbourhoods to be more vulnerable to climate change than others. Understanding where these differences lie is necessary as part of proposing solutions for the range of waterfront spaces in the city.

To do this, a constructed scale was created to classify which neighbourhoods were more vulnerable to the severe and extreme effects of climate change. This constructed scale is referred to as a "climate change impact score". This score was made by first assigning an ordinal range to the geodata relating to climate change and is based on what was used by the geodata owner (e.g. RIVM for heat) or in the literature. Next, the resulting ranges were given an impact score where the most severe or detrimental impacts equalled a score of one and the remaining ranges either a score of two or three depending on the data type. These scores were attributed to reclassified geodata and then summarised within the waterfront neighbourhoods. The scores were added so that neighbourhoods with the smallest scores had the highest vulnerability to climate change and neighbourhoods with the largest scores the least vulnerability.

Table 5.2 summarises how the impact score was devised and what assumptions were made to create the ordinal ranks.

				IMPACT SCORE (1 = MOST IMPACT, 3 = LEAST IMPACT)		
Data description (time)	**unit**	**Explanatory notes**	**range**	**1**	**2**	**3**
Drought - groundwater level drop summer (current)	m	Based on intervals in source data.	ordinal	up to 8m	1.5-2	<1.5
Precipitation deficit (trend)	mm	Based on intervals in source data.	ordinal	120	90	60
Groundwater level drop (2050WH)	m	Based on intervals in source data.	ordinal	drop or increase	no change	
Water depth 1:100 year pluvial flood (current)	mm	Based on intervals used in data and research.	ordinal	>200	<200	
Water depth 1:1000 year pluvial flood (current)	mm	Based on intervals used in data and research.	ordinal	>200	<200	
Increase number of days with 15mm or greater of rain (2020-2050WH)	days	Based on the limits of the data.	ordinal	4 more days	2 more days	
Water depth 1:100 year fluvial flooding (current)	mm	Based on intervals used in data and research.	ordinal	>200	<200	
Chance of >200mm deep flooding in 1:100 event (2050WH)	mm	Based on intervals used in data and research.	ordinal	> moderate or high chance	small chance and below	
Waterfront areas with high heat stress levels (current)	C	Based on RIVM recommendations for extreme heat stress.	ordinal	>41C	<41C	
Duration of heat release by water bodies (current)	days	Based on intervals in source data.	ordinal	>10 days	<10 days	
Duration of high night time temperatures (current)	days	Based on estimation of what may be considered undesirable.	ordinal	>1 week	<1 week	
Duration of high night time temperatures (2050WH)	days	Based on estimation of what may be considered undesirable.	ordinal	>1 week	<1 week	

Table 5.2.Constructed scale for climate change impacts in Amsterdam's neighbourhoods that contain waterfronts.

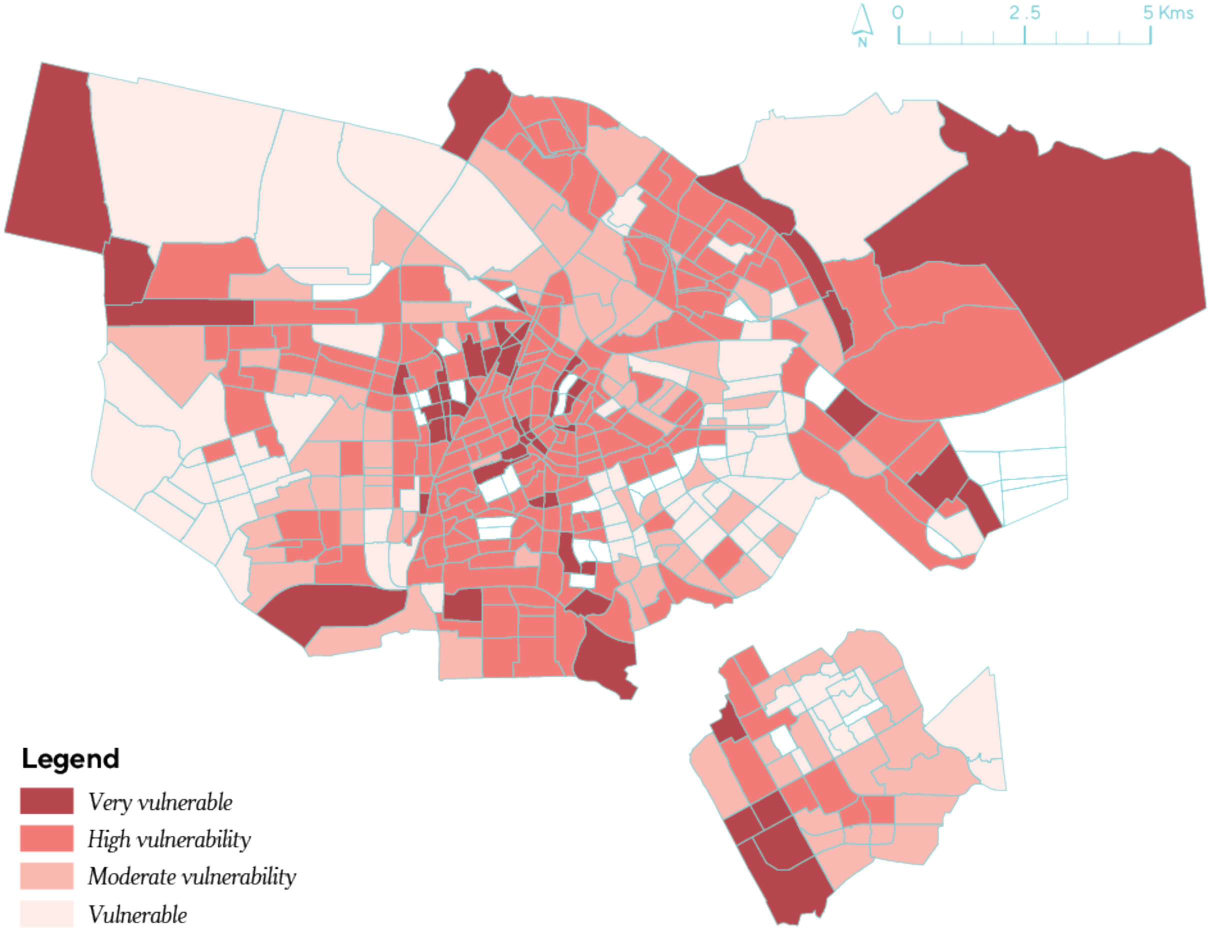


Figure 5.8. Map of Amsterdam's neighbourhoods with waterfronts ranked according to vulnerability as a result of climate change impact score. Data credit: KEA, Gemeente Amsterdam, BGT.

The impact score is used as a way to order the neighbourhoods for this research and to understand what the overall differences are between waterfront neighbourhoods – indeed it would also be possible to change the impact scores to give preference to some effects over others. To answer the research question of this chapter it is sufficient to use the impact score to compare neighbourhoods and in later chapters use the detailed breakdown of scores for the design of possible solutions.

An unabridged version of the table can be found in Appendix E and also includes the impact scores for each neighbourhood. *Figure 5.8* visualises the results ordering them further using a quartile classification to create groups of neighbourhoods based on their vulnerability to climate change. The map provides insight into the climate change vulnerability that these waterfront neighbourhoods face and how waterfront spaces can serve to alleviate this.

What is also visible in the map is the wide spatial distribution of "very vulnerable" waterfront neighbourhoods and the high number of "high vulnerability" neighbourhoods and the way in which the latter class of neighbourhoods connects the very vulnerable areas together. This in combination with what is known about the population densities in some waterfront neighbourhoods (refer *Figure 4.4*) highlights the importance of addressing climate change to limit the adverse effects on the city's inhabitants and urban assets.

5.3. RESILIENCE BY RENOVATION IN AMSTERDAM'S QUAY WALL WATERFRONTS

The effects of climate change in Amsterdam's quay wall waterfronts have a direct impact upon the social and ecosystem processes that take place within them and if left unaddressed will result in the degradation and reduction of functions and services that waterfront spaces provide to the city's inhabitants. Climate change is relevant to the renovation of the quay walls because almost all the water-related impacts of climate change are detrimental towards efforts to "flatten the curve" of the quay wall renovation and in the medium to long term may increase the amount of quay walls that need to be renovated before the end of their anticipated lifespan.

Waterfront spaces contain social and ecosystem functions and processes and it is because of this complexity that it is possible to use waterfront spaces for learning and adaptation to societal challenges like the quay wall renovation and climate change. Because these challenges are long-term and complex in nature in addition to being in the "urban", there is no instant nor uniform solution. While this may frustrate the technical and economic imperatives of the quay wall renovation programme (Gemeente Amsterdam, 2019), this situation presents an opportunity to question if instantaneous and uniform solutions are the appropriate response to the complexity and uncertainty of urban challenges.

Climate change adds to existing uncertainties within urban areas and by appreciating the hybridity and uniqueness of urban socio-ecological ecosystems there can be an alternative approach that uses the system and its processes to affect widespread changes (Schuetze, Bohemen, & Bueren, 2012). Although climate change adds uncertainty, an approach that aims for infrastructural and socio-ecological resilience can offer an alternative to the Sisyphean task of looking for certainty in uncertainty.

"Climate resilience" is a term that is generally used to refer to an ecosystem's ability to, after a period of time, recover and maintain its basic functions and characteristics after a climate-related disturbance (Andersson et al., 2017). The implications of a specifically infrastructural and socio-ecological climate resilience in Amsterdam's quay wall waterfronts are that climate-related disturbances (including those leading to quay wall renovation) are accepted as inevitable but that it is possible to learn, adapt, and improve upon the processes that can address the drivers of climate change. Climate resilience for the quay wall waterfronts therefore relates to taking an iterative approach to the challenges of climate change, creating opportunities for learning from methods used in different contexts, and adapting the approach to successive waterfront areas, and with each iteration improving the way in which uncertainty can be used to benefit the functions of the waterfront.

The quay wall renovation process is an opportunity to advance the city's goals for climate adaptation in a resilient way. In the previous chapter a proposal was made to "spread the curve" in addition to current efforts to "flatten the curve" of quay wall replacement (refer *Figures 4.9-4.10*) and in doing so extend the scope of the renovation programme to most the city's waterfront neighbourhoods. This creates an opportunity to include climate resilient measures that can address the vulnerability of waterfront neighbourhoods to the effects of climate change (refer *Figure 5.8*) that also accelerate the processes that lead to quay wall degradation. The combination of the two challenges is not novel – it has already been identified by the Dutch Environmental Agency (PBL) that strategic opportunities need to be found to combine climate adaptation measures alongside planned infrastructural works (Ligtvoet, van Oostenbrugge, Knoop, Muilwijk, & Vonk, 2015).

The capacity for the quay wall renovation programme to be adapted for increasing resilience to climate change is already visible in some sites where the "reduce" method has been applied. For example, steps have already been taken to increase permeability and vegetated areas as seen in Nieuwe Herengracht (*Images 5.6-7*) demonstrating how methods to extend the lifespan of the quay wall waterfronts can be used to increase resilience.

An approach of "Resilience by Renovation" is proposed in this thesis for the quay wall waterfront renovation to take advantage of the social and ecosystem significance that waterfront spaces have in the city by using the renovation to do two things: i) reduce the vulnerability of waterfront spaces to climate change; and ii) provide ecosystem services that can be accessed and shared at the scale of the neighbourhood and city.

5.3.5 Functional requirements for increasing resilience in waterfront spaces

This thesis proposed that resilience in Amsterdam's quay wall waterfronts is achieved at the scale of the waterfront because at this scale the intersections of social and ecosystem functions and processes can be altered and, if successful, can be replicated to other parts of the urban waterfront network. By making changes to the form and function of the waterfront it is possible to increase infrastructural resilience which seeks to foster sustainable social practices that can support broader goals towards climate mitigation (Schäfer & Scheele, 2017).

To do this, a list of functional requirements and their respective indicators is required to determine how the effects of climate change can be addressed in waterfront spaces. The list on the right sets out the functional requirements to achieve climate resilience in Amsterdam's quay wall waterfronts.

The functional requirements for resilience are proposed to act as a guide for enhancing and/or restoring ecosystem processes in urban areas to increase resilience and are imagined to be used in combination with conventional engineering solutions to drought, flood, and heat.

The approach of restoring ecosystem processes is particularly useful for water-related challenges where accepting the presence of water – and in some cases inviting water in – are better for dealing with the complexity and uncertainty of urban contexts (Tjallingii, 2012; Woltjer & Al, 2008). This is also the case for addressing heat via vegetation as mechanical methods of outdoor cooling are contradictory to long term aims of climate change mitigation.

Functional requirements	**Solution Indicator**
Increase infiltration to soil – Drought, Flood	Increase permeability of ground surface and/or drain to areas that are permeable
Increase water storage areas for future re-use or for controlled discharge to stormwater network – Drought, Flood	Construct water storage areas and make necessary connections for storage and/or discharge
Provide additional areas that can be temporarily inundated and drained at a later time – Flood	Plan and construct areas where water can be collected in case of overflow to other areas in the street
Reduce use of materials with high thermal mass - Heat	Remove or replace materials with materials that have better thermal properties
Increase use of broadleaf vegetation to increase evapotranspiration - Heat	Species selection
Shade or cover building surfaces to reduce heat absorption and release - Heat	Provide space and necessary supporting structures to shade surfaces from direct sunlight
Use plants and trees that are able to withstand heat, drought, and flood – All	Location-specific species selection

5.4. CONCLUSION

Although the anticipated effects of climate change may appear gradual or negligible from year to year, the cumulative effects of these changes still pose a threat to urban systems and the populations that depend on them (Rijksoverheid, 2016). A changing climate affects the socio-ecological systems of the city and its waterfront spaces and it does so in ways that also expedite the degradation of the quay wall structures.

Therefore, addressing the effects of climate change and particularly those related to the water system is a way to reduce the rate at which the quay wall waterfronts need to be replaced while also providing additional protection to the people and property that are affected by flood and drought. Although heat does not pose the same direct threats to the quay wall structures it is a driver for the changing precipitation and evaporation patterns that in turn increase the chances of floods and drought. Additionally, heat affects the social functions of the quay wall waterfront spaces and the increasing temperatures – if left unaddressed – will limit the range of tangible and intangible functions that waterfronts provide to the city.

In the last section, a "Resilience by Renovation" strategy was proposed to build upon the "flatten" and "spread" strategies proposed in Chapter 4. A "Resilience by Renovation" strategy proposes that the effects of climate change be addressed in combination with the quay wall renovation as a way to act upon climate change while also slowing the processes that lead to quay wall replacement. In the following chapter the research findings and recommendations of chapters four and five are applied to specific scenario sites in Amsterdam to explore how the form and function of urban waterfront spaces would change.

6. SOLUTION 3: "NATURE-BASED SOLUTIONS" FOR AMSTERDAM'S QUAY WALL WATERFRONTS

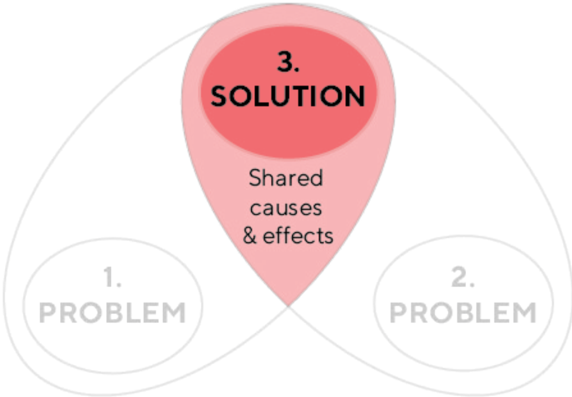


Figure 6.1. Chapter 6 content with respect to theoretical framework.

The challenges of delaying quay wall replacement and increasing climate resilience in Amsterdam's quay wall waterfronts spaces are the result of processes that take place at the scale of the city to the waterfront. Therefore, a solution that seeks to address both challenges simultaneously needs to be able to integrate processes occurring across scales and do so within the unique context of waterfront spaces in the city. In the previous chapter a strategy for both challenges - "Resilience by Renovation" - was proposed and now what remains is a method for this strategy to materialise in Amsterdam. "Nature-based Solutions" (NBS) is an umbrella concept for ecosystem-based approaches that can be used to interpret the conceptual and operational outcomes of the previous chapters and transform them – through the process of design – into material solutions.

In previous chapters, the idiosyncrasies of climate change's effects on waterfront neighbourhoods were described and showing that an NBS approach cannot consist of only a top-down solution. Indeed, taking a socio-ecological approach to waterfronts requires changes at different scales. A bottom-up, waterfront-scale approach is needed for addressing both challenges related to quay wall renovation and climate change in such a way that recognises the range of variables and process scales that waterfront spaces contain.

In this chapter, the research question:

"What Nature-based Solutions concepts can be applied to make Amsterdam's quay wall waterfront spaces more resilient to climate change while also delaying quay wall replacement?"

is being addressed by elaborating upon the decision to use a "Green Infrastructure" and "Ecosystem-based Adaptation" approach for the generation of possible solutions. In the second part of the chapter the research question:

"What are the spatial opportunities and limitations of using a Nature-based Solutions approach to address climate change alongside the renovation of Amsterdam's quay wall waterfront spaces?"

is used to summarise the anticipated NBS benefits within each landscape scenario site and is followed by an additional evaluation in which the strategy and solutions are evaluated with respect to the previous three research objectives and the socio-ecological systems present in waterfront spaces, prefacing the conclusion of this thesis.

6.1. "NATURE-BASED" CONCEPTS, PRECEDENTS, AND TECHNIQUES FOR RESILIENCE BY RENOVATION

This section begins by providing more detail on the two concepts selected for "Resilience by Renovation" strategy: Green Infrastructure (GI) and Ecosystem-based Adaptation (EBA). *Figure 6.2* illustrates the relationship between EBA and GI with respect to the umbrella concept of NBS and their potential for operationalisation as observed by Pauliet et al (2017). For this thesis, these concepts are used at different scales of the city: GI is used to create an overall city-scale strategy for increasing resilience by way of increasing vegetation alongside renovation, and EBA is used to create specific design techniques that address the previously listed functional requirements while providing ecosystem services to people in and around waterfront spaces in the city.

This is followed by an overview of NBS projects that have been implemented in recent years, summarising the lessons learned and how they can be applied to the "Resilience by Renovation" strategy in the case of Amsterdam's quay wall waterfronts.

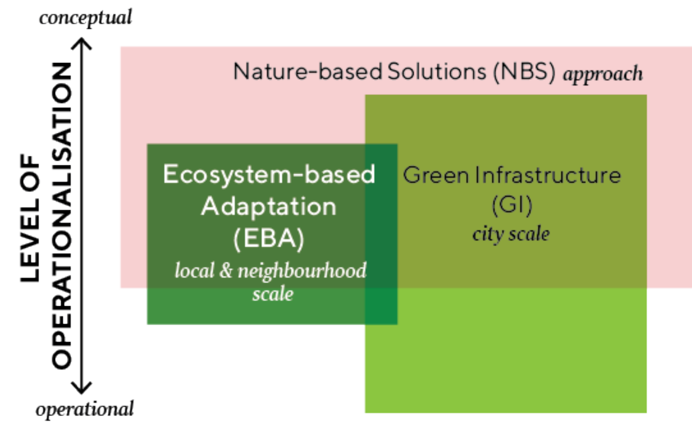


Figure 6.2. Level of operationalisation for NBS concepts. Diagram adapted from Pauleit, Zölch, Hansen, Randrup, & Konijnendijk van den Bosch, 2017, p. 41

6.1.1 Green Infrastructure for quay wall waterfronts as ecosystem service distribution network

An NBS approach to resilience by renovation is given structure at the city scale by using the concept of GI to show how actions taken at the street scale can be a part of a city-wide strategy that increases the amount and distribution of green spaces and the ecosystem services that they provide. GI is a practical approach to increasing the amount of green (vegetated) areas in the city with an emphasis on strategically planning and implementing a network of natural and semi-natural areas that integrates other environmental features and provides a wide range of ecosystem benefits (EU Commission, 2013; IUCN, 2016). In the context of achieving climate change resilience by way of renovation in quay wall waterfront spaces, a green infrastructure approach means that wherever possible green areas should be increased and connected to existing strategies e.g. biodiversity fostering, passive recreation, or urban agriculture. The adoption of a GI approach to the city scale places emphasis on the land side functions of the quay wall waterfronts. Given what is known about the closely monitored and heavily regulated water network in Amsterdam, a pragmatic approach towards water-related challenges is preferred and as a result interventions are focussed on land-side measures..

A land-based GI approach creates a network of spaces along the city's quay wall waterfront network providing a structure onto which EBA techniques can be applied to, for example, regulate water levels and in doing so delay quay wall degradation processes. A GI approach to climate resilience at a city scale conceptualises Amsterdam's waterfront spaces as a distribution network of dynamic green spaces that assist with adaptation in addition to providing ecosystem services at all three scales of the city, neighbourhood, and waterfront (e.g. reducing UHI effect, improving air quality, and increasing stormwater detention, respectively). The map in *Figure 6.3* illustrates how, at a city level, this green distribution network overlaps with the waterfront network, taking advantage of its extensiveness in the city.

6.1.2 Ecosystem-based adaptation for local climate resilience measures

The multi-scalar nature of the quay wall waterfront challenges cannot be sufficiently addressed with top-down strategies - action must also happen at the scale of the waterfront. To paraphrase from van Timmeren (2012) climate integrated designs such as those being undertaken in this thesis need to be addressed as much as possible at the human scale which in this case is the scale of the waterfront. To do this, the NBS concept of EBA is used.

Ecosystem-based Adaptation (EBA) is a concept characterised by actions that uses ecosystem services and biodiversity as part of a climate adaptation strategy to help people adapt to the negative effects of climate change (CBD, 2009a). To date it has been used in the agriculture and forestry sectors but also has applications for urban areas where it is used as a

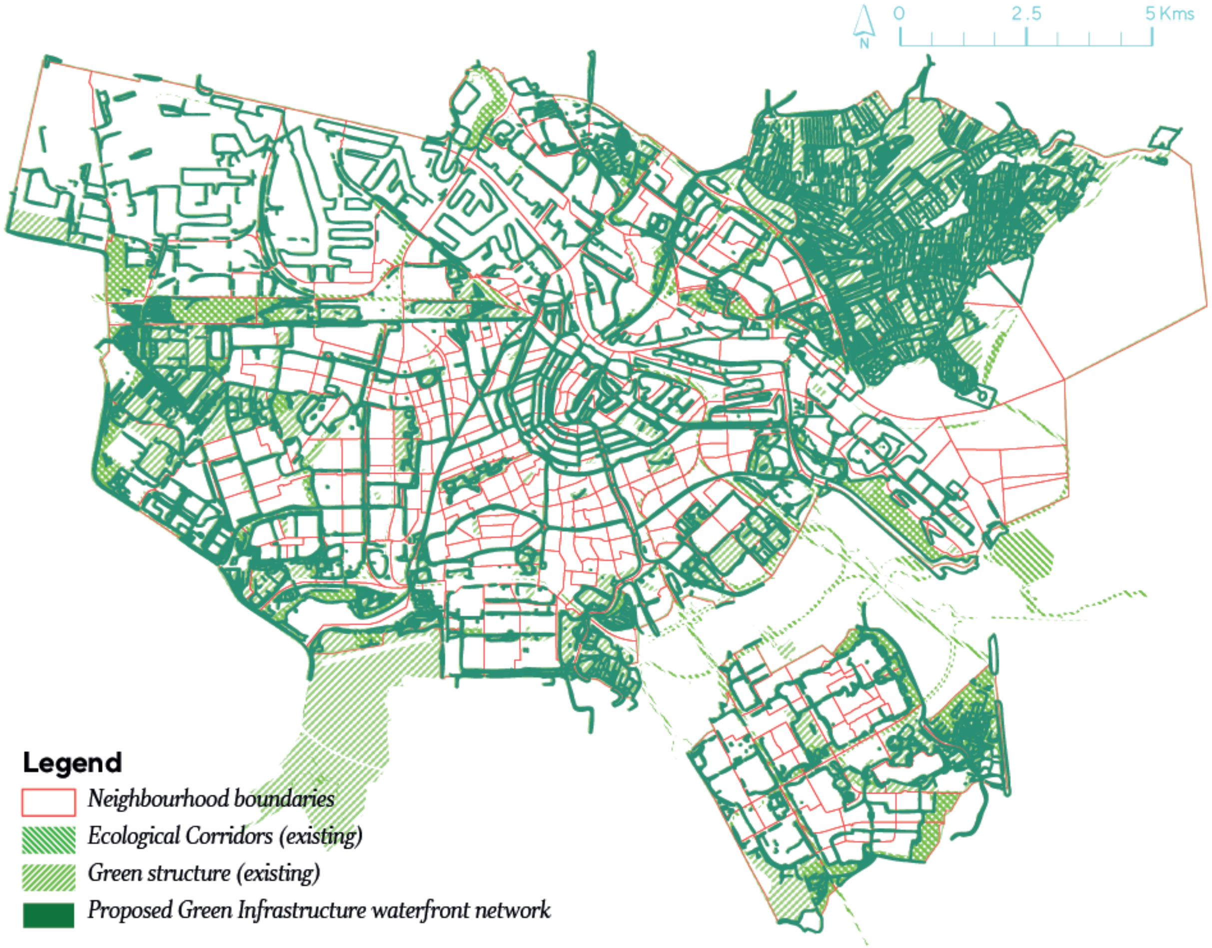


Figure 6.3. Map showing the adapted Green Infrastructure approach to Amsterdam's quay wall waterfronts. Data credit: BGT, Gemeente Amsterdam.

people-focused, cost-efficient, comprehensive, and multifunctional approach to the design and improvement of green infrastructures (Pauleit et al., 2017).

In this thesis EBA is used as an approach to materialise the functional requirements (refer sections 4.3.2 and 5.3.1) with outcomes that aim to restore and improve natural processes and biodiversity respectively to generate ecosystem services while also increasing the climate resilience of a particular area. A connection with the social system in waterfronts is also made by designing EBA techniques that in some way can be adapted – or even adopted – by people living near waterfronts and therefore supports the stated aims for socio-ecological resilience.

6.1.3 NBS case studies: insights from abroad

NBS approaches like GI and EBA have been in use prior to the adoption of NBS as an umbrella concept (Cohen-Shacham et al., 2019) but since their inclusion and re-framing as part of a suite of ecosystem-based approaches it is possible to appreciate where their methods overlap towards achieving the societal challenges that NBS approaches aim to address.

Table 6.1 (page over) provides a summary of methods that have been used in NBS projects within Europe to address urban challenges that are related to this thesis. Because the majority of NBS projects in the literature are located in Europe the result is an increased transferability of the methods used for this thesis. The projects in the table were selected based on their stated aims with a preference given to projects addressing water-related challenges and doing so at different scales of the city. As can be seen in the table, most of the projects addressed more than one category of urban challenges, further demonstrating the ability for NBS projects to provide co-benefits beyond those that the measures seek to generate. The detailed case study results are in Appendix F.

Case study findings at the city and street scale

The city scale NBS case study projects provided two insights into the opportunities and limitations of using an NBS approach for city-scale strategies:

1. Transfer of knowledge is possible between cities as there are similarities in the approaches that can be taken despite these range of reasons and geographic differences.
2. All three selected city-scale NBS projects focused on increasing the amount of green spaces in the city and relied upon different groups in society to increase the amount of green areas in the city.

Additionally, the lessons learned from the city-scale case studies are that large and dense cities like Barcelona, Berlin, and London do not have the capacity nor space to add extensive green spaces within city limits and are instead looking for ways to either consolidate and improve the quality of existing green spaces or find opportunities to add smaller areas and while doing so increase the number and spread of these small spaces throughout the city. In the context of Amsterdam's quay wall waterfronts, the renovation programme should be treated as an opportunity to add both permanent and temporary green spaces to the city.

At a local and neighbourhood scale the approaches to achieving more climate resilient spaces varied greatly: NBS projects included community bottom-up initiatives focused on participation rather than implementation as well as top-down plans and projects that were implemented as part of larger urban development initiatives. Unifying themes between the projects included:

1. Within the water flow regulation category, the case study projects demonstrated the range of different approaches and techniques that could be adapted to the quay wall waterfronts of Amsterdam.
2. The importance of citizen participation is emphasised across all projects.

A particularly relevant lesson learned (although not related to the design of measures) was that testing in the form of pilot projects or smaller test sites prior to scaling-up is valuable for settings where high numbers of people are affected by the designs and more so when there are different groups like businesses, residents, workers, etc. In the "ZOHO", "The Missing Link", and "Green Corridor" projects (De Urbanisten, 2016; Mayor of London, 2016; UrbanGreenBlueGrids, 2020) the successes attributed to them were by in large due to being performed at a small spatial scale (e.g. a section of a street) and by encouraging the participation of people who were affected by these interventions.

In summary, the case studies showed how local conditions (spatial and social) play a large part in shaping how NBS concepts are applied and eventually implemented. In urban contexts the complex systems that take place in urban spaces can present challenges to the effectiveness of approaches that must avoid disrupting or damaging adjacent functions and structures respectively. The case studies indicate that when such conflicts occur, stakeholder engagement and citizen participation are an important part of overcoming project issues.

Table 6.1. Selected Urban NBS projects with a summary of interventions proposed by the EU Commission (2015) report on NBS.

				Air quality regulation	Climate regulation	Water flow regulation		Water purification and waste treatment	Health
			Summary of methods for urban challenges adapted from the EU Commission (2015)	*Protect urban green spaces, to absorb gaseous pollutants and trap particulates. Plant trees alongside roads to trap particulates.*	*Protect urban green spaces to store carbon.*	*Plant green roofs/walls to encourage interception of rainfall. Establish rain gardens (planted depressions or swales). Use underground water storage systems. Use rainwater tanks to store water for future reuse.*		*Create ponds and wetlands to collect, store and clean water before gradual release into water courses (SUDS). Improve treatment of contaminated land through phytoremediation.*	*Make green spaces attractive to access Link schools/world to housing through green spaces Increase biodiversity within green areas (shown to reduce stress)*
Source	**Project Name**	**Location**	**Scale**			**Flood**	**Drought**		
EU Commission, 2015	Retrofitting SUDS in urban regeneration area	Malmo, Sweden	Neighbour-hood			X		X	X
	Severn Trent Water Ripple Effect investigation	Birmingham, UK	Neighbour-hood			X	X	X	
	Biotope Area Factor	Berlin, Germany	City		X		X		
IUCN, 2016	Barcelona Green Infrastructure and Biodiversity Plan 2020	Barcelona, Spain	City	X	X		X		X
Frantzeskaki, 2019	Boomjes Promenade	Rotterdam, The Netherlands	Waterfront			X			X
	ZOHO raingardens	Rotterdam, The Netherlands	Neighbour-hood		X	X	X		
	The Green Corridor	Antwerp, Belgium	Neighbour-hood		X	X			X
Somar-akis, G., et al, 2020	“NBS for a leading sustainable city” (Vauxhall ONE project)	London, UK	City & Street	X		X			X

6.1.4 EBA design techniques for Amsterdam's quay wall waterfronts

In this section EBA design techniques are proposed as a way to use ecosystem processes to address climate change effects like drought, heat, and flood and by doing so reduce the impact of processes that degrade the quay wall structure. To summarise from the literature (IUCN, 2016; Pauleit et al., 2017; Somarakis et al., 2019), an EBA approach for designing is should have the following characteristics in addition to meeting the functional requirements:

- A focus on reducing the negative effects of climate change.
- Using nature and natural processes wherever possible.
- Increase biodiversity and improve ecological functions that support biodiversity.
- Do not jeopardise the functions of related ecosystems.
- Can be combined with conventional engineering infrastructures if necessary.
- Are accessible and safe for the people living near and using the space.
- Increase opportunities for learning raising awareness of climate change.

The following subsections contain the range of possible "typical" EBA design techniques that can increase climate resilience in quay wall waterfront spaces while delaying the processes that lead to the wall's replacement. The techniques are divided into five categories that relate to where in a waterfront space they could be applied, from what general material, and specific construction principles used. The range of techniques shown in this section are not exhaustive and serve to demonstrate the range of what is possible for different components of waterfront spaces.

The measures contain symbols indicating which climate change effect is being addressed. A short explanatory text accompanies each technique including how it assists in reducing the processes that degrade the quay wall structure.

Legend

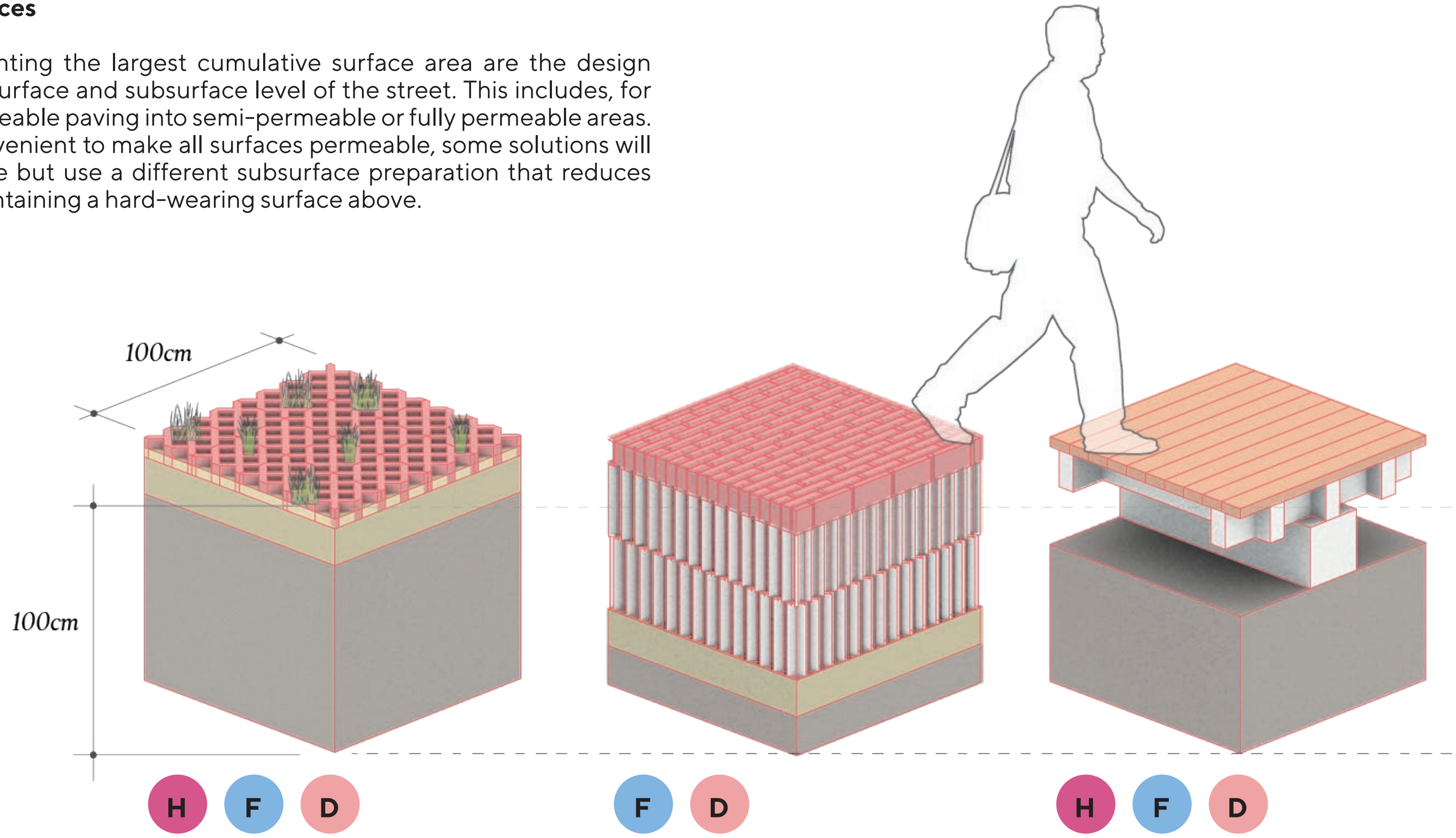
F *Flood*

D *Drought*

H *Heat*

Nature-based materials and surfaces

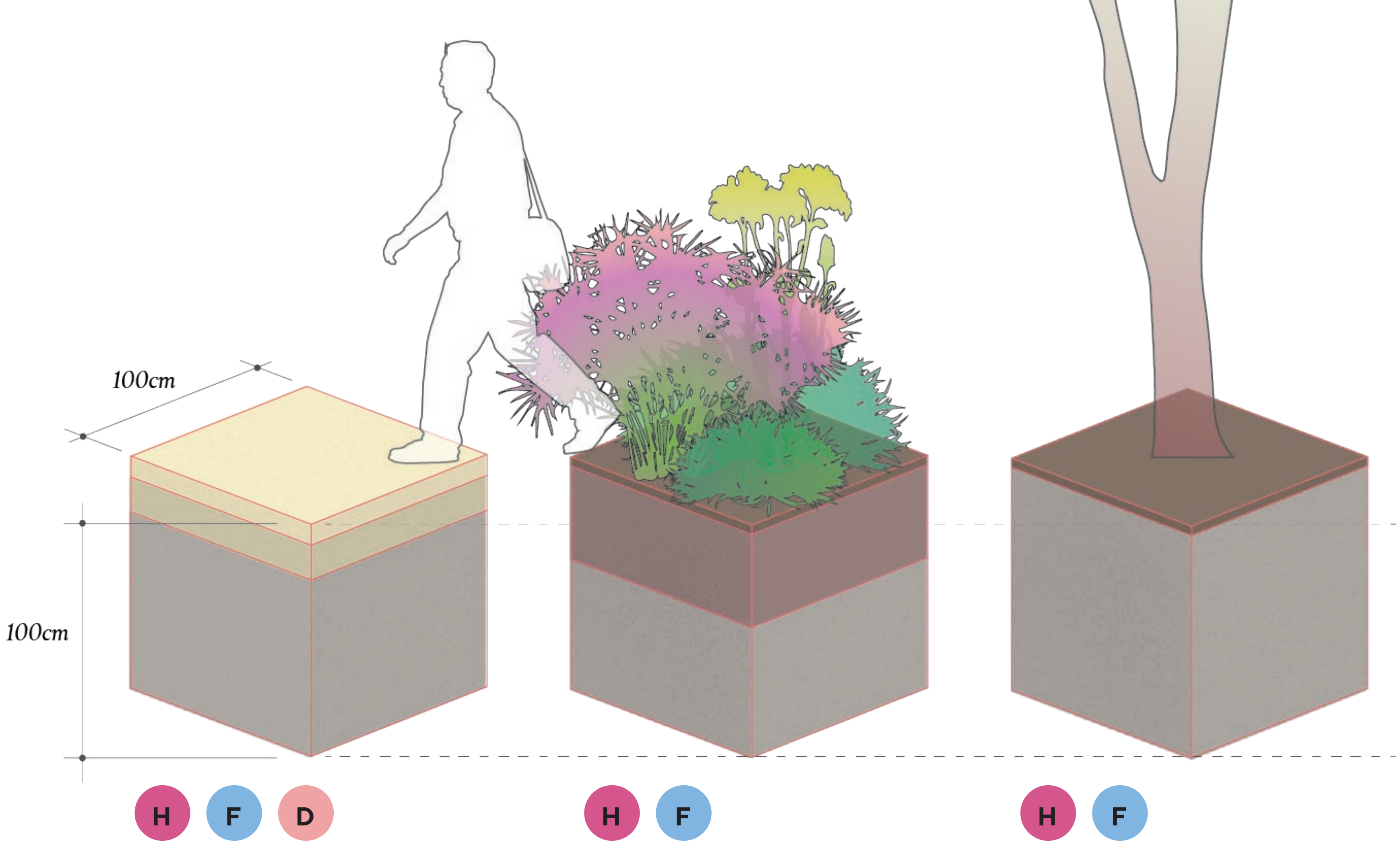
At the smallest scale but representing the largest cumulative surface area are the design changes that can be made at the surface and subsurface level of the street. This includes, for example, the conversion of impermeable paving into semi-permeable or fully permeable areas. As it is not always possible nor convenient to make all surfaces permeable, some solutions will have the same surface appearance but use a different subsurface preparation that reduces compaction of soil layers while maintaining a hard-wearing surface above.



PERMEABLE PAVING
Paving units with openings for better infiltration through to a lightly compacted subsurface to aid with groundwater recharge. Also reduces the weight behind the wall.

PAVING ON STRUCTURAL CELLS
Proprietary lightweight plastic crates with cellular structure used provide structural support to paving and reduce the weight placed to the back of the wall. Can be backfilled with soil to accommodate plant roots which help with detaining moisture in the soil.

SUSPENDED TIMBER DECKING
Timber decking supported on a structure that promotes air flow and water infiltration to assist with groundwater recharge. Also assists with reducing heat at ground surface behind the wall.



GRAVEL OR SAND PAVING
Compacted sand or loose gravel paving increases permeability and assists with groundwater recharge. Also reduces weight behind the wall.

GARDEN BED WITH MULCH TOP LAYER
Garden beds with topsoil above the natural soil layer increases infiltration as well as reducing temperatures via plant evapotranspiration. Promotes moisture retention and can be used to reduce risk of erosion where paving has been removed to reduce weight.

TREE PIT WITH MULCH TOP LAYER
Tree pits can be backfilled with site soil although it is better to have soils with more organic matter to increase water retention. Where possible, tree pits should also be constructed with root barriers in the direction of the quay wall to protect the wall from invasive woody roots.

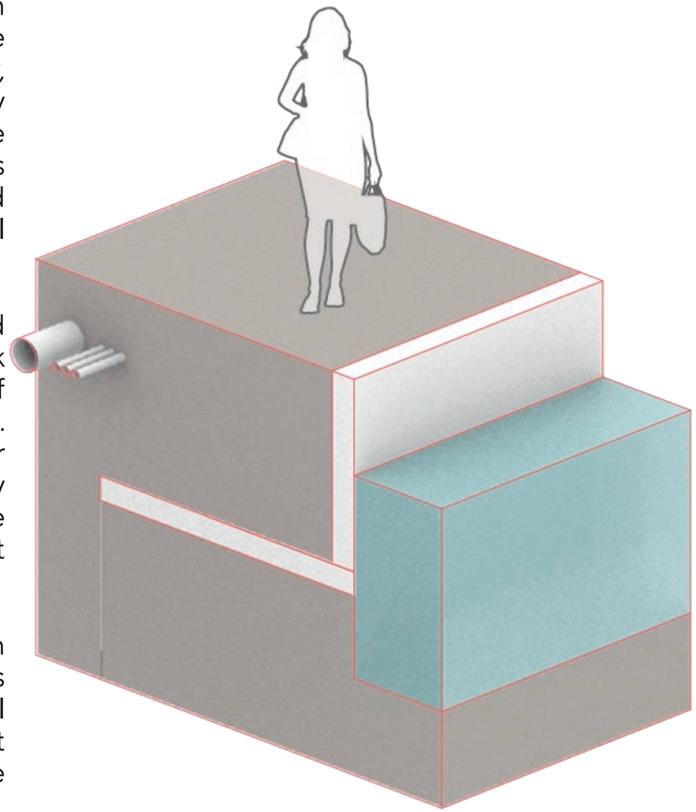
Nature-based land side solutions

The focus of the research so far has been upon the quay wall structural system on the land side of Amsterdam's waterfronts. Consequently, the number of measures related to the quay wall structure is far greater than those on the water side. There are two types of measures in this section: changes to the ground behind the wall structure, and changes to the wall structure itself.

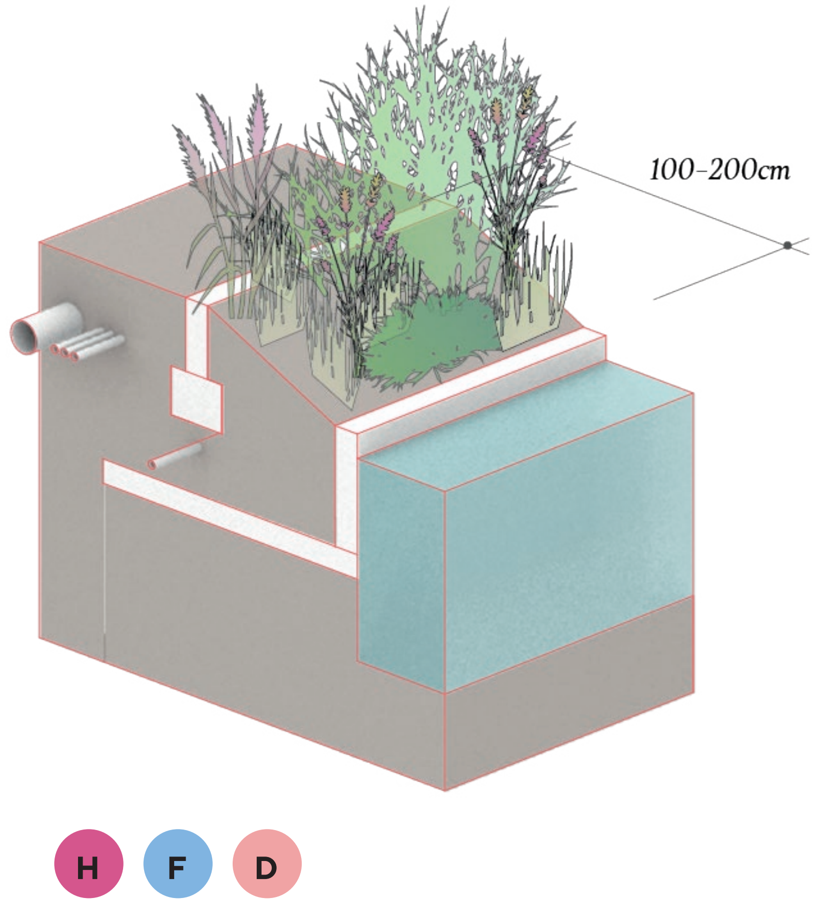
Designs for measures that change the ground level are meant to decrease loads to the back of the wall while also increasing the capacity of this zone for water infiltration and collection. As a result, these solutions are options for localised topographic change and will finally be combined with the materials, water side solutions (if any), and implemented in context to the wall system type.

Although structural designs are not within the scope of the thesis, this section contains speculations on how changes to the wall component of the quay wall create different spatial conditions which in turn affect the social system and ecosystem in the city.

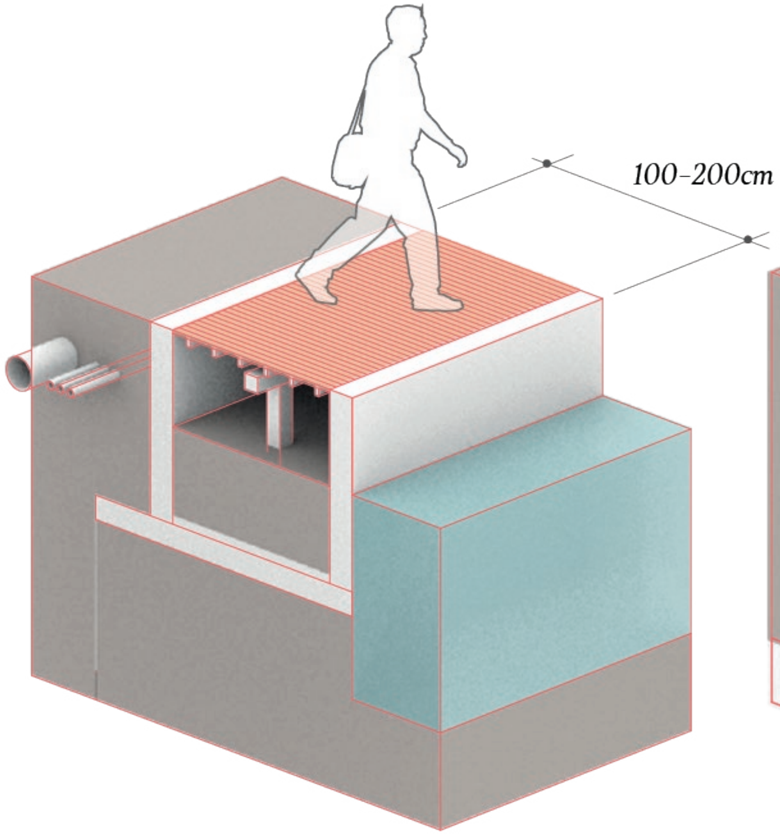
It is acknowledged that changing height of the walls in a way that affects the flow of water in the canals would represent a "flexible" approach to water management – a topic that is discussed extensively in Mens (2015) and Tempels & Hartmann (2014).



NEW WALL TYPE
This drawing indicates the shape of the walls that are being installed now in the "replace" method in which a new wall placed on top of the existing relieving floor (Royal Haskoning DHV, 2020). Unless otherwise stated, this "replace" method is the default wall type referenced in the designs.

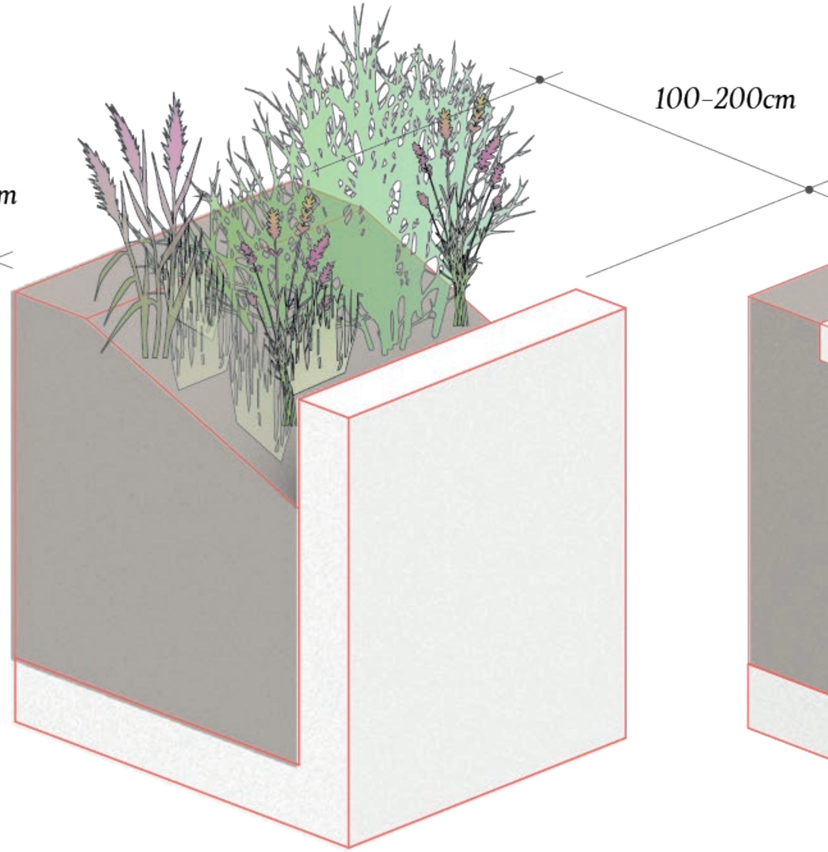


SLOPED EXCAVATION BEHIND LOWERED NEW WALL
New "replaced" walls can be built at a lower height which reduces retaining requirements on the wall structure. In this case, an embedded retaining wall is proposed at a distance behind the lowered wall to support a flat surface for vehicle and pedestrian access. The sloped edge leading down to the water can be retained with geotextiles and flood-tolerant planting as the root zones may be at the groundwater level in some cases.



H F D

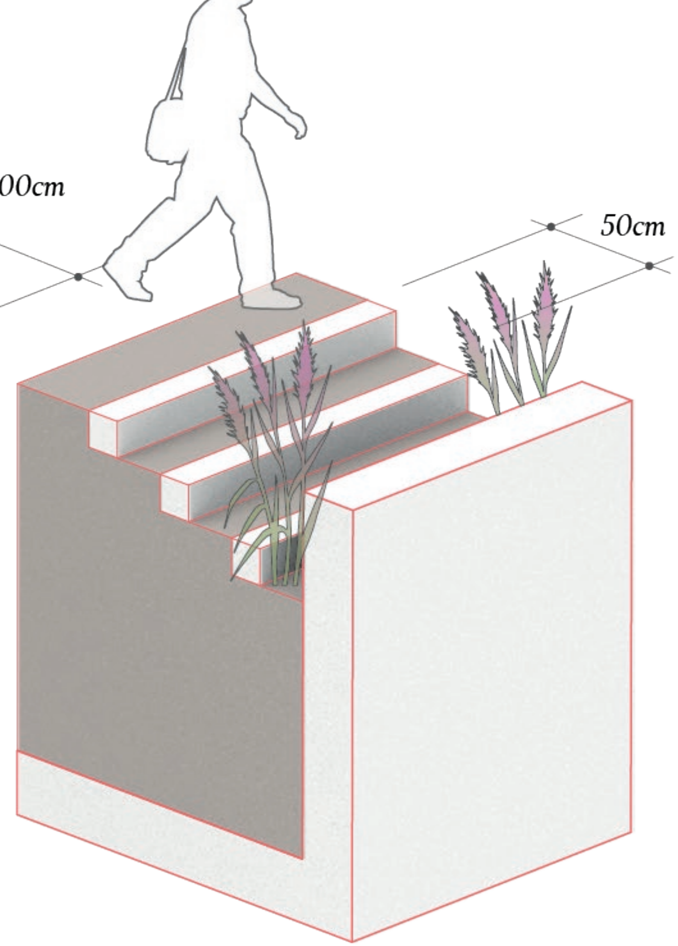
WALL AS TRENCH STRUCTURE
In streets that are too narrow for growing street trees, a "U" shaped structure could be used. In the drawing above, an option is shown where lightweight timber decking can be suspended between the trench walls and over the soil below. The continuous trench of soil inside the trench can be used for planting or phytoremediation but water will need to be collected and discharged out at specific points as there is no connection to the groundwater table.



H F

SLOPED EXCAVATION BEHIND EXISTING WALL
Removing soil behind the wall can reduce loads on the wall structure and assist in prolonging the lifespan of the wall. The soil slope can be stabilised with geotextiles and plants with non-invasive root systems.

This technique is limited by the height of the groundwater table. If soil is excavated beyond the groundwater level, ponding will occur at the lowest level of the slope.



H F

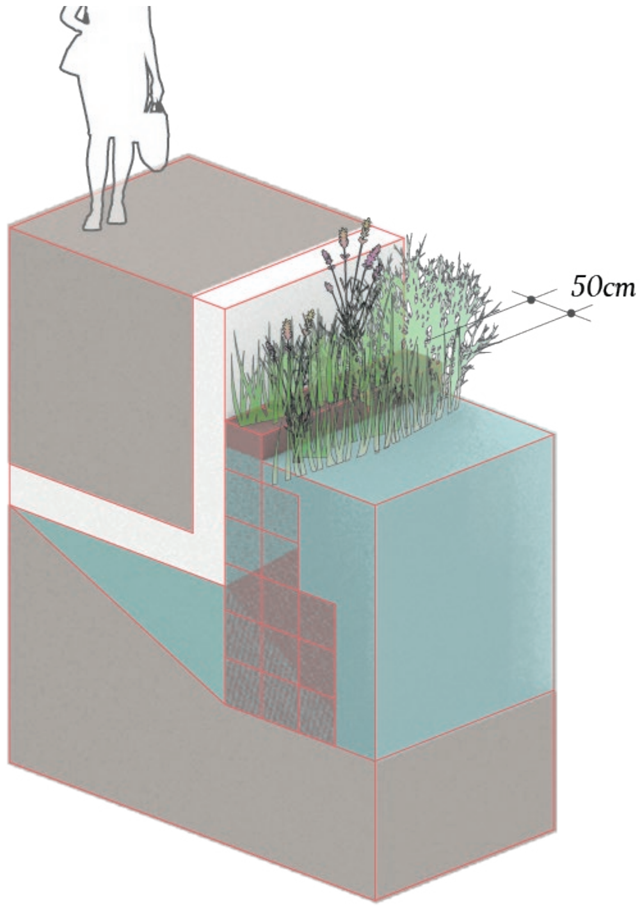
STEPPED EXCAVATION BEHIND EXISTING WALL
Precast concrete sleepers can be used to create terraced steps on the excavated slope behind an existing wall. The sleepers also assist with retaining the soil. The terraced areas can be planted or backfilled with gravel or other lightweight paving materials.

This technique has the same limitation with respect to the groundwater table as the sloped excavation technique (left).

Nature-based water side solutions

Designs for supports on the water side of the wall are characterised by their narrowness in comparison to land side designs. This is due to the complexity of maintaining the correct water level and volume in the canal as the addition of large objects changes the volume of water within a particular area of the canal water system.

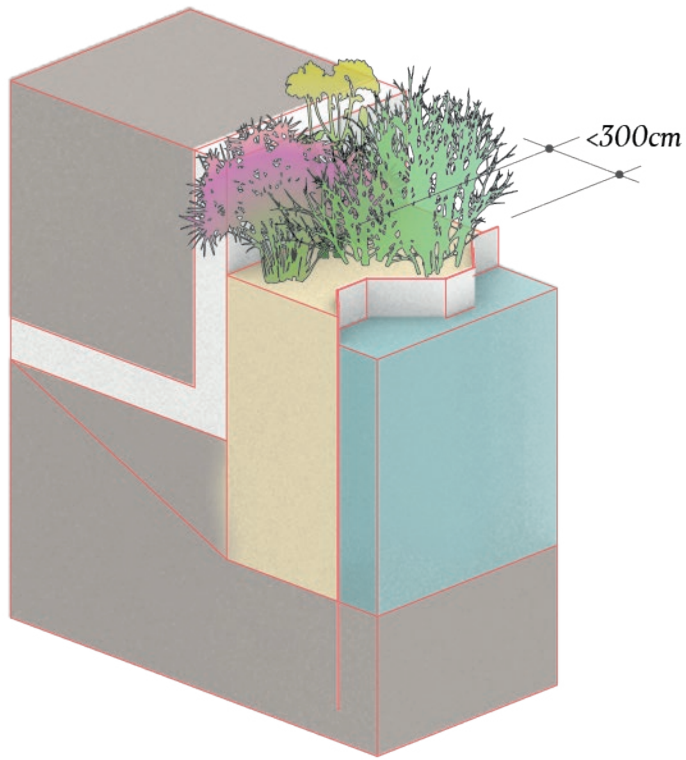
Water side solutions tend towards measures that reduce the rate of scouring on the base of the quay wall structure by protecting the wall and canal floor from disturbance. Additionally, they are intended to be effective as standalone features that require little to no integration with the wall structure or land side features.



H

GABION REINFORCING STRUCTURE
Gabion blocks can be stacked along the edges of quay walls that need to be reinforced from the waterside. The gabion walls can host water plants at the top which can also assist in regulating temperatures by shading the masonry wall cladding.

This technique is only suitable where the water body is wide enough and water quality is not jeopardised by disruption from the gabions.



H F

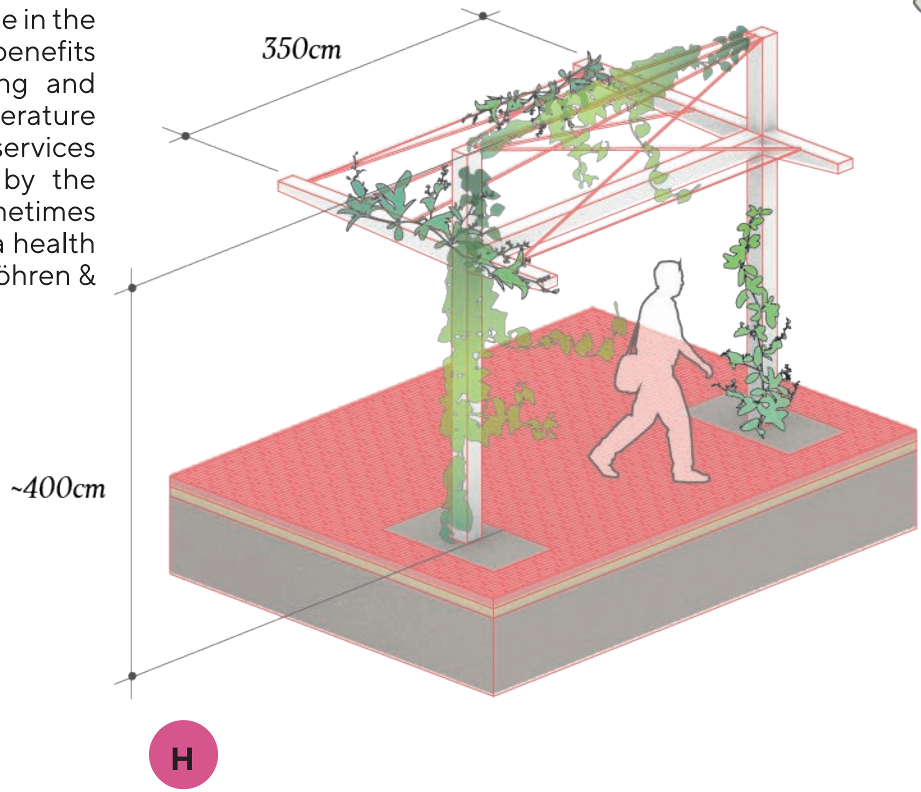
SHEET PILE REINFORCEMENT PLATFORM
Steel sheet pile is driven into the floor of the canal at a distance from walls that needs to be reinforced. To do this, a secondary steel frame is built between the sheet pile and the existing quay wall and the space backfilled with sand. The surface of the backfilled sand must be below the water level of the canal so that it can also serve as an overflow area in case of high water levels in the canal.

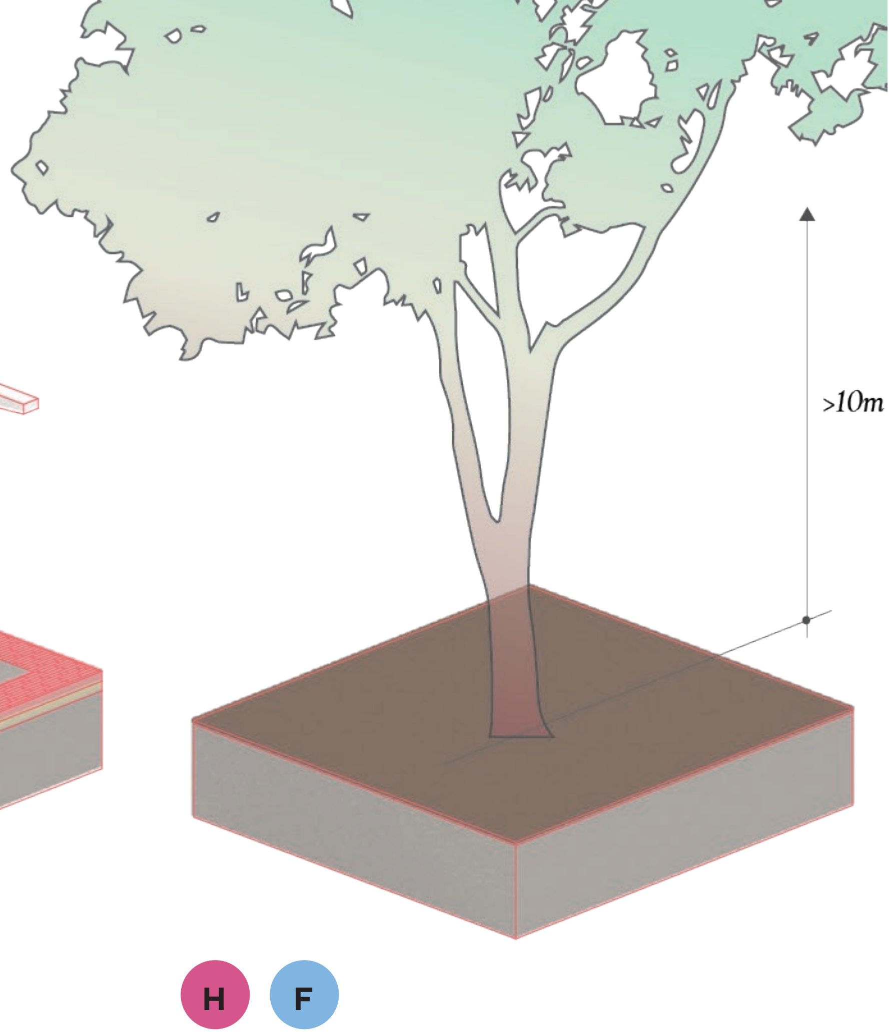
This is the "reinforce" method used by the municipality. Refer Appendix C for more details.

Nature as measure

A recurring characteristic of NBS projects is the presence of plants. It is well documented that the addition of plants in the form of trees, shrubs, and/or groundcovers can improve the local amenity of an area. This can come in the form of qualitative and quantitative benefits like increasing a sense of wellbeing and reducing the experienced air temperature (Heaviside, 2017). The ecosystem services provided by plants can be offset by the ecosystem disservices that they sometimes cause like release BVOCs that pose a health risk to vulnerable populations (von Döhren & Haase, 2015).

Like all the measures in this section, using plants as a measure requires an understanding of the local conditions that they will be situated in and what climate adaptation benefits they are providing. The following examples show the range of ways in which plants can be used in an NBS project.

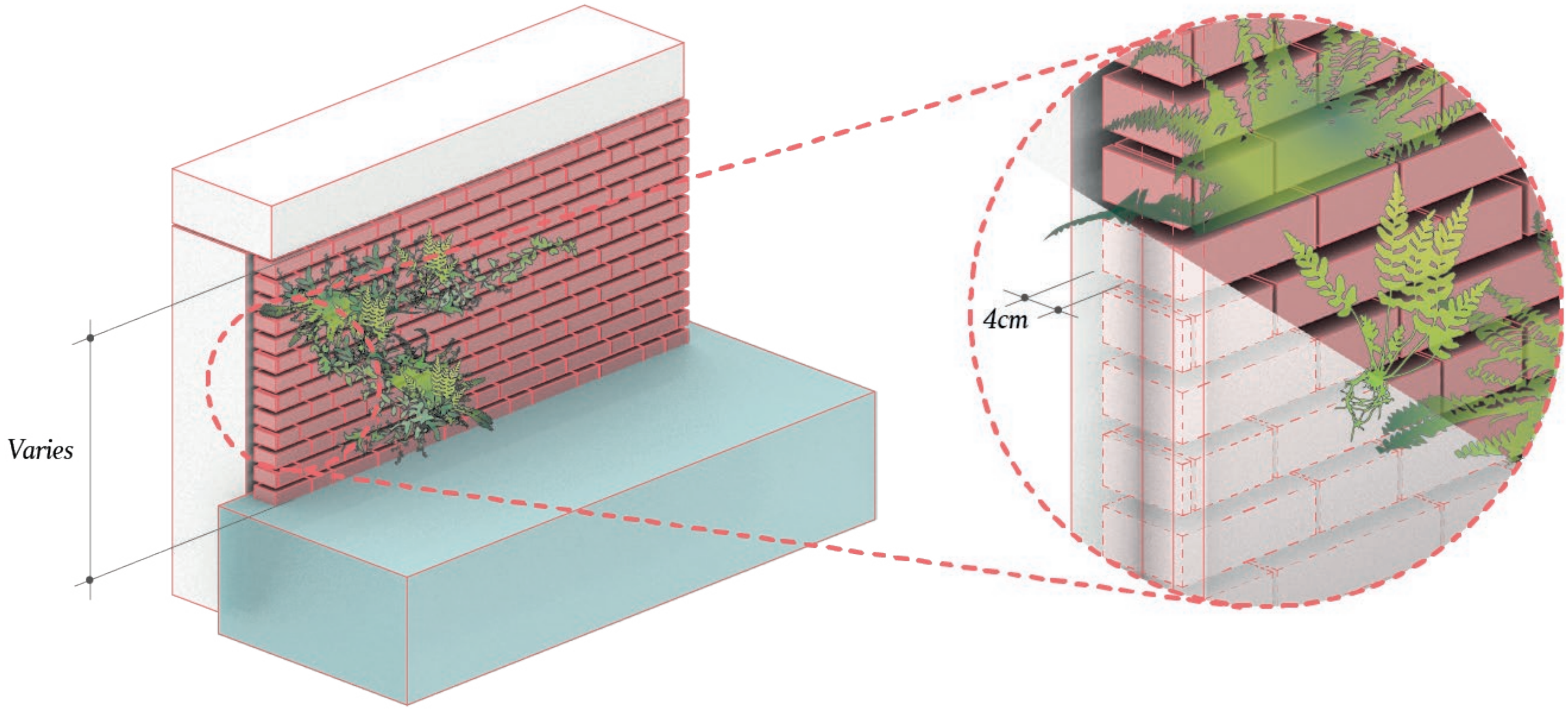




ARBOUR STRUCTURE
In places where trees cannot be planted an arbour structure can be installed with set down footings that are lower than the soil level at the base of the columns so that climbing plants can eventually cover the structure and provide similar benefits to trees like shading and cooling via evapotranspiration. This measure reduces the presence of large woody roots which can jeopardise the quay wall structure.

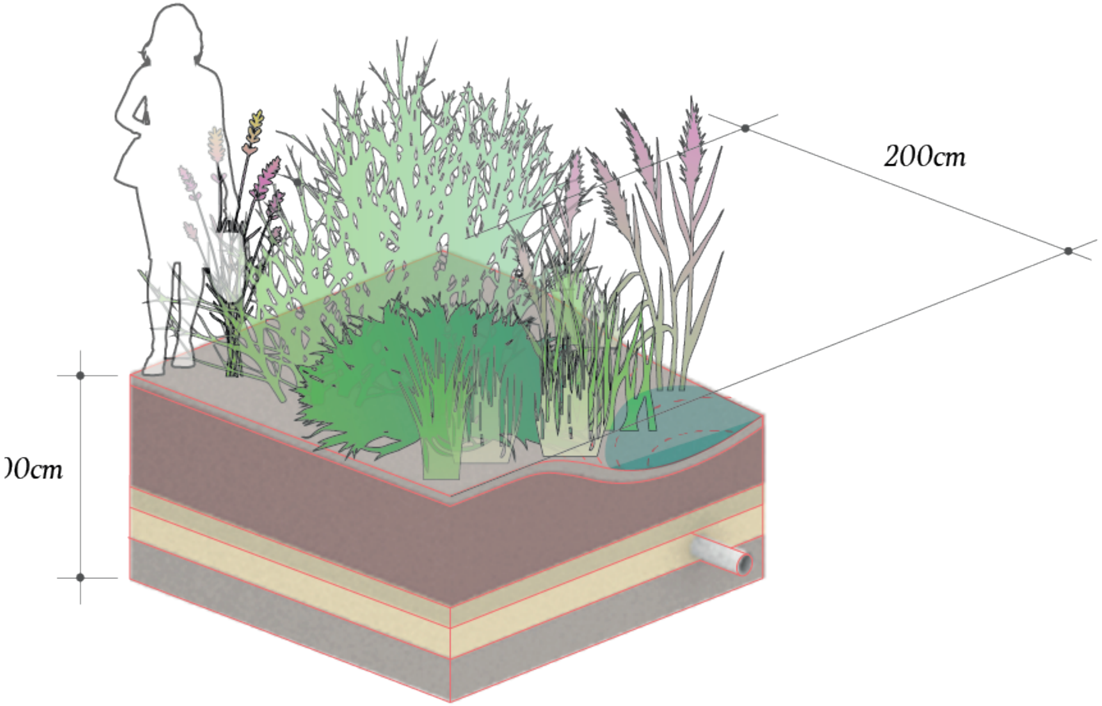
This technique is intended for use as part of a modular system.

TREE PLANTING
Trees can be secured in the soil via staking, guying, and root ball anchors to reduce movement behind the wall. For this research the specific ecosystem benefits of trees is their ability to increase stormwater detention and reducing temperatures around the wall.



H

GREEN QUAY WALLS
Xerophytic plants can already be found growing on the city's quay walls. Enthusiasts for the plants claim that they are also a part of the heritage of the walls. This technique proposes that in some locations the brick cladding is installed using a dry fixing method which creates a small air gap between the bricks and the main structure so plants can be intentionally grown in these areas and reducing the risk to the main structure behind. The additional benefit of the air gap between the brick cladding and concrete wall is that airflow is possible between the damp porous bricks close to the water assisting in localised evaporative cooling near the water's surface.

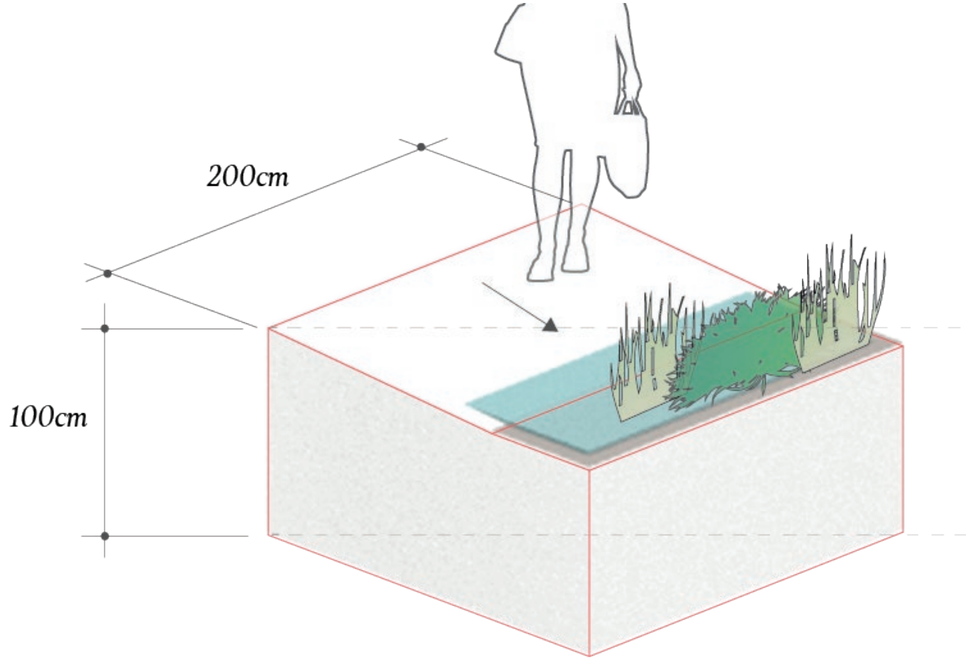


H F D

SWALES AND RAINGARDENS
Swales and raingardens increase infiltration of stormwater to natural ground assisting in the recharging of the groundwater table. Raingardens and swales are constructed in depressions in the local landscape. Stormwater can be collected in these areas and in some cases pond for a period of time, reducing pressure on the conventional stormwater drainage infrastructure. In some areas plants can also be substituted for gravel.

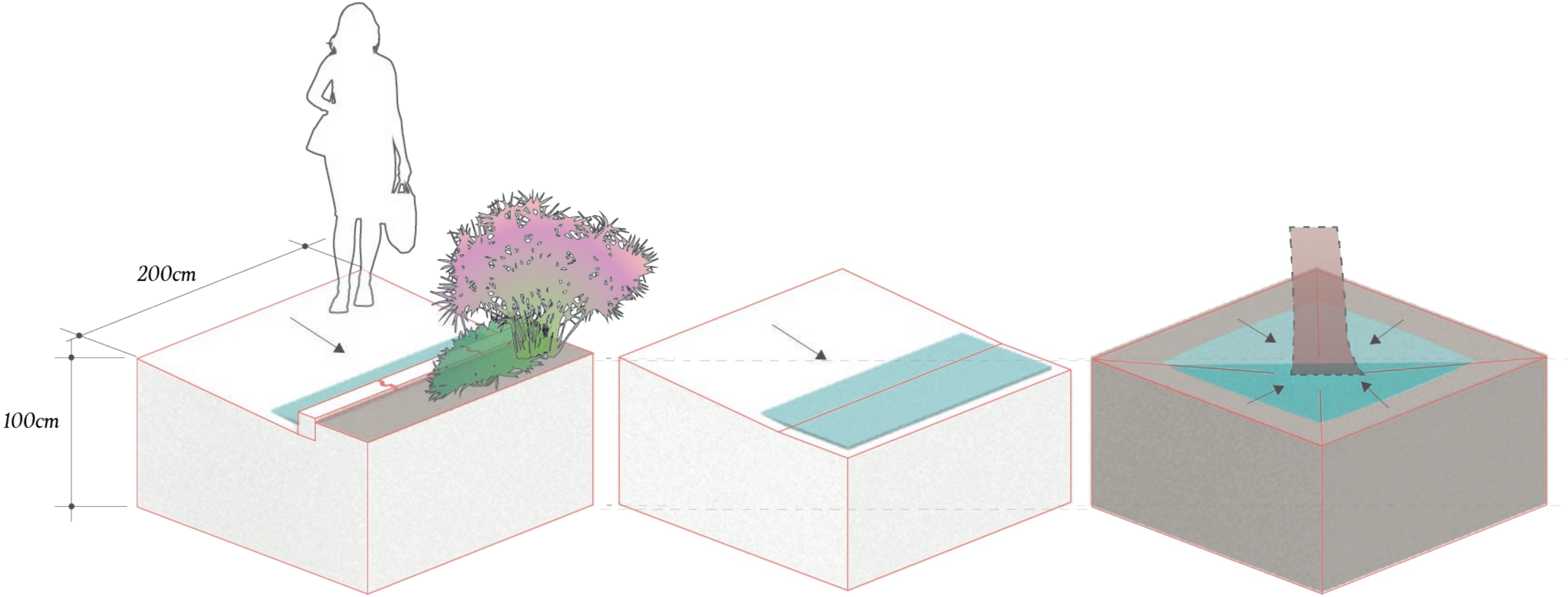
Construction methods

In addition to the design measures previously outlined, there are construction techniques that can be used alongside the measures to increase the efficacy of the measures. The examples shown provide an indication of what techniques are possible as ultimately local site factors will determine the ability for them to be used.



F D

SURFACE FALL TO GARDEN BED
Wherever possible, paved surfaces should be designed and installed to drain towards garden bed areas. This is especially so where garden bed is next to the water so that stormwater runoff – which contains chemicals and heavy metals from the road areas – is prevented from immediately entering the surface water network of the canal.



F

OPEN JOINTS BETWEEN KERBSTONES
Where surfaces drain towards raised edges of gardens, the kerbstones used to retain the garden beds should be installed with small gaps between them to allow water to pass through to the garden bed areas behind.

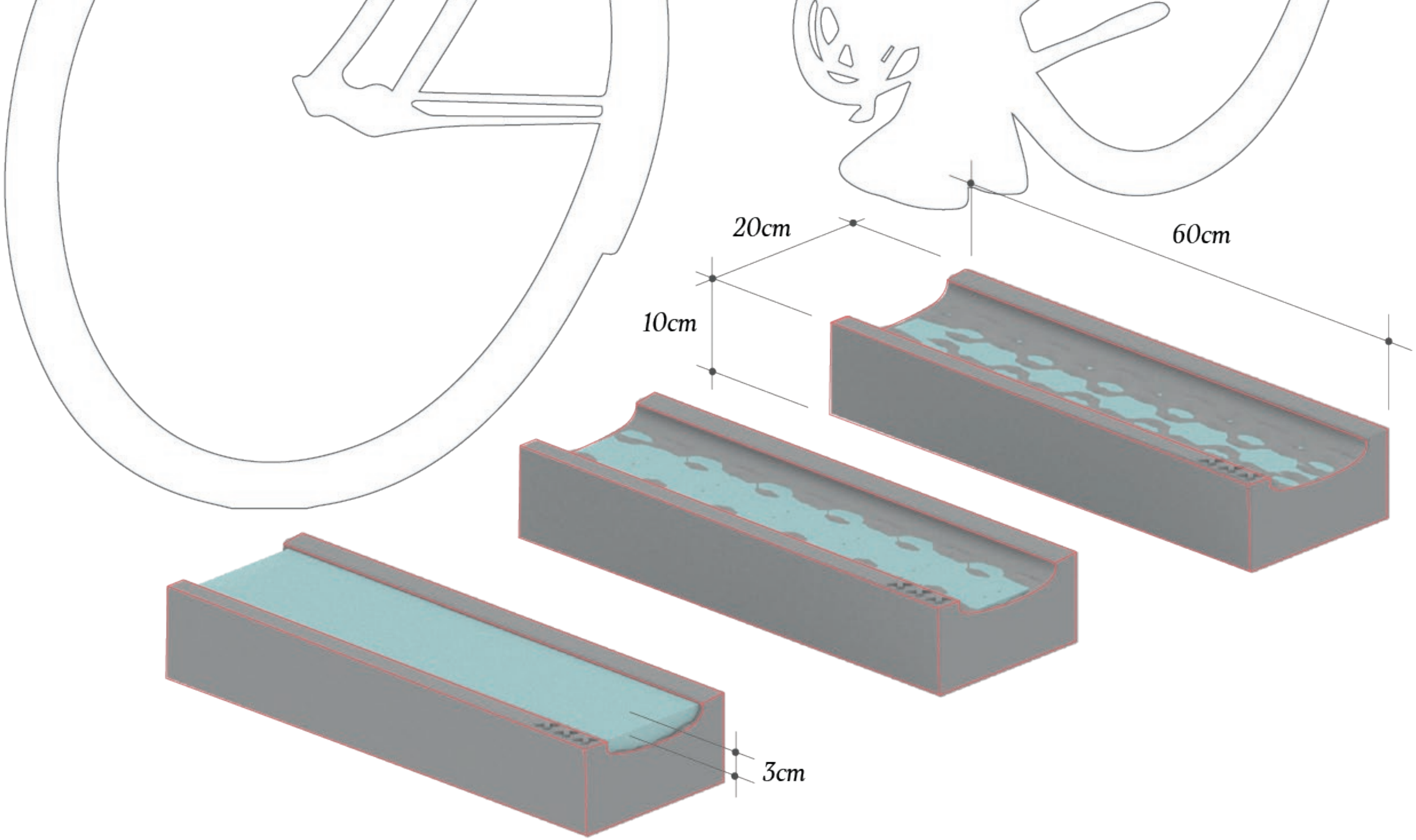
F D

SURFACE FALL TO DRAINAGE CHANNEL
Wherever possible, paved areas should be designed and installed to drain towards drainage channels or kerbs where the water can be directed to passive or engineered stormwater infrastructure.

F D

LOCALLY GRADE SOIL AROUND TREE BASE
In some locations it may be possible to slope the surfaces immediately below the trunk of the tree to encourage water to infiltrate around the root zone of the tree.

This technique is only applicable to recently planted juvenile trees.



F

DRAINAGE CHANNELS
Custom-designed drainage channels can be cast from concrete and installed in and around paved areas to collect and direct water to the desired areas in a landscape. Ridges cast into the inside surface of the channel serve to provide a non-slip surface for cyclists and pedestrians.

6.2. A SPATIAL PLAN FOR SPREADING RESILIENCE BY RENOVATION

A "nature-based" approach to the "Resilience by Renovation" strategy is supported at the city scale by taking the concept of GI to create a sequence of linear green spaces alongside quay wall waterfront network of Amsterdam to increase the amount of green spaces that in turn build climate resilience throughout the city. How this materialises at the scale of the waterfront is done by using the concept of EBA to generate a range of typical design techniques that fulfil the functional requirements from previous chapters. When these techniques are used in concert, they can provide a range of ecosystem services that can be varied based on the climate vulnerability of the waterfront and the neighbourhood that it is in.

With the approach, method, and techniques established it is possible to revisit the previous maps and synthesise their contents to show which neighbourhoods will receive what renovation method and how this relates to their vulnerability to climate change. The maps in *Figure 6.4* show the locations of the 360 neighbourhoods covered by the strategy and in total:

- 30 neighbourhoods with waterfront spaces will contain "replace" renovation measures
- 76 neighbourhoods with waterfront spaces will contain "reinforce" renovation measures
- 254 neighbourhoods with waterfront spaces will contain "reduce" renovation measures

The 88 neighbourhoods that are not part of the proposed implementation strategy are excluded because the neighbourhoods contain a majority of buildings constructed later than 1970 and have lower population densities in comparison with the rest of the city.

To determine which EBA design techniques should be used and in what combination, the detailed results of the climate change impact score is used to create a design brief for each neighbourhood. Appendix E contains the detailed climate change scoring for each neighbourhood and are used as part of the landscape scenario sites in the following chapter.

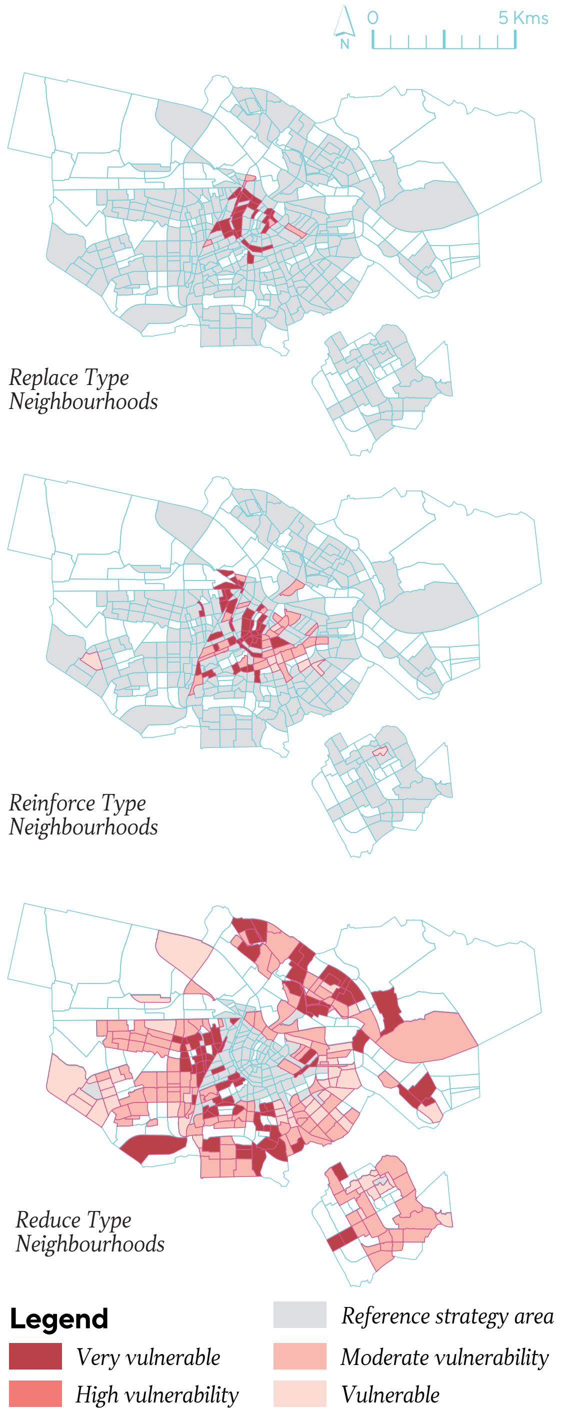


Figure 6.4.Spreading resilience by renovation strategy - renovation methods and locations. Image credit: Noelle Teh 2020.

6.3. NATURE-BASED RESILIENCE BY RENOVATION FOR AMSTERDAM'S QUAY WALL WATERFRONTS

6.3.5 Landscape scenarios for Amsterdam's quay wall waterfronts

Landscape scenarios were used to explore and demonstrate how the design techniques could be applied to waterfront spaces. Scenarios are useful for exploring outcomes in complex urban contexts – it is a way to test a range of possible solutions that could be adopted and analyse them in comparison to each other to identify parameters that recur between them (Gerber, Kurath, Schurk, & Zuger, 2018). For the waterfront landscape scenarios to be created, a selection of seven landscape scenario sites was made based on the following criteria:

- All three renovation methods must be represented.
- A narrow and standard with scenario must be represented.
- Wherever possible the neighbourhoods with the highest impact score for quay wall renovation and climate change should be selected.

With these three criteria the combined impact scores and classifications performed in previous chapters resulted in a list of landscape scenario sites are as follows:

- Scenario 1: Passeerdersgracht, Centrum.
- Scenario 2: Singel, Spuistraat Noord, Centrum.
- Scenario 3: Oudezijds Voorburgwal, Oude Kerk, Centrum.
- Scenario 4: Singel, Reguliersbuurt, Centrum.
- Scenario 5: Korte Water, De Punt, Nieuw West.
- Scenario 6: Plantage Muidergracht, Plantage, Centrum*.
- Scenario 7: De Wittenkade, Staatsliedenbuurt Noordoost, West.

*Plantage Mudergracht does not have the highest vulnerability to climate change within the "reduce" wall type but was chosen because it is spatially more similar to other sites in Amsterdam in comparison to Sluisbuurt (under construction), and Nassaukade (park side near Leidseplein).

All scenario sites are a 60 metre long section of the street with buildings shown as a single mass to provide scale and proportion to the site. As a final condition for the landscape scenarios, all sites must retain the use functions that are present in that specific waterfront – the area coverage of a function can change but existing functions (e.g. vehicle access) cannot change. Repeated again here for reference, these social functions are:

- Street functions including car and bicycle parking, carriageways, pedestrian footpaths, street lighting, and street trees.
- Residential functions for docked houseboats including provision points for services and informal garden spaces on the street.
- Recreational and social functions like informal and formal seating areas sometimes in combination with more explicit recreational functions like small platforms extending into the water for swimming.
- Emergency service access providing space for emergency vehicles to access and attend to emergencies in the buildings and spaces along the water.
- Intra-city transportation functions including the leisure and tourist boats transporting passengers and cargo boats transporting bulky or heavy goods like construction materials.
- Residential functions in the form of house boats.
- Recreational and social functions leisure boats, swimming, kayaking, etc.
- Emergency service access providing space for emergency vehicles to access and attend to emergencies in the buildings and spaces along the water.

Additionally, the functional requirements for both the quay walls and climate change are repeated here with additional clarification on how they will be measured in the landscape scenario site proposals.

The tables on the following page contain the indicators used for comparison between the scenario sites before and after the design measures are integrated so that insights (refer Sections 6.3.6 and 6.3.7) from the design proposals can be discussed with generalisations made to the neighbourhood and city scale. The results for each scenario site are in Appendix J.

Table 6.2.Functional requirements and measurement aimed at delaying wall replacement.

Functional requirements to delay quay wall replacement	Indicator	Measurement
Reduce heavy loads next to the wall	Removal of materials or functions which involve the use of heavy machinery or objects behind the wall on land side.	M2 area directly next to the wall without carparking or loading areas for heavy vehicles
Reduce fluctuations in groundwater table level	Increase infiltration of water through the soil to recharge ground water table.	M2 area designed to be permeable to water
Regulate temperatures around the quay wall structure	Decrease exposure of wall components and improve cooling abilities of the structure and surfaces adjacent to it.	M2 area with plants and/or trees
Protect canal bed from erosion	Decrease exposure of canal bed to scouring forces caused by water traffic.	Lineal metres where wall is protected from scouring
Reduce live loads next to the wall	Stabilisation of trees next to quay walls. Relocation of vehicular traffic away from the wall's edge.	M2 area directly next to the wall without carparking or loading areas for heavy vehicles

Table 6.3. Functional requirements and measurement aimed at climate change adaptation.

Functional requirements for climate adaptation	Indicator	Measurement
Increase infiltration to soil – Drought, Flood	Increase permeability of ground surface and/or drain to areas that are permeable	M2 area designed to be permeable to water
Increase water storage areas for future re-use or for controlled discharge to stormwater network – Drought, Flood	Construct water storage areas and make necessary connections for storage and/or discharge	M2 area designed to collect and detain water for future reuse or discharge
Use plants and trees that are able to withstand heat, drought, and flood – All	Location-specific species selection	Species name (if any)
Provide additional areas that can be temporarily inundated and drained at a later time – Flood	Plan and construct areas where water can be collected in case of overflow to other areas in the street	M2 area designed to collect and detain water for future reuse or discharge
Reduce use of materials with high thermal mass - Heat	Remove or replace materials with materials that have better thermal properties	M2 area where brick or concrete paving has been removed
Increase use of broadleaf vegetation to increase evapotranspiration - Heat	Species selection	Species name (if any)
Shade or cover building surfaces to reduce heat absorption and release - Heat	Provide space and necessary supporting structures to shade surfaces from direct sunlight	Number of trees and/or m2 of vegetated areas added to the space

Site Scenario #1: Passeerdersgracht, Passeerdersgrachtbuurt, Centrum

REPLACE | HIGH WALL IMPACT SCORE | HIGH CLIMATE CHANGE VULNERABILITY

Pop. Density HIGH

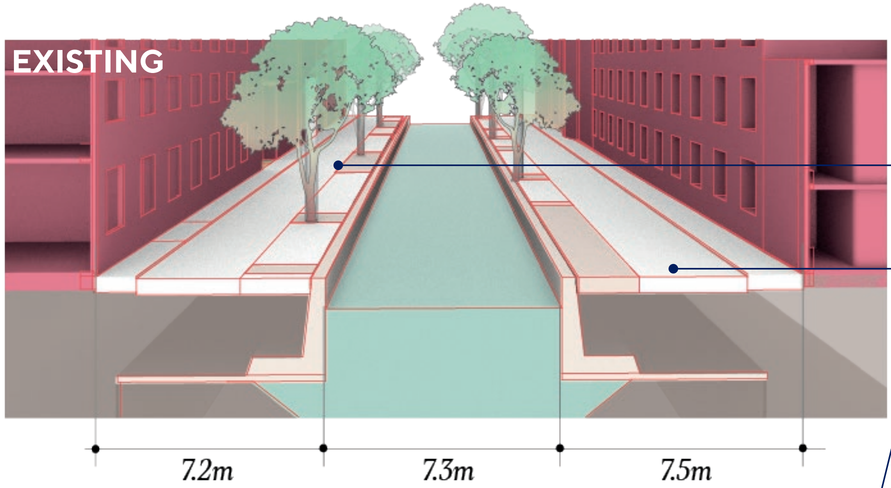
% Area quay wall HIGH

CLIMATE CHANGE EFFECT SUMMARY

Passeerdersgracht is vulnerable to groundwater levels dropping in summer and the fluctuation of the groundwater table is expected to continue into the future. In summer the waterfronts are vulnerable to high heat stress, worsened by the water releasing additional heat at night - adding to the prediction for a longer number of continuous nights with warm temperatures. The neighbourhood is also vulnerable to pluvial flooding with an increase in days with >15mm rain and in the event of 1:100 or 1:1000 year events a flood depth of more than 200mm.

SITE CONDITION NOTES

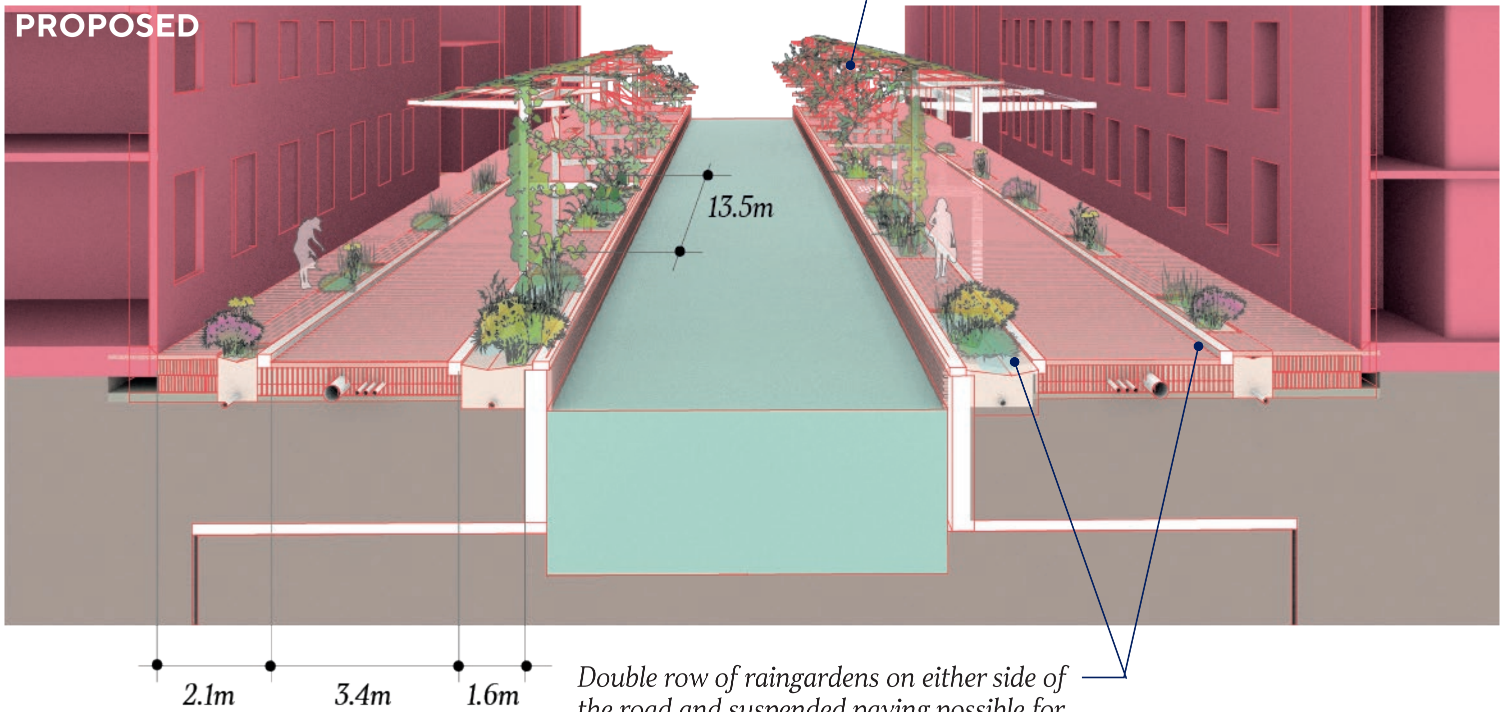
The composition of the top 4.5m layer of soil is unknown and rests on a 8.5m deep layer of clay. The groundwater level is at approximately -0.49NAP.



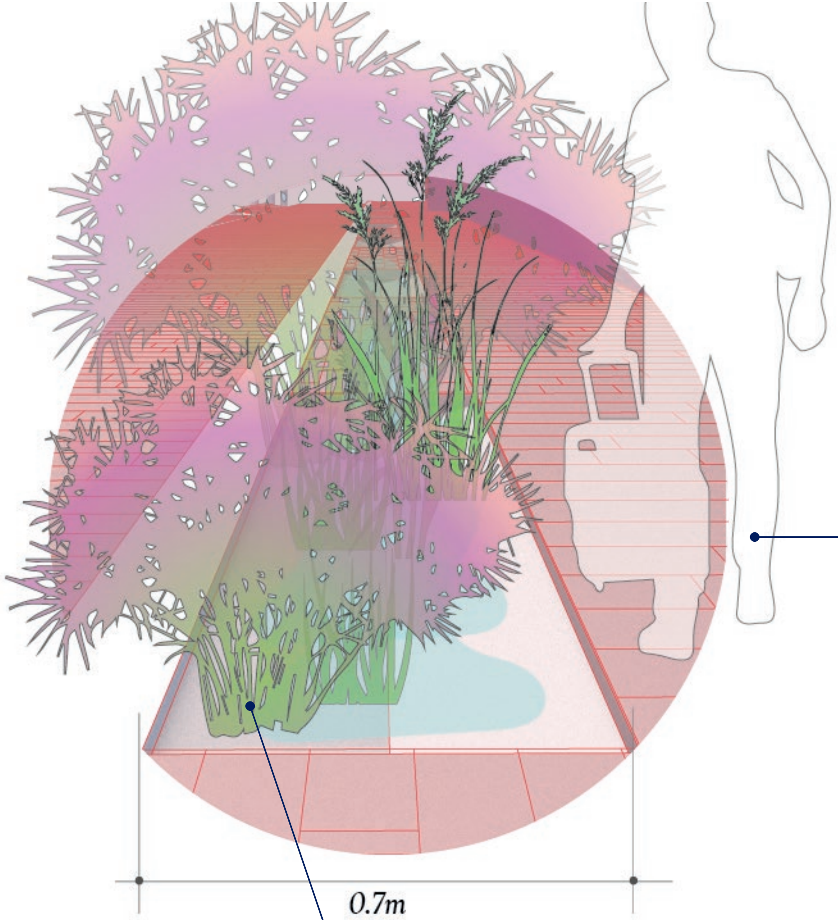
Street with 1.3m wide pedestrian footpath and parallel parking between trees.

Street with 1.7m wide pedestrian footpath parallel parking between trees.

Street is too narrow for new street trees to be planted together with 6m emergency clearance - arbours are used instead for shade and green.



Double row of raingardens on either side of the road and suspended paving possible for parallel parking behind wall.



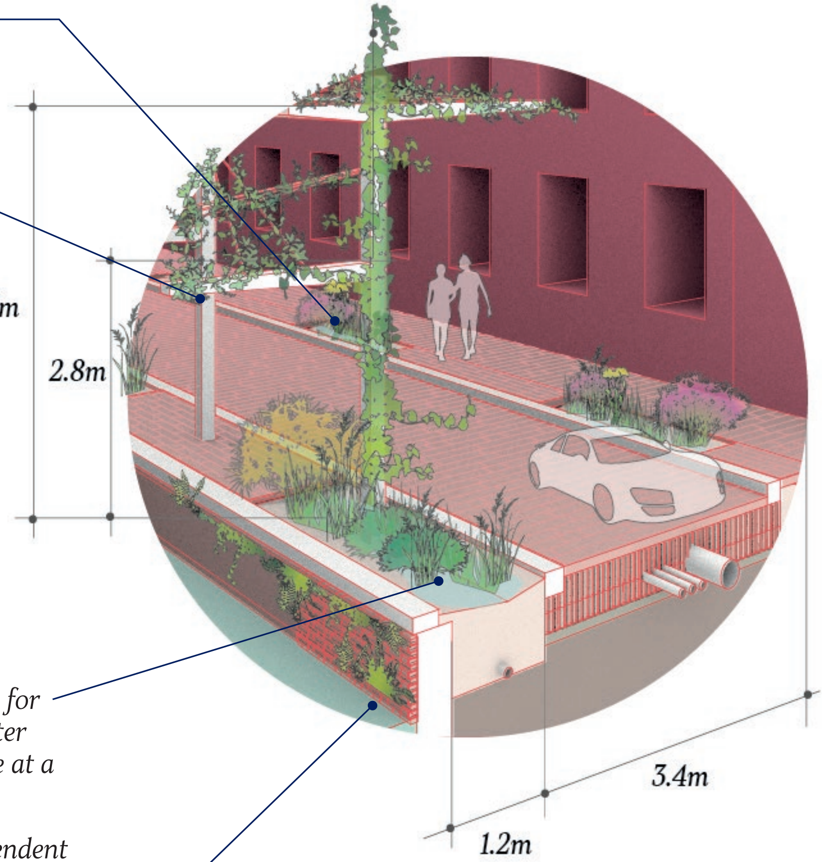
Traditional paving units can be installed on structural cells in areas where open permeable paving is not appropriate.

Raingarden bed constructed with a valley parallel to the roads surface. Planted with drought and flood tolerant plants for stormwater attenuation.

Note: Depth of raingarden dependent on groundwater table.

Raingardens along the pedestrian footpaths contain plants that assist with cooling the street.

Arbors are constructed along the length of the street to act as a frame for climbing plants. When established, the climbing plants on the arbors can provide shade and some of the evapotranspiration benefits of trees.



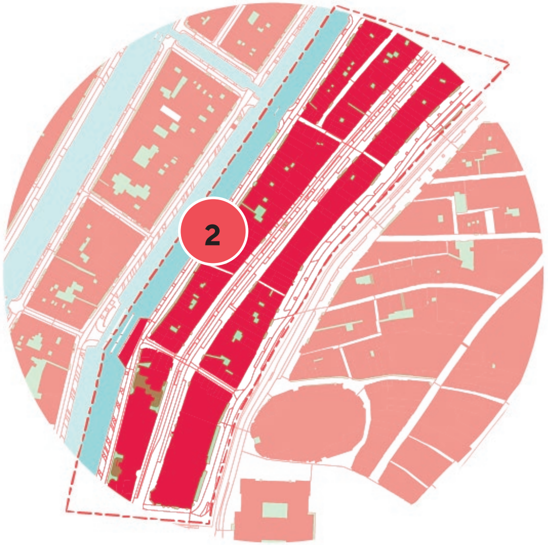
Valley in raingarden soil profile for collecting and storing stormwater for infiltration and/or discharge at a slower rate.

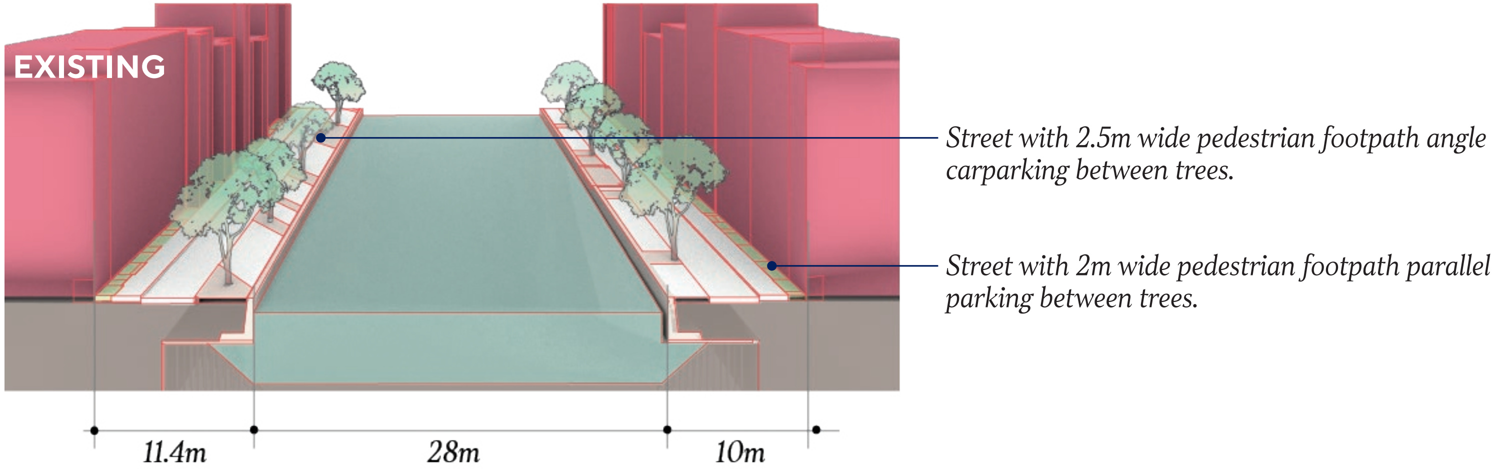
Note: Depth of raingarden dependent on groundwater table.

Green canal wall with xerophytic plants growing on custom brick wall cladding on quay wall.

Site Scenario #2: Singel, Spuistraat Noord, Centrum

REPLACE | HIGH WALL IMPACT SCORE | HIGH CLIMATE CHANGE VULNERABILITY





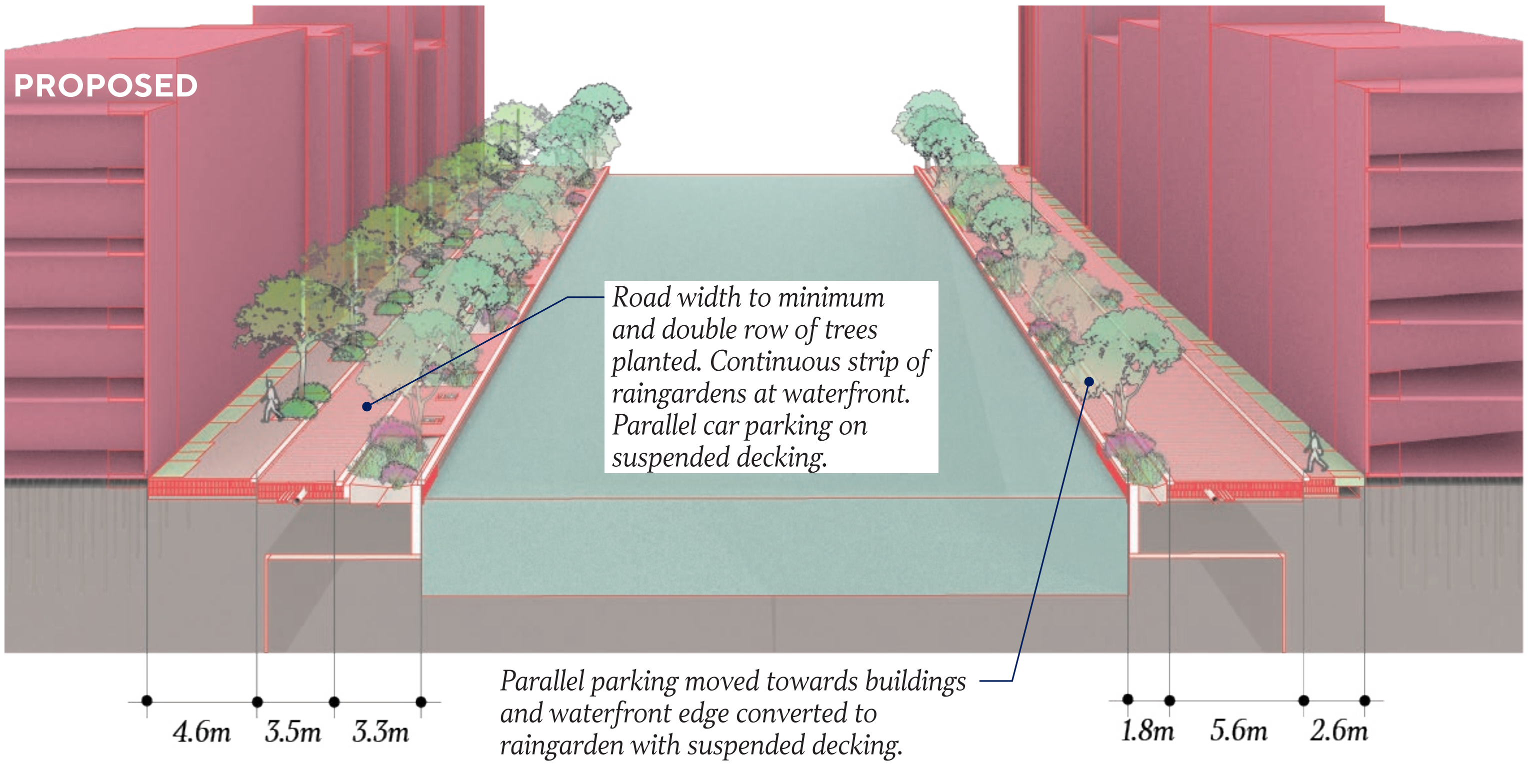
Pop. Density	**HIGH**
% Area quay wall	**HIGH**

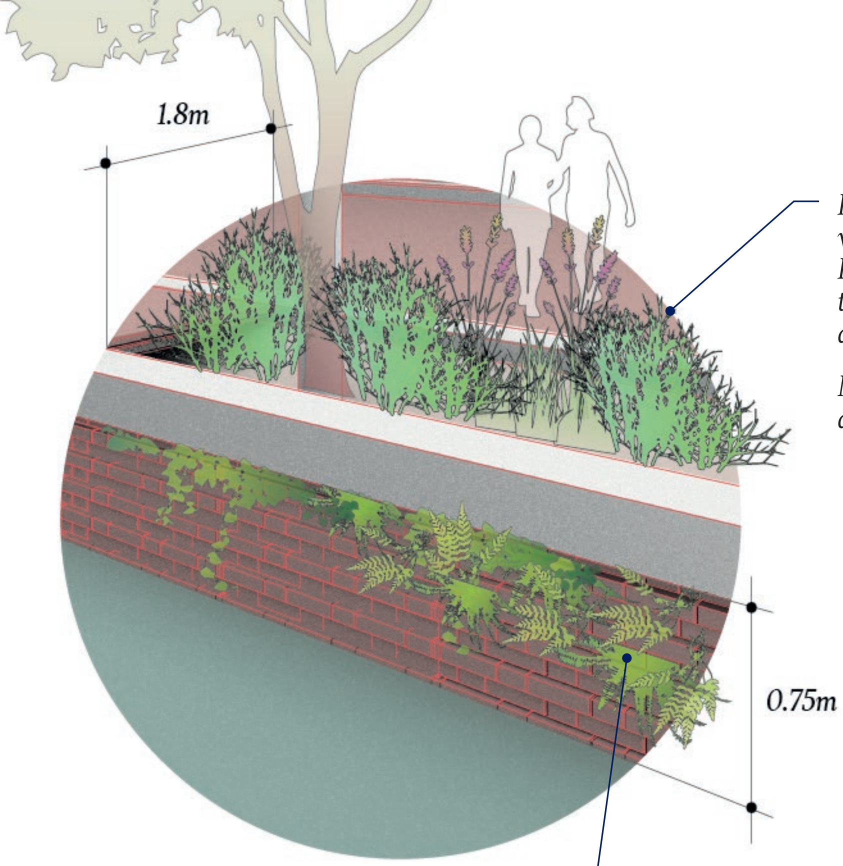
CLIMATE CHANGE EFFECT SUMMARY

This section of Singel is vulnerable to groundwater levels dropping in summer and the fluctuation of the groundwater table is expected to continue into the future. In summer the waterfronts are vulnerable to high heat stress, exacerbated by the water releasing additional heat at night - adding to more than 10 continuous nights (current and predicted) with warm temperatures. The neighbourhood is also vulnerable to pluvial flooding with an increase in days with >15mm rain and in the event of 1:100 or 1:1000 year events a flood depth of more than 200mm.

SITE CONDITION NOTES

The top 6m of the soil is peat followed by a 1m layer of clay then sand until beyond 10m depth. The groundwater level is at approximately -0.37NAP.

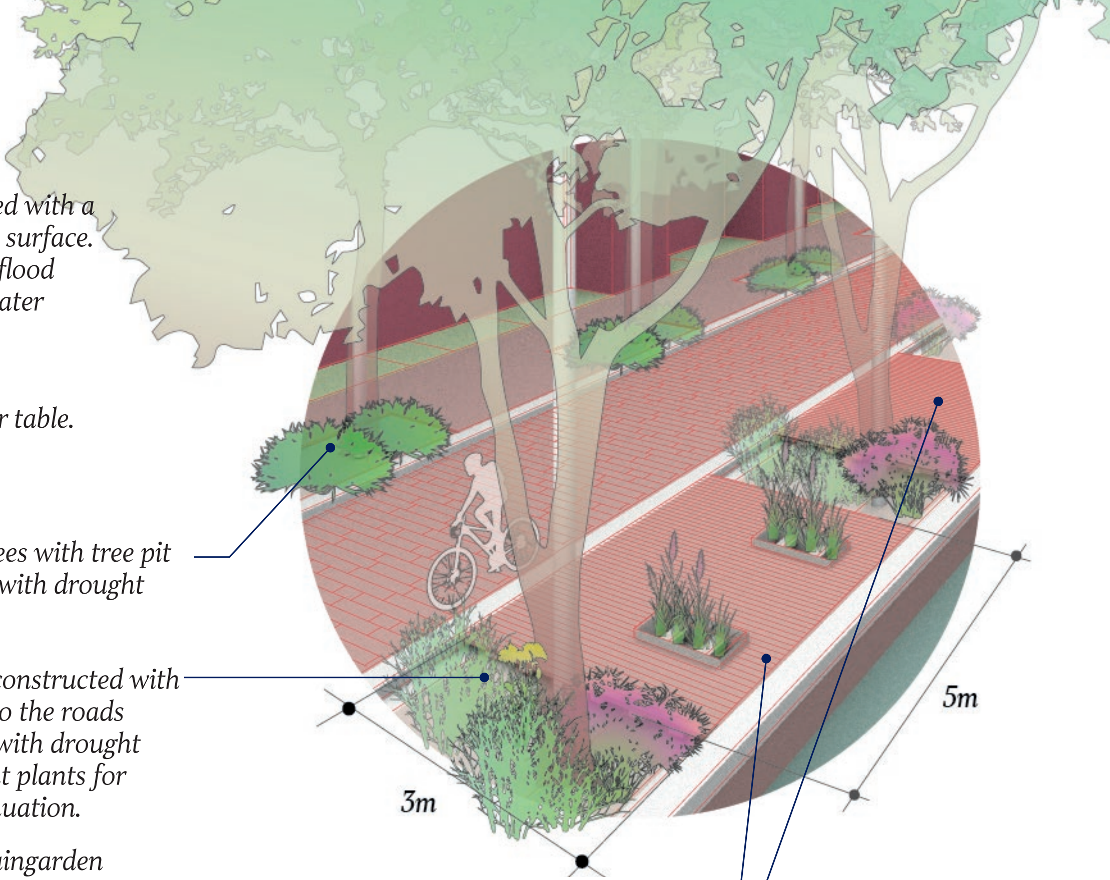




Raingarden bed constructed with a valley parallel to the roads surface. Planted with drought and flood tolerant plants for stormwater attenuation.

Note: Depth of raingarden dependent on groundwater table.

Green canal wall with xerophytic plants growing on custom brick wall cladding on quay wall.



Double row of trees with tree pit surfaces planted with drought tolerant species.

Raingarden bed constructed with a valley parallel to the roads surface. Planted with drought and flood tolerant plants for stormwater attenuation.

Note: Depth of raingarden dependent on groundwater table.

Suspended structure behind quay wall constructed from timber and with openings for planting. Some suspended structures can be included for heavy vehicles as needed by street occupants.

Site Scenario #3: Oudezijds Voorburgwal, Oude Kerk, Centrum

REINFORCE | HIGH WALL IMPACT SCORE | HIGH CLIMATE CHANGE VULNERABILITY

Pop. Density **MEDIUM**

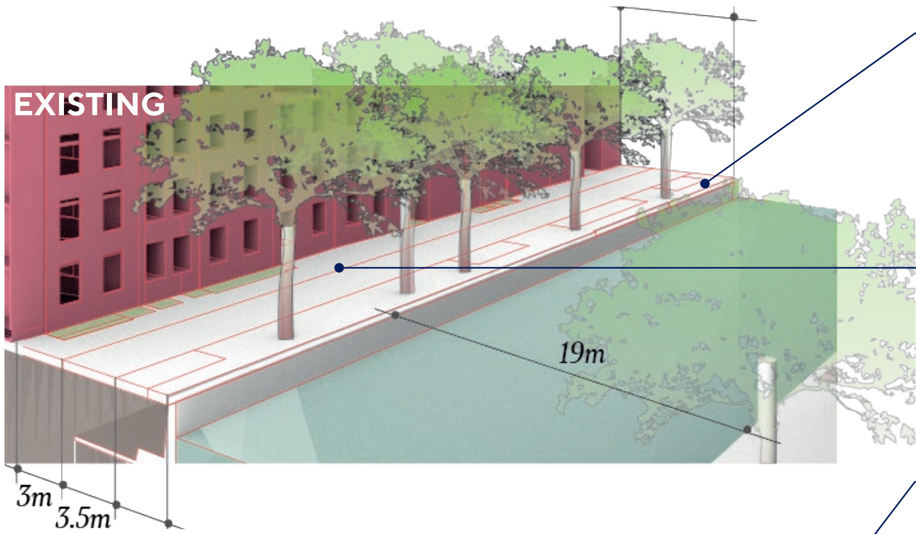
% Area quay wall **HIGH**

CLIMATE CHANGE EFFECT SUMMARY

This section of Oudezijds Voorburgwal is vulnerable to groundwater levels dropping in summer and the fluctuation of the groundwater table is expected to continue into the future. In summer the waterfronts are vulnerable to high heat stress, worsened by the water releasing additional heat at night - adding to more than 10 continuous nights (current and predicted) with warm temperatures. The neighbourhood is also vulnerable to pluvial flooding with an increase in days with >15mm rain and in the event of 1:100 or 1:1000 year events a flood depth of more than 200mm.

SITE CONDITION NOTES

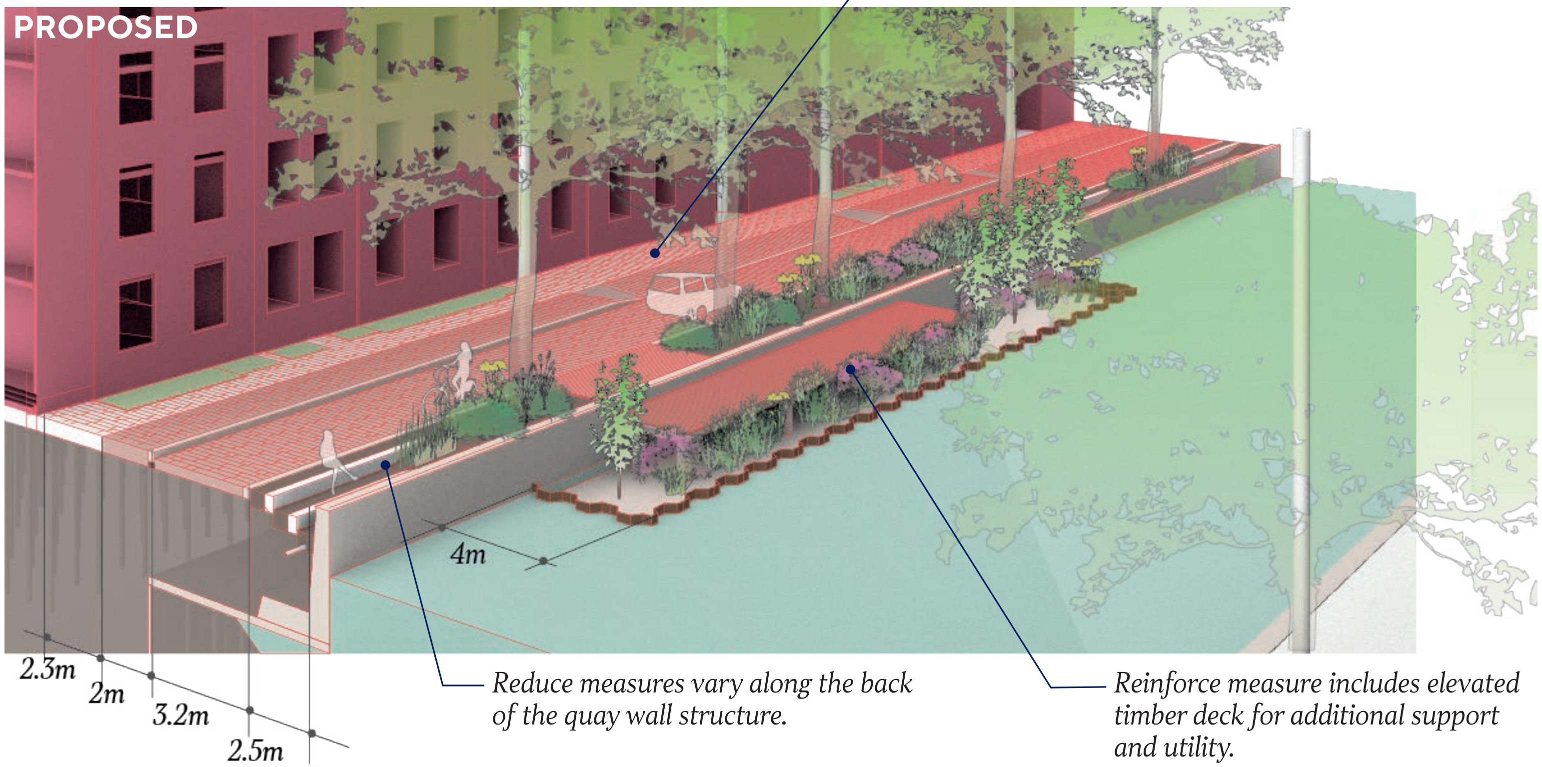
The top 2m of the soil is sand followed by a peat layer until 7.25m beyond which is clay until 15m depth. The groundwater level is at approximately -0.44NAP.



Car parallel parking in between trees.

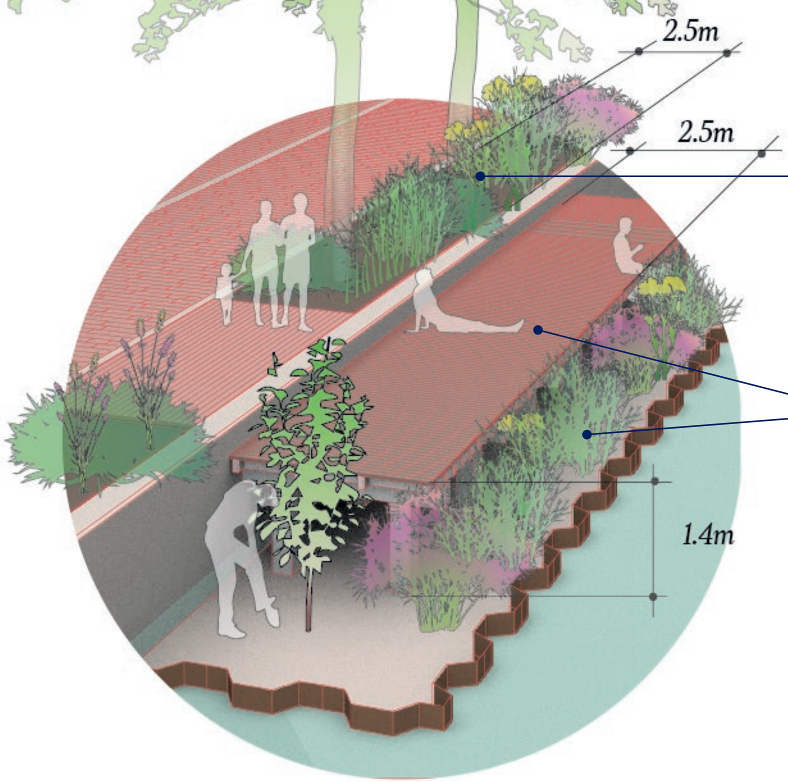
Footpath width varies depending on building outline and entry design. Can be as narrow as 1.2m.

Existing footpaths are a minimum of 2.5m with parallel parking and up to 4m with no parking.



Reduce measures vary along the back of the quay wall structure.

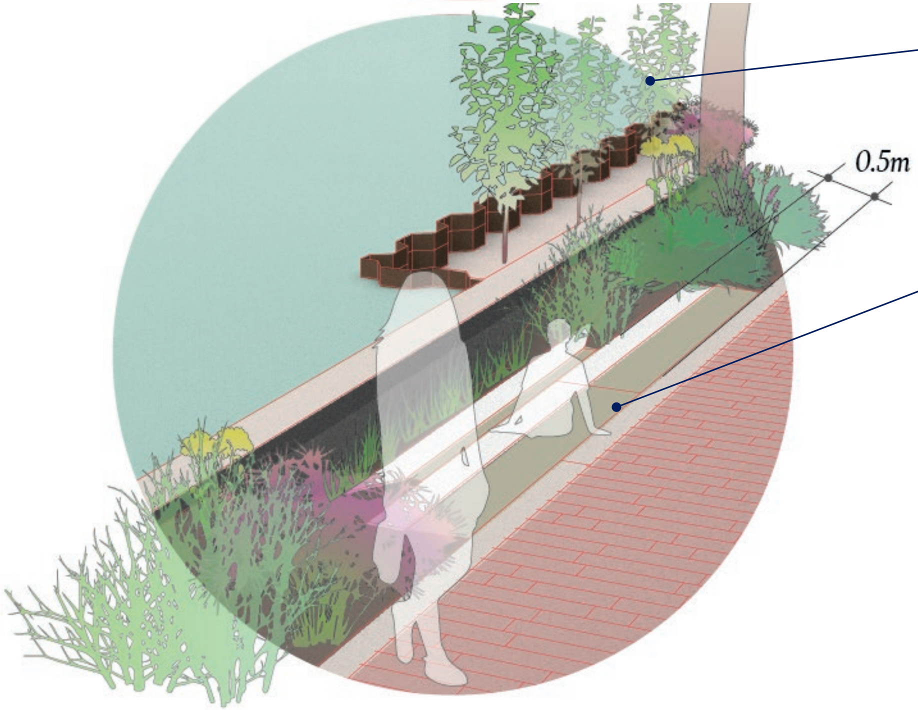
Reinforce measure includes elevated timber deck for additional support and utility.



Raingarden bed constructed with a valley parallel to the roads surface. Planted with drought and flood tolerant plants for stormwater attenuation.

Note: Depth of raingarden dependent on groundwater table.

Sheet pile platform backfilled with sand and planted with flood tolerant plant species. Suspended timber deck added to create additional social spaces and to potentially reinforce remaining height of the wall.



Juvenile trees can use the reinforcement platform as a nursery to grow until they are ready to be transplanted locally during the "replace" works.

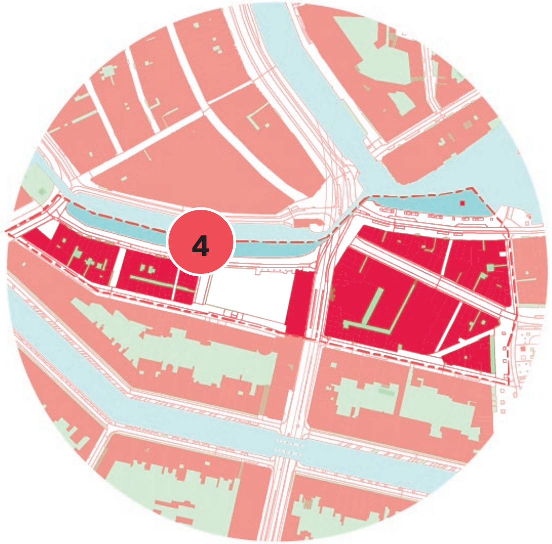
Excavate soil from behind the quay wall and build suspended structure over the soil to limit ability for heavy vehicles to park behind the wall.

Concrete sleepers retain the soil and can be treated to provide additional public seating.

Note: depth of excavation limited by groundwater table level.

Site Scenario #4: Singel, Reguliersbuurt, Centrum

REINFORCE | MODERATE WALL IMPACT SCORE | MODERATE CLIMATE CHANGE VULNERABILITY



Pop. Density **MEDIUM**

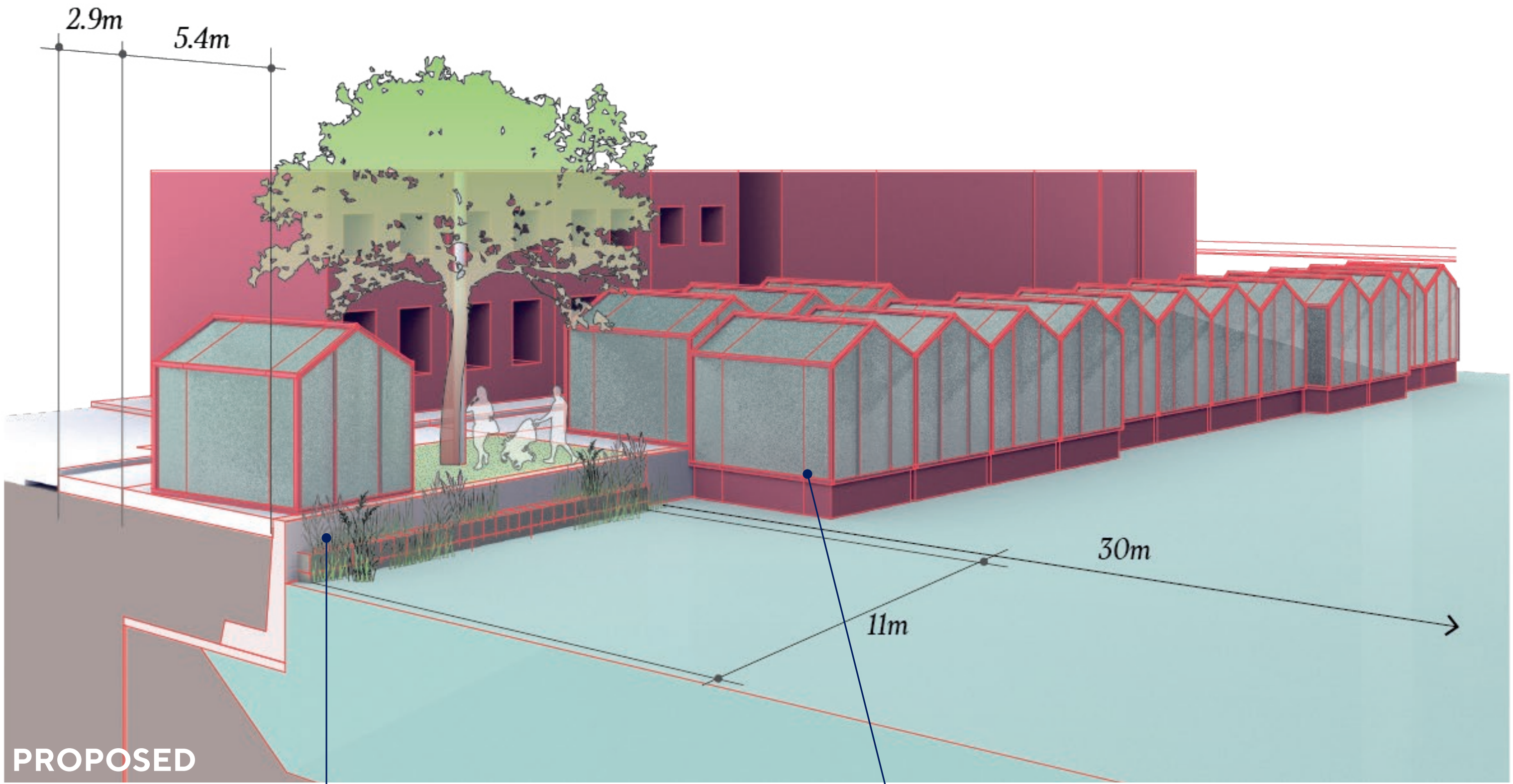
% Area quay wall **MEDIUM**

CLIMATE CHANGE EFFECT SUMMARY

This section of Singel is also Amsterdam's flower market. It is vulnerable to groundwater levels dropping in summer and the fluctuation of the groundwater table is expected to continue into the future. In summer the waterfronts are vulnerable to high heat stress, worsened by the water releasing additional heat at night - adding to more than 10 continuous nights (current and predicted) with warm temperatures. The neighbourhood is also vulnerable to pluvial flooding with an increase in days with >15mm rain and in the event of 1:100 or 1:1000 year events a flood depth of more than 200mm.

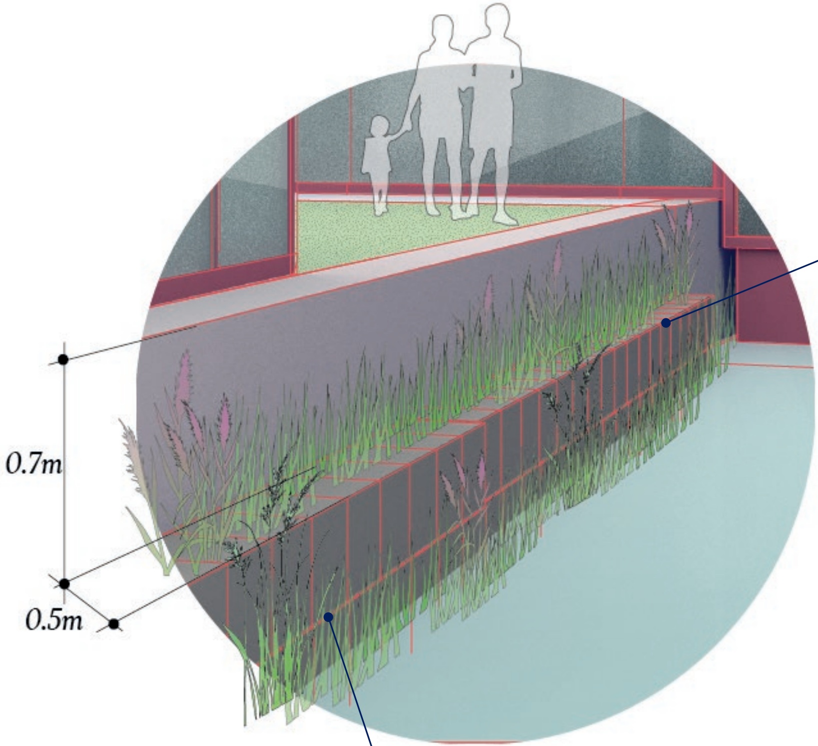
SITE CONDITION NOTES

The composition of the top 2m of soil is unknown. From 2m onwards The soil is predominantly clay until 11m. The groundwater level is at approximately -0.44NAP.



Gabion blocks can be used to reinforce the wall in places between the market sheds. Plants, and potentially flowering plants, could also be combined with the gabions in this location.

Flower market stalls occupy most of the waterfront spaces in this location. The lightweight shelters also extend over and into the water for most of the length of this street.



Gabions used to support the wall with flood tolerant plants grown in top layer to shade and cool wall surface behind.

**note: gabion units can reduce water current - needs to be checked with on site conditions.*

Gabion blocks can be stacked higher than the water's surface and different plants (eg: xerophytes) grown to shade the wall's surface.

Site Scenario #5: Korte Water

REINFORCE | HIGH QUAY WALL IMPACT SCORE | MODERATE CLIMATE CHANGE VULNERABILITY

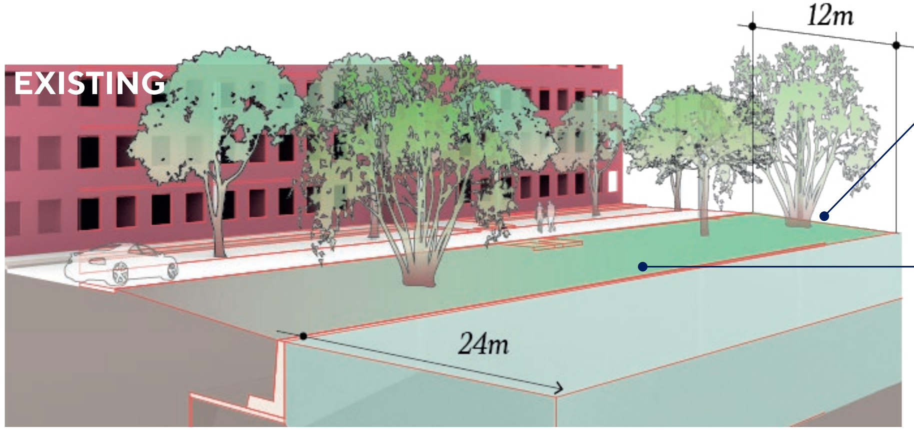
Pop. Density	**HIGH**
% Area quay wall	**HIGH**

CLIMATE CHANGE EFFECT SUMMARY

Korte Water is vulnerable to groundwater levels dropping in summer. In summer, the water releases additional heat at night and it is predicted that there will be more than 10 continuous nights with warm temperatures. The neighbourhood is also vulnerable to pluvial flooding with an increase in days with >15mm rain and in the event of 1:100 or 1:1000 year events a flood depth of more than 200mm. Fluvial flooding is also a risk in the neighbourhood both now and in the 2050 scenario when there is more than a moderately high chance that it will have more than 200mm of fluvial flooding in a 1:100 year event.

SITE CONDITION NOTES

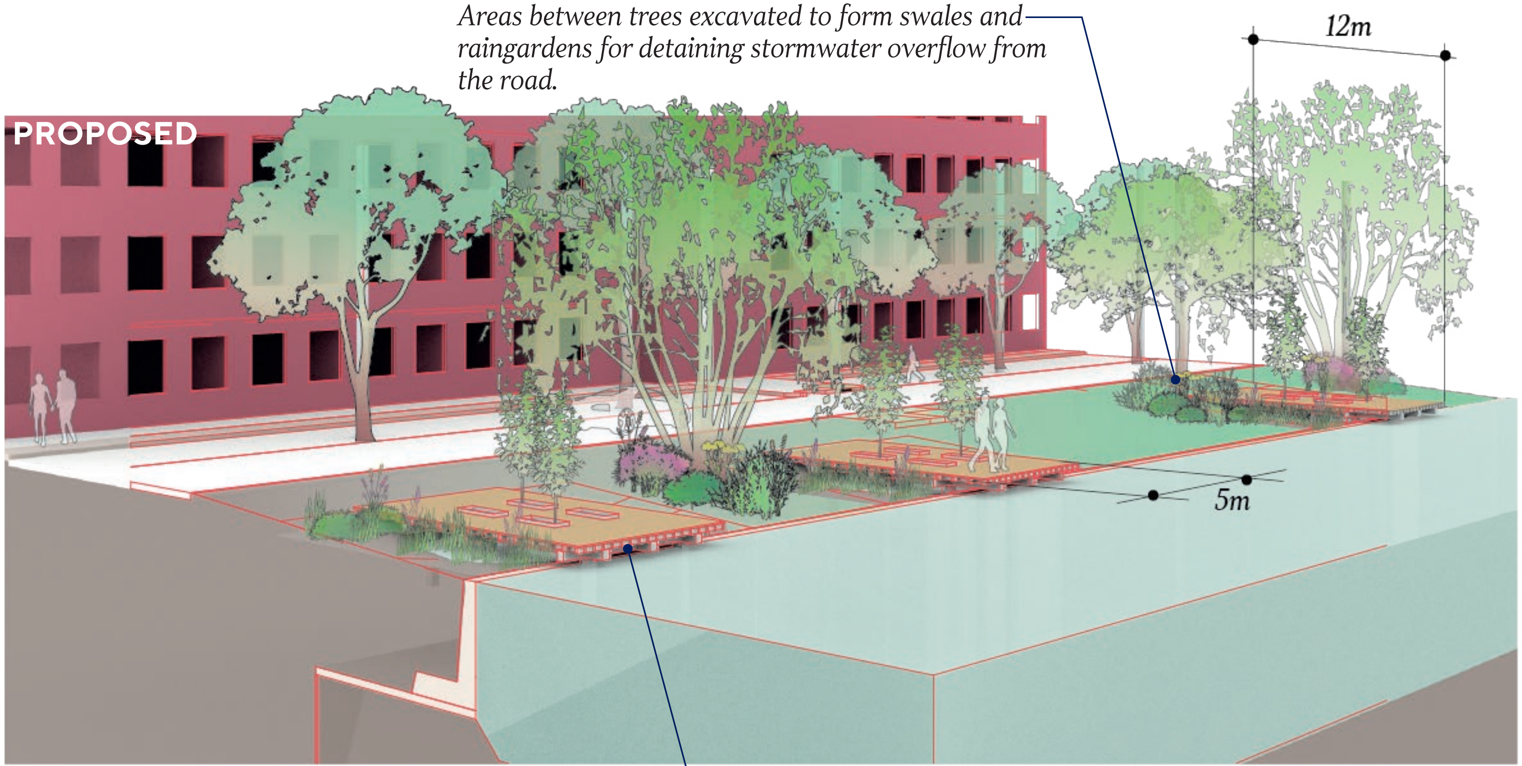
The composition of the top 7m of soil is clay. The groundwater level is at approximately -2.00NAP.



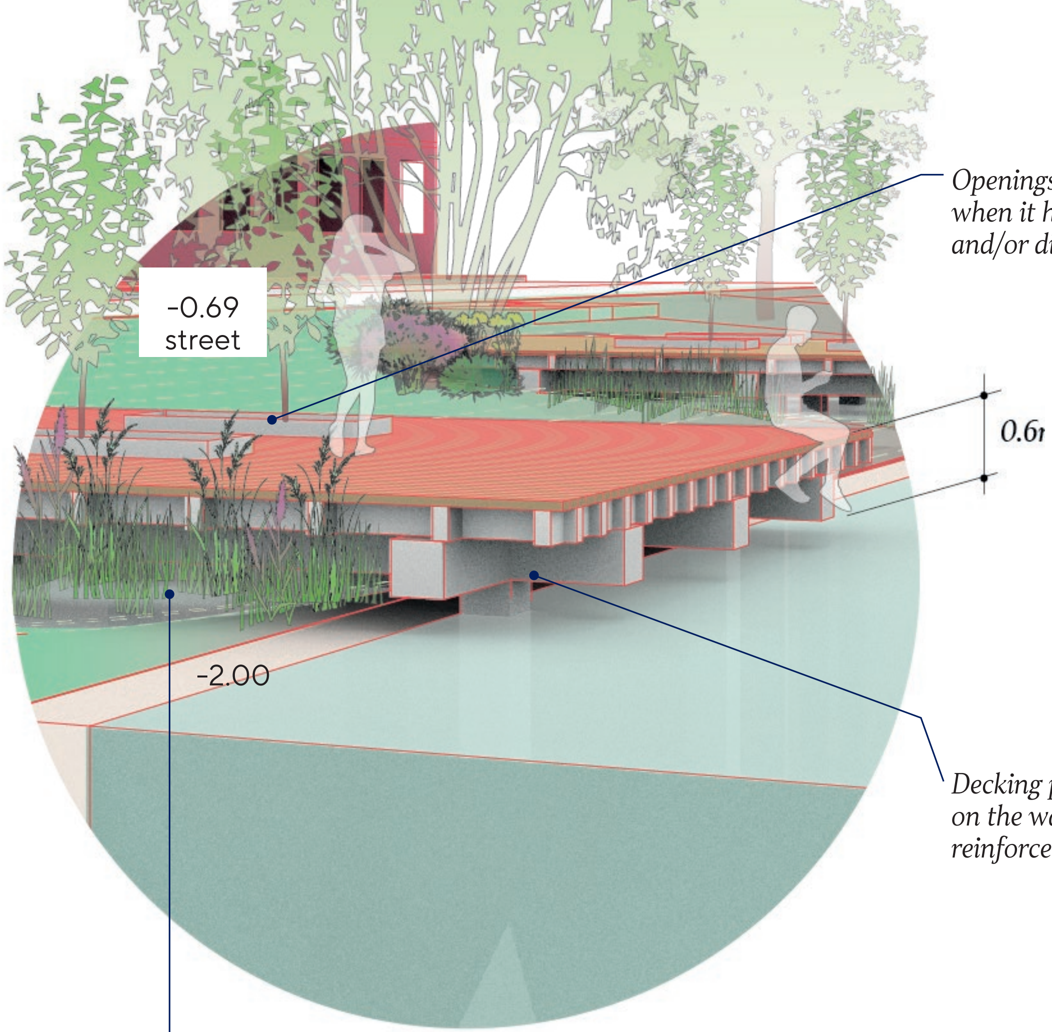
Wide and planted easement between canal and road. No determined function.

Top of canal wall appears to be close to the top of the water level.

Areas between trees excavated to form swales and raingardens for detaining stormwater overflow from the road.



Suspended timber decks create a pedestrian surface out to the water. Posts supporting the deck can also be used in the water side for reinforcement.



Openings in the decking provide UV light to water when it has been collected prior to slow infiltration and/or discharge.

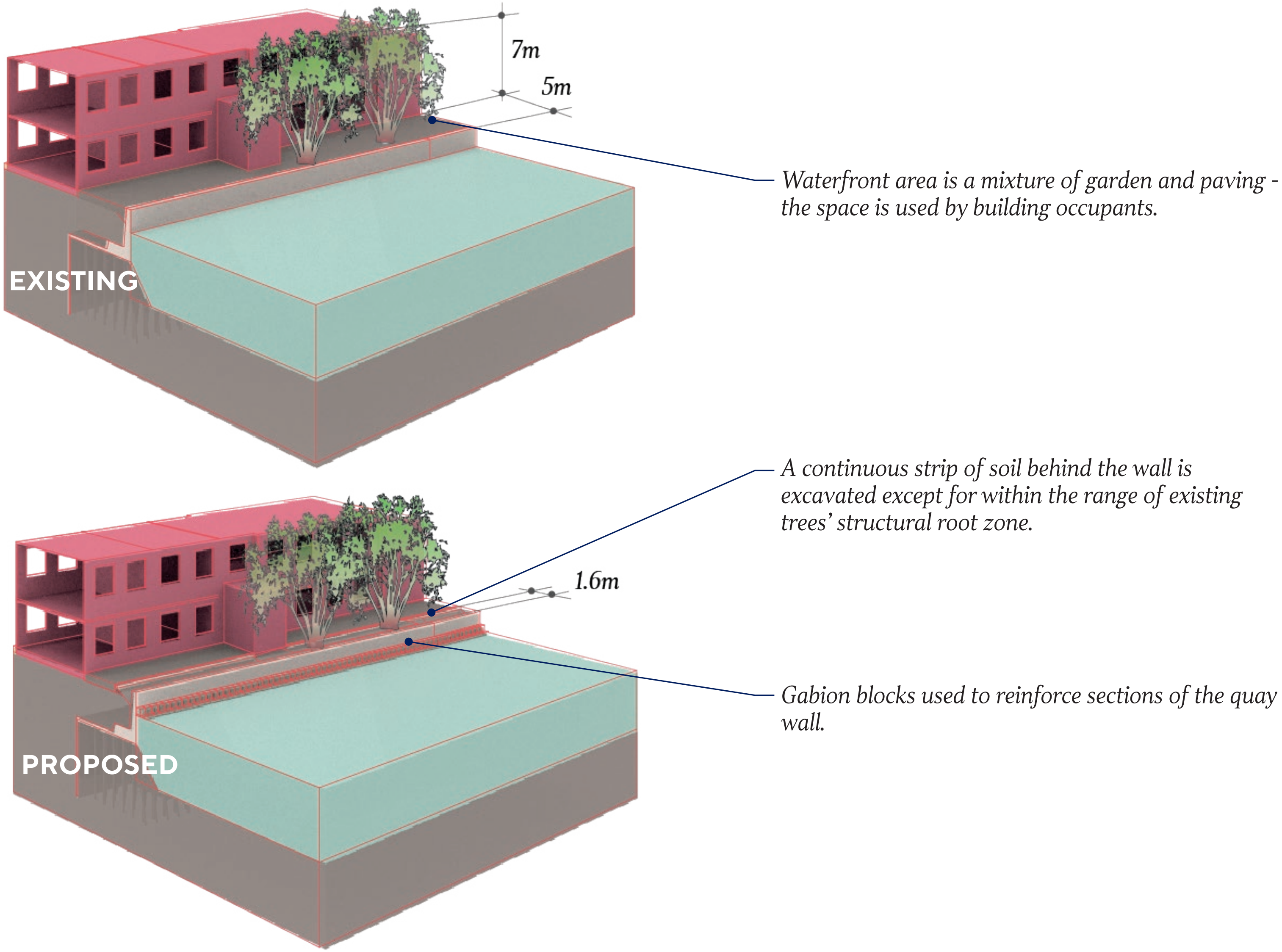
Decking posts can be driven into the canal ground on the water side of the wall to form an underwater reinforcement frame for the wall.

Excavated areas behind the wall are transformed into raingarden and swale areas that can be used to collect and detain stormwater. The water can either be allowed to infiltrate for local recharge of the groundwater table or drained into underground pipes for discharge to the conventional stormwater system.

Note: Depth of raingarden dependent on groundwater table.

Site Scenario #6: Plantage Muidergracht, Plantage, Centrum

REDUCE | LOW QUAY WALL IMPACT SCORE | MODERATE CLIMATE CHANGE VULNERABILITY



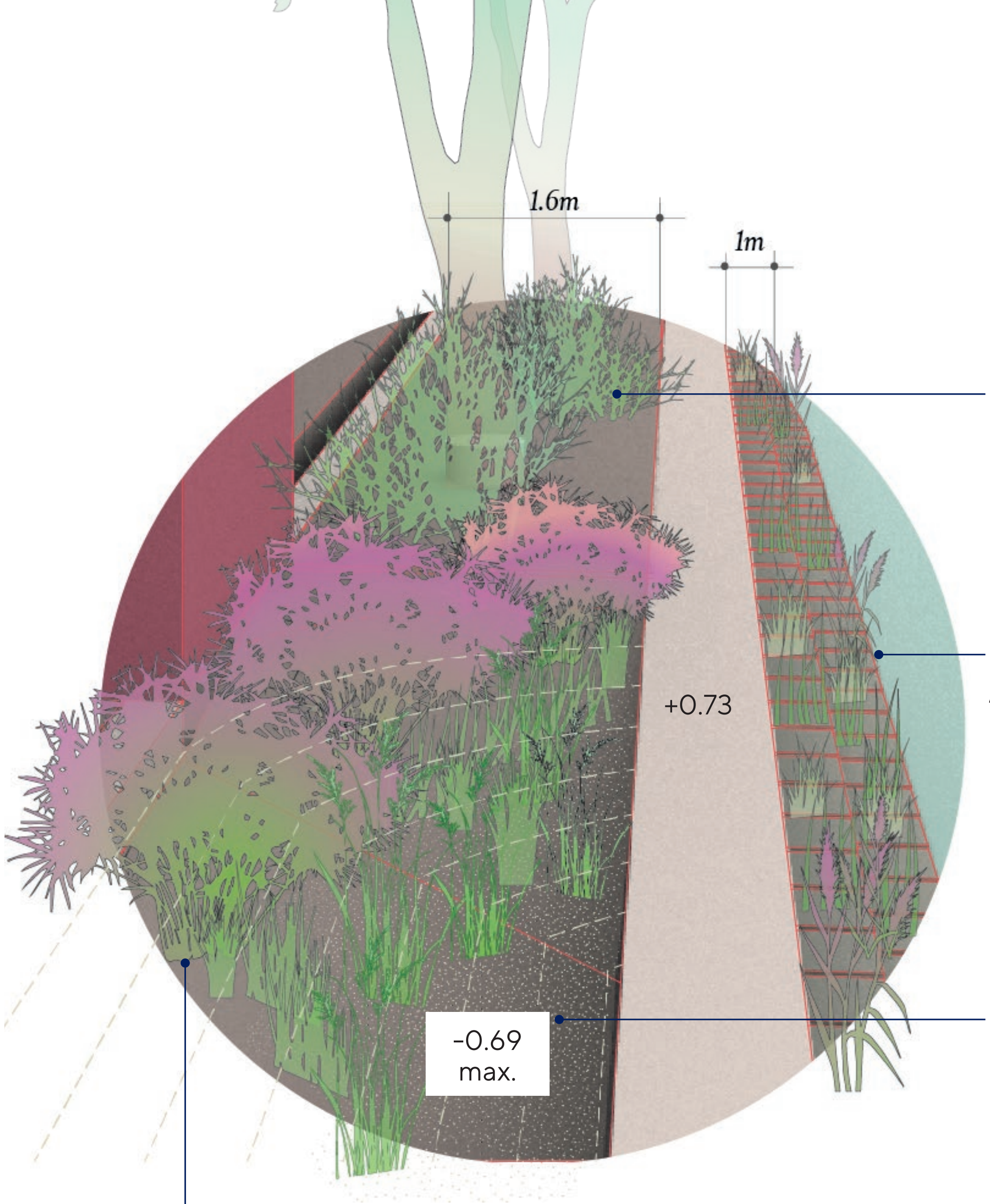
Pop. Density	**LOW**
% Area quay wall	**MEDIUM**

CLIMATE CHANGE EFFECT SUMMARY

Plantage is vulnerable to groundwater levels dropping in summer. In summer the water releases additional heat at nigh. In future it is also predicted that the continuous duration of warm nights will increase in the neighbourhood. The neighbourhood is also vulnerable to pluvial flooding with an increase in days with >15mm rain and in the event of 1:100 or 1:1000 year events a flood depth of more than 200mm.

SITE CONDITION NOTES

The composition of the top 0.7m layer of soil is sand followed by peat until 3.3m which rests on clay to a depth of 10.5m. The groundwater level is at approximately -0.69NAP.



Maintain soil height at existing trees and slope down to lowest point of excavation at all times avoiding damage of structural roots.

Gabions used to support the wall with flood tolerant plants grown in top layer to shade and cool wall surface behind.

**note: gabion units can reduce water current - needs to be checked with on site conditions.*

Swale planting and gravel to cover exposed soil.

Soil from the back of the wall with the top level retained by a concrete sleeper or kerbstone block. Stabilise soil surface with geotextiles, plants, and/or gravel.

Note: depth of excavation limited by groundwater table level.

Site Scenario #7: De Wittenkade, Staatsliedenbuurt Noordoost, West

REDUCE | HIGH QUAY WALL IMPACT SCORE | HIGH CLIMATE CHANGE VULNERABILITY

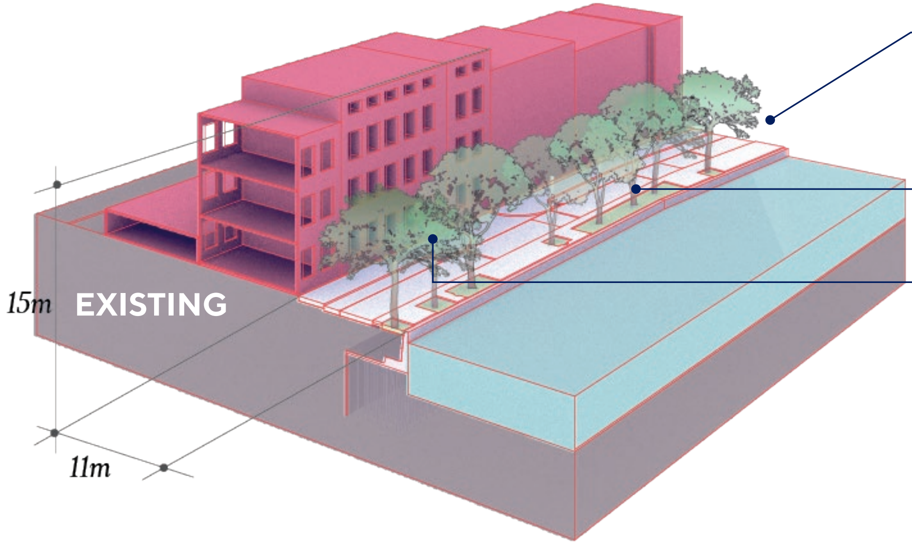
Pop. Density	**HIGH**
% Area quay wall	**HIGH**

CLIMATE CHANGE EFFECT SUMMARY

Plantage is vulnerable to groundwater levels dropping in summer and has an annual precipitation deficit of more than 120mm. In summer the water releases additional heat at night. In future it is also predicted that the continuous duration of warm nights will increase in the neighbourhood. The neighbourhood is also vulnerable to pluvial flooding with an increase in days with >15mm rain and in the event of 1:100 or 1:1000 year events a flood depth of more than 200mm.

SITE CONDITION NOTES

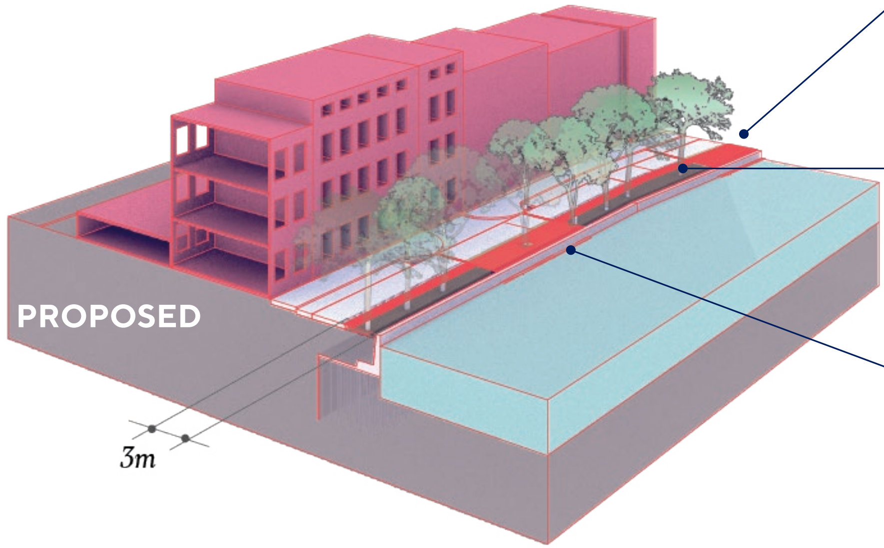
The composition of the top 2.5m layer of soil is clay followed by peat until 5.7m which rests on clay to a depth of 13.2m. The groundwater level is at approximately -0.34NAP.



3m wide pedestrian waterfront area with informal garden beds and paved areas with seating. Houseboats line the canal with some houseboats appropriating parts of the waterfront area as semi-private garden areas.

Trees are well established and some grow in informal garden bed areas.

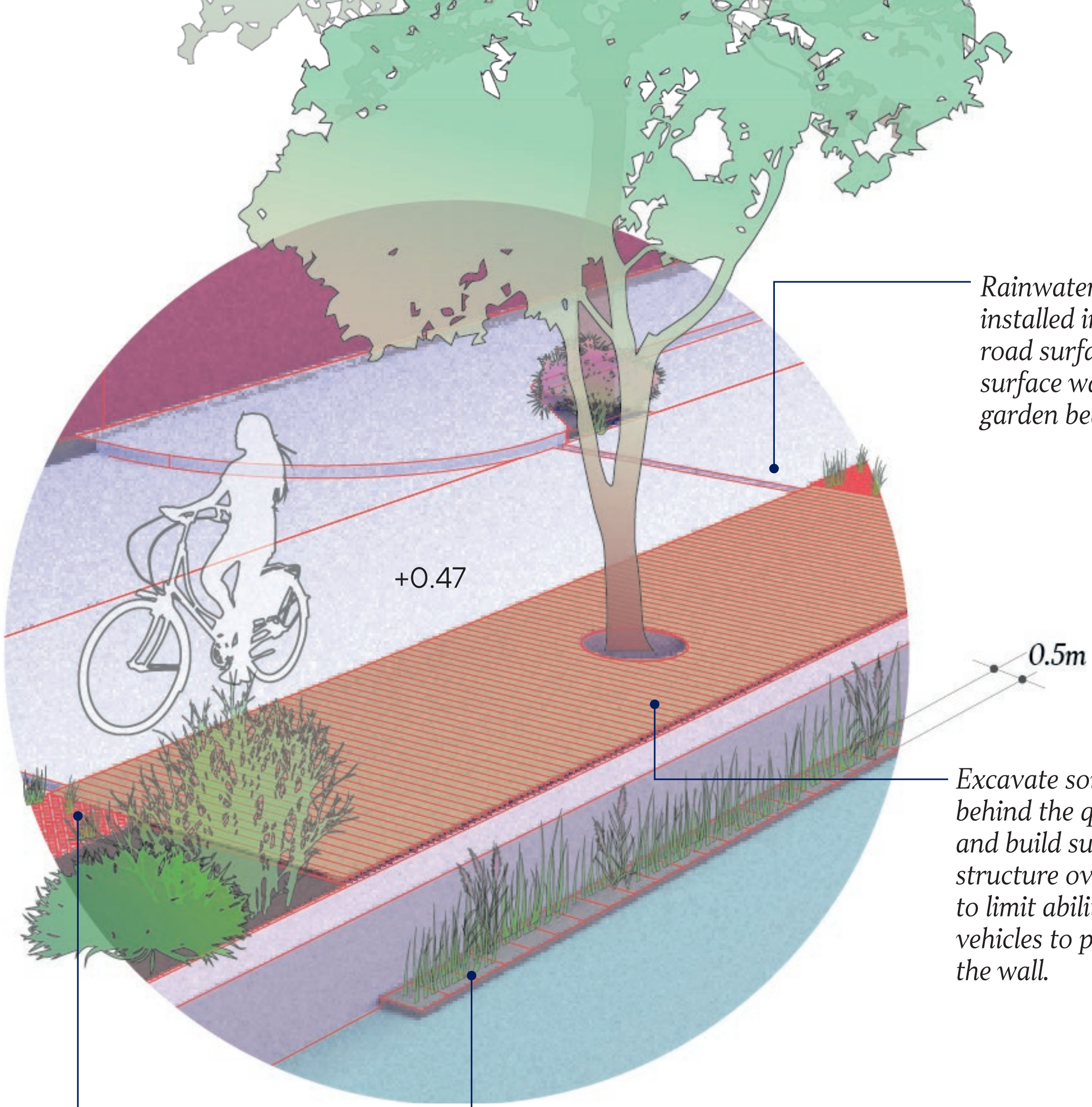
On-street parking is located against the inner pedestrian pathway.



Suspended decking increases infiltration without reducing public seating areas and bicycle parking. Used to deter opportunistic car parking.

Garden bed areas are consolidated and pedestrian footpath in this area converted to permeable paving units.

Gabion blocks used to reinforce sections of the quay wall and located between house boats.



Rainwater channels installed into existing road surface to channel surface water into garden bed areas.

Excavate soil from behind the quay wall and build suspended structure over the soil to limit ability for heavy vehicles to park behind the wall.

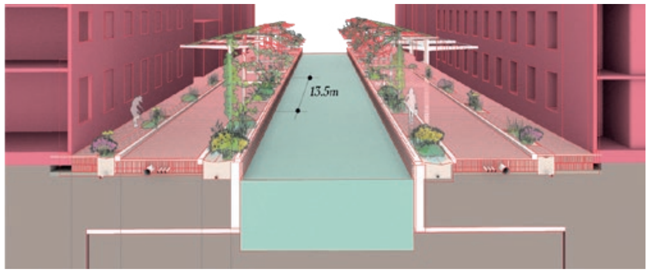
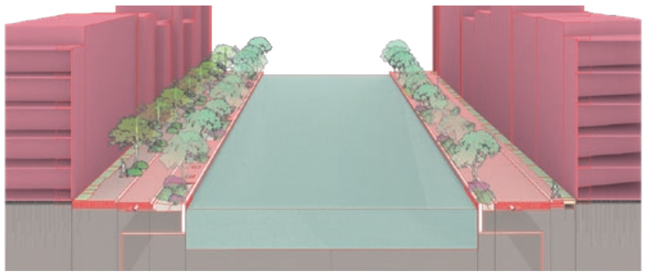
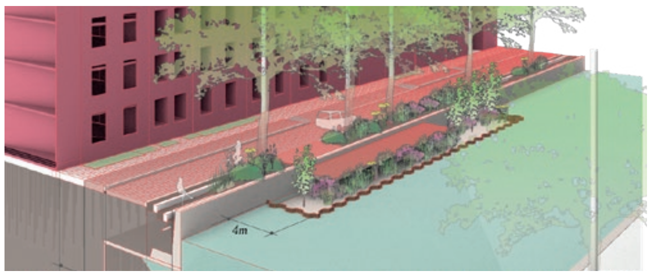
Solid concrete pavers replaced with permeable paving units.

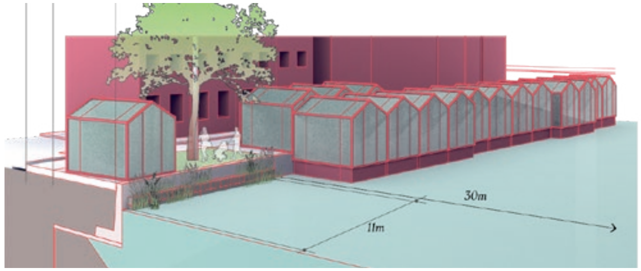
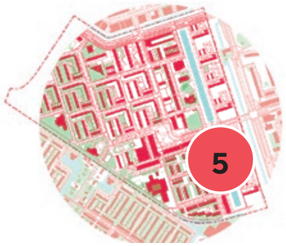
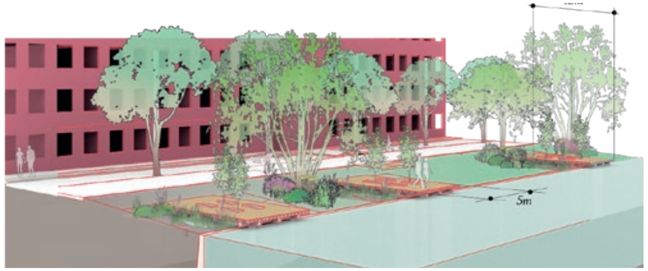
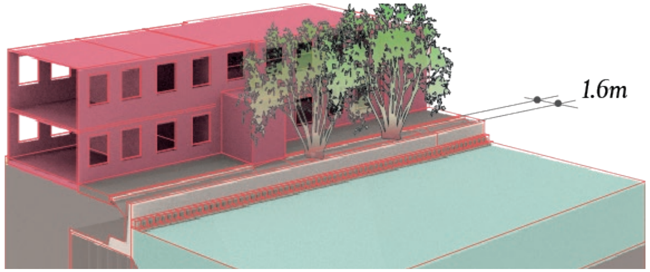
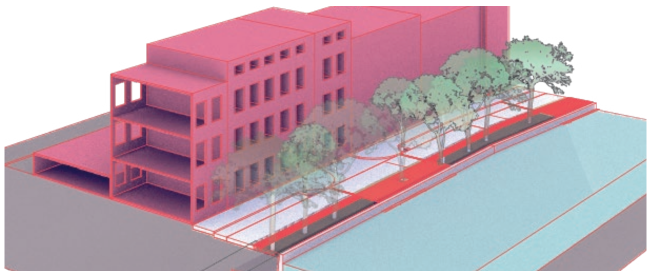
Gabions used to support the wall with flood tolerant plants grown in top layer to shade and cool wall surface behind.

**note: gabion units can reduce water current - needs to be checked with on site conditions.*

6.3.6 *Summary of "Resilience by Renovation" landscape scenarios*

The matrix below and on the following page provides a summary of the NBS benefits achieved in the seven scenarios and provides a means for comparing the scenarios to one another and in context to the specificities of their locations, renovation type, or design measures.

SITE NUMBER AND LOCATION	**QUAY WALL & CLIMATE SCORES**	**WIDTH (m) AFFECTED**	**PRINCIPAL NATURE-BASED MEASURES USED**
  *Site #1: Passeerdersgracht, Passeerdersgrachtbuurt*	REPLACE method HIGH % quay wall area HIGH population density VERY VULNERABLE climate change impact score	7.2-7.5m on land No change to water	• Paving on structural cells: increases permeability. • Raingarden: increases permeability, vegetation, and evapotranspiration. • Arbour structure: provide shade over land and water and increase evapotranspiration. • Green quay walls: shade wall surfaces and increase evapotranspiration.
  *Site #2: Singel, Spuistraat Noord*	REPLACE method HIGH % quay wall area HIGH population density VERY VULNERABLE climate change impact score	9-9.9m on land No change to water	• Paving on structural cells: increases permeability. • Raingarden: increases permeability, vegetation, and evapotranspiration. • Trees: increase stormwater detention, provide shade, and increase evapotranspiration. • Green quay walls: shade wall surfaces and increase evapotranspiration.
  *Site #3: Oudezijds Voorburgwal, Oude Kerk*	REINFORCE method MODERATE % quay wall area MODERATE population density VERY VULNERABLE climate change impact score	8.1m on land 3.8m on water	• Stepped excavation: reduce weight, increase permeability. • Raingarden: increases permeability, vegetation, and evapotranspiration. • Suspended timber decking: increase permeability.

SITE NUMBER AND LOCATION	QUAY WALL & CLIMATE SCORES	WIDTH (m) AFFECTED	PRINCIPAL NATURE-BASED MEASURES USED
  *Site #4: Singel, Reguliersbuurt*	REINFORCE method MODERATE % quay wall area MODERATE population density VERY VULNERABLE climate change impact score	5.4m on land 3.5m on water	• Gravel paving: increase permeability and reduce weight. • Gabion reinforcing structure: reinforce wall from the water-side, reduce scouring.
  *Site #5: Korte Water, De Punt*	REINFORCE method HIGH % quay wall area HIGH population density VULNERABLE climate change impact score	8m on land 1m over water	• Raingarden: increases permeability, vegetation, and evapotranspiration. • Suspended timber decking: increase permeability. • Trees: increase stormwater detention, provide shade, and increase evapotranspiration.
  *Site #6: Plantage Muidersgracht, Plantage*	REDUCE method MODERATE % quay wall area LOW population density HIGH VULNERABILITY climate change impact score	1.5m on land 2.8m on water	• Sloped excavation: reduce weight, increase permeability. • Garden bed: increase stormwater detention, vegetation, and evapotranspiration.
  *Site #7: De Wittenkade, Staatsliedenbuurt Noordoost*	REDUCE method HIGH % quay wall area HIGH population density HIGH VULNERABILITY climate change impact score	3m on land 2m on water	• Permeable paving: increase permeability. • Suspended timber decking: increase permeability. • Garden bed: increase stormwater detention, vegetation, and evapotranspiration.

6.3.7 *Analysis of landscape scenarios in context to research objectives and urban socio-ecological system.*

The matrix below and on the following page is an analysis of the difference scenarios with respect to the research objectives. In the two columns on the right an appraisal is made on how the changes to the waterfront space would affect the socio-ecological system of the waterfront in its location.

SITE NUMBER & LOCATION	QUAY WALL RENOVATION REQUIREMENTS SUMMARY	CLIMATE CHANGE RESILIENCE REQUIREMENTS SUMMARY	SOCIAL IMPACT	ECOSYSTEM IMPACT
 *Site #1: Passeerdersgracht, Passeerdersgrachtbuurt*	**REPLACE TYPE** **4/5 requirements met** Some heavy loads were reinstated - carparking zones were allowed for in limited amounts along the wall - the intention being that these would be for loading vehicles and disabled access carspaces.	**7/7 requirements met** Almost all of the waterfront land surface has been converted into permeable surface, increasing infiltration through to the ground. Due to the limitation of space however trees have been replaced with an arbour structure onto which climbing plants will be trained.	• Water side functions are maintained. • Bicycle parking areas maintained & car spaces reduced. • New street complies with current emergency access widths. • Increased area for small social spaces along the waterfront.	• Land area available for water storage and buffering increased. • Increase in capacity for cooling with planted areas with scope to include biodiversity planting in raingarden areas. • Removal of trees compensated with climbing plants although these do not offer the same stormwater retention benefits.
 *Site #2: Singel, Spuistraat Noord*	**REPLACE TYPE** **4/5 requirements met** Some heavy loads were reinstated - carparking zones were allowed for in limited amounts along the wall - the intention being that these would be for loading vehicles and disabled access carspaces.	**7/7 requirements met** Almost all of the waterfront land surface has been converted into permeable surface, increasing infiltration through to the ground. The reconfiguration of street functions has resulted in more space for plants and trees that assist reducing vulnerability to heat.	• Water side functions are maintained. • Bicycle parking areas maintained & car spaces reduced. • Increased area for small social spaces along the waterfront • Increased garden areas for residents on pedestrian footpath side.	• Land area available for water storage and buffering increased. • Increase in capacity for cooling with planted areas with scope to include biodiversity planting in raingarden areas. • Additional row of trees doubles tree-related ecosystem services in the street.
 *Site #3: Oudezijds Voorburgwal, Oude Kerk*	**REINFORCE TYPE** **5/5 requirements met** Measures were taken on both sides of the wall although the changes were restricted to surface-level changes (e.g. moving parking towards building).	**6/7 requirements met** The strip of landscape behind the wall was mostly converted into a planted terrace that can be inundated if needed but also contains plants that assist with cooling and moisture retention. The reinforcement platform also adds more plants to the waterfront space.	• Canal width reduced, potentially increasing congestion of boats. • Bicycle parking areas maintained & car spaces reduced and moved towards building side. • Increased area for small social spaces along the waterfront. • Extension of small gathering area over the reinforcement platform.	• Land area available for water storage and buffering increased. • Increase in capacity for cooling with planted areas with scope to include biodiversity planting in raingarden areas.

SITE NUMBER & LOCATION	QUAY WALL RENOVATION REQUIREMENTS SUMMARY	CLIMATE CHANGE RESILIENCE REQUIREMENTS SUMMARY	SOCIAL IMPACT	ECOSYSTEM IMPACT
 *Site #4: Singel, Reguliersbuurt*	**REINFORCE TYPE** **5/5 requirements met** Most of the waterfront length was occupied by flower market structures, limiting the extent that measures could be applied.	**4/7 requirements met** The area is very vulnerable to drought, flood, and heat but due to the flower market structures there is limited space on the land and water side. The addition of plants on the gabion wall and under the existing tree represent the extent of what can be done.	• Water side functions decreased as gabions limit boat mooring. • Bicycle parking and seating areas removed from directly behind the wall.	• Land area available for water storage and buffering increased. • Increase in planted areas with scope to include biodiversity planting in raingarden areas. • Increase in capacity for cooling with garden areas below the tree. • Erosion of canal bed limited by gabion blocks.
 *Site #5: Korte Water, De Punt*	**REINFORCE TYPE** **5/5 requirements met** Four out of five requirements were already met in the existing site except for the wall reinforcement.	**4/7 requirements met** Half of the are in the existing landscape was converted into raingardens to detain water as the neighbourhood is prone to both flooding and drought. Additional plants and trees were added to address high vulnerability to heat.	• Water side functions decreased as gabions limit boat mooring. • Increased area for small social spaces along the waterfront. • Open lawn space reduced, limiting functions that require wide open spaces.	• Land area available for water storage and buffering increased. • Increase in capacity for cooling with planted areas with scope to include biodiversity planting in raingarden areas. • Erosion of canal bed limited by decking post structure.
 *Site #6: Plantage Muidersgracht, Plantage*	**REDUCE TYPE** **5/5 requirements met** Two of the five requirements were already met in the existing site. The wall reinforcement was added as an option although it is not part of the typical "reduce" measures.	**6/7 requirements met** The strip of landscape behind the wall was mostly converted into a raingarden too address the high vulnerability to flood in the neighbourhood. Although heat and drought were less of a challenge additional plants were added in this zone.	• Water side functions decreased as gabions limit boat mooring. • Existing private carparking area reduced.	• Land area available for water storage and buffering increased. • Increase in capacity for cooling with planted areas with scope to include biodiversity planting in raingarden areas. • Erosion of canal bed limited by gabion blocks.
 *Site #7: De Wittenkade, Staatsliedenbuurt Noordoost*	**REDUCE TYPE** **5/5 requirements met** Two of the five requirements were already met in the existing site. The wall reinforcement was added as an option although it is not part of the typical "reduce" measures.	**7/7 requirements met** The strip of landscape behind the wall was mostly converted into a raingarden too address the high vulnerability to drought and flood in the neighbourhood. Heat being less of an issue was still addressed by adding more planted areas and trees nearer to the building line.	• Water side functions decreased as gabions limit boat mooring • Existing small social spaces retained and increased along waterfront. • Increased garden areas for residents on pedestrian footpath side.	• Land area available for water storage and buffering increased. • Increase in capacity for cooling with planted areas with scope to include biodiversity planting in raingarden areas. • Erosion of canal bed limited by gabion blocks.

6.4. CONCLUSION

In this chapter the NBS approaches of GI and EBA were used to design spatial strategies and techniques for the "Resilience by Renovation" strategy proposed in Chapter 5. At the scale of the city, a GI design strategy for Amsterdam's quay wall waterfront proposes a green network of spaces in parallel to the water network to distribute ecosystem services to the city's inhabitants. The proposed green space network provides ecosystem services at the scale of the waterfront by the application of the EBA design techniques that improve and increase soil water processes often in combination with additional vegetation.

The landscape scenario sites illustrate how the GI and EBA approaches can be practically applied together in a small sample of waterfront sites identified from the "Resilience by Renovation" spatial plan. Within the three renovation methods of "Replace", "Reinforce", and "Replace" the landscape scenarios illustrate how, in all three methods, it is possible to integrate measures to increase resilience and reduce the occurrence and impact of processes that can degrade the quay wall structure. The design techniques and scenarios illustrate that by combining the two challenges (climate change and quay wall renovation) there is a potentially to create a unique waterfront space network that formally expresses the local specificities within Amsterdam's urban ecosystem.

Although the design changes that affect the form and function of the waterfront spaces are driven by concerns about climate change and quay wall renovation, the design explorations show that there are also significant changes that may need to be made to the social system of the city. First are the impacts relating to car traffic and parking in waterfront areas as the reduced number of car spaces will reduce the convenience (and revenue) generated while also decreasing the weight, heat, and pollution that cars generate locally. At the time of writing there are current plans to reduce the number of car spaces in the city by 7,500-10,000 (Gemeente Amsterdam, 2020) indicating that there is willingness – at least politically – to reduce the number of car spaces. Second are the impacts of increasing the amount and type of green and/or social spaces along the waterfront. While green spaces reduce heat and promote soil moisture retention, they can also limit direct access to the water, again changing the nature of the city's quay wall waterfronts and in some cases having the consequence of limiting certain activities (e.g.: boat access).

The NBS approaches and subsequent design explorations show that while it is physically possible to implement measures that increase resilience and delay quay wall renovation, there are potentially significant changes and conflicts resulting from the re-purposing and reinterpretation of what the quay wall waterfronts do and represent in the city.

This page is intentionally left blank

7. CONCLUSION

The renovation of the city's waterfronts is a long-term process that has recently attracted interest and concern because of the amount of quay walls that will require renovation in the next 5-10 years. The renovation of the walls is an unavoidable task that is complicated further by the uncertainties posed by climate change and its impacts on urban waterfronts. The research and results of this thesis demonstrate and identify the opportunities to combine measures to increase climate change resilience alongside the renovation of Amsterdam's quay wall waterfronts. These opportunities were identified by having analysed the city as an urban ecosystem containing complex and multi-scalar processes that take place and intersect in waterfront spaces. By conceptualising the city as an urban system comprised of interrelated social and ecosystem interactions, the shared causes and effects of climate change and quay wall degradation were identified and operationalised into functional requirements to inform the future designs.

In addition to identifying shared causes and effects of quay wall renovation, the analysis showed that a universal solution is not appropriate nor feasible due to the physical and spatial variations between waterfronts and their vulnerability to climate change and quay wall degradation. Instead, the strategy of "Resilience by Renovation" was proposed as an adaptation on existing plans to "flatten the curve" of quay wall replacement. The strategy proposed that 360 of Amsterdam's waterfront neighbourhoods will have a range of current renovation methods (reduce, reinforce, replace) implemented along their quay wall waterfronts. The three renovation methods - reduce, reinforce, and replace - are made specific to their context by using design measures that address neighbourhood and waterfront scale effects of climate change.

The "Resilience by Renovation" strategy in combination with the functional requirements provided the "where", "when", and "what" needed for this solution and design-driven thesis. To explore and propose a design solution for the established variables, an NBS approach was used given its suitability towards interdisciplinary approaches towards complex urban challenges and especially those relating to urban infrastructures. The specific NBS approaches of GI and EBA were used to generate types of design measures and techniques across the spatial scales of the city, neighbourhood, and waterfront. When applied at different scales of the city, the EBA techniques used are used in combination along the length of the waterfront with each site contributing to a city-scale GI strategy that seeks to create a connected and extensive green space network. It is acknowledged that further research would be required to test more scenario sites in more locations to fully appreciate the local specificities of a city-scale strategy like the one proposed in this thesis.

Within the seven landscape scenarios sites generated the opportunities of the "Resilience by Renovation" strategy is given spatial possibility in the specific contexts of seven waterfront locations in Amsterdam. The sites chosen were exemplars of the three renovation methods and contained a range of vulnerabilities to climate change, and served to demonstrate the range of opportunities and limitations encountered when materialising solutions in the city. Opportunities identified included: adding more areas for water infiltration benefiting flood protection and groundwater table stabilisation; and increasing the number and size of green spaces along waterfronts providing possibilities to increase biodiversity while also regulating temperatures. Limitations pertained to mainly the space available and existing functions within the waterfronts selected – in all cases there was a reduction in space for car parking and a limitation of points where the water can be accessed for boating or other recreational activities.

The final design proposals resulting from the research visualise how increasing climate change resilience is possible and beneficial alongside the renovation of Amsterdam's quay walls and that it can be done within the limited areas affected areas by the renovation. Based on an analysis of the landscape scenario sites, even with only 1.5 metres of land width changed throughout all 200 kilometres of quay wall, it would be possible to add 300 square kilometres of area towards making Amsterdam's waterfront spaces climate adaptive and resilient for future years to come.

8. DISCUSSION

The results of this thesis show that there is a real and material potential for affecting city-wide change with respect to climate change adaptation by using the quay wall renovation process as an opportunity for urban change. The research questions that were used to gain this knowledge could also be used to investigate the social and ecological impacts of changing Amsterdam's waterfront spaces. Additionally, as spaces with so much imbued meaning and significance in Amsterdam, the quay wall waterfronts would also benefit from an analysis at a smaller scale although this runs the risk of focusing only on the waterfront spaces – and especially those that are marked as most urgent for renovation – which adds to sociospatial inequalities that have been linked to urban greening initiatives – including those labelled as NBS projects - in other cities (Anguelovski, Irazábal-Zurita, & Connolly, 2019; Raymond et al., 2017).

The scope of this thesis was limited to the Municipality of Amsterdam's boundary however this study could also be extended to the metropolitan region of Amsterdam (MRA) which in turn may yield very different results with respect to what drivers need to be addressed in the short term and future to provide the most benefits to people who perhaps work or study in Amsterdam but live in adjacent municipalities. Indeed additional research and proposals is needed to address metropolitan and regional drivers and effects of climate change.

The results and recommendations made in this thesis are also dependent on the of the municipality's research into innovations for reducing the impacts of the quay wall renovation. Should there be a way to reinforce or replace the walls without disturbing the land side, there may not be the same opportunities to reconfigure waterfront spaces of the city. Indeed, with a different construction method there could be other opportunities and measures to be taken that would yield different material results in the city's waterfronts. It would be also interesting to approach the two challenges again differently to see if the functional requirements would change, and if so, how and why. In addition to changing the approach to the challenge, there is also potential to use the same questions but on a different waterfront city – perhaps Venice, Italy or Bangkok, Thailand – where those city's extensive canal networks are also in need of renewal due to age, changing urban environments, and climate change.

The resources available for this thesis were limited and this affected the time spent and scale possible for the research. For example, more interviews with not only engineers but residents and other interested parties would shed more light into the nature of the challenge – research that would be best done with Dutch language skills. Nevertheless, the research undertaken for this thesis has provided insight into the complex and subjective nature of the city's quay wall waterfronts. Citizens' stories frequently appear in the city's news outlets supporting the observation that waterfront spaces are socially significant spaces in Amsterdam and it is because of the high social and cultural value to the city that the results of this thesis could be researched further to explore to what extent can Amsterdam's waterfronts – especially those in the Canal Ring – be changed in appearance and function in the imagination of 'Amsterdammers' and in the way the city represents itself to others. For example, to what extent should the city's inhabitants endure the consequences of climate change or maintain a centuries old edifice? Does this shed light on an underlying hesitation to see what the city is now versus what it was?

Finally as a reflection upon the thesis with respect to the aims of the MSc MADE programme, although it was not included in the motivations of the research, using an NBS approach for this thesis showed the value of interdisciplinary approaches that offer a diverse range of approaches and perspectives that can be taken to urban challenges and their solutions. Although interdisciplinary approaches do not neatly rest within any particular discipline, the process and results of an interdisciplinary approach also gives insights into the complexities of trying to find "best fit" solutions and communicating these results to researchers from distinct fields or the general public. Urban infrastructures, like the quay wall waterfronts, are complex spaces that are used on a daily basis by people who are typically unaware of the dependencies that exist within them. By taking a spatial and material approach, the components of urban infrastructures the system challenges that they embody were easier to understand which may also offer some insight for similarly visually and spatially minded people and disciplines.

9. APPENDIX

A. Data schedules

B. Interview & meeting list

C. Interview questions and notes

D. Site visit photos

E. Combined climate change and quay wall renovation impact scores

F. Case study projects

G. DINOLoket subsurface data for landscape scenario sites

H. Waternet Peilbuizen data for landscape scenario sites

I. Landscape scenario sites: combined impact and vulnerability s core

J. Measurements of results for landscape scenario sites

A. DATA SCHEDULES

Data Type	Program	File Name(s)	Description	Source	Reference Notes
JSON	GIS	Bomen_p1	Tree locations		
	GIS	Bomen_p2	Tree locations		
	GIS	Bomen_p3	Tree locations		
	GIS	Bomen_p4	Tree locations		
	GIS	MonumentalBomen	Tree locations		
	GIS	EcologicalStructure	Open space strategy	https://maps.amsterdam.nl/open_geodata/	Used for Green Infrastructure strategy.
	GIS	MainGreenStructure	Open space strategy		
	GIS	Wijken_Nhoods	Administrative boundaries		Used to set boundaries to study area. Data attributed to these boundaries.
	GIS	Stadsdelen	Administrative boundaries		
	GIS	Districts	Administrative boundaries		
	GIS	Practice Areas	Administrative boundaries		
CSV	GIS/XLS	2020-buurten-1-01	Population data at neighbourhood level	https://data.amsterdam.nl/datasets/04hDn1XztquLvQ/bevolking-metropoolregio-amsterdam/	Joined to geodata tables for population-related analysis. Referenced in Chapters 4, 5, 6.
SHP	GIS	PKS_Klimaateffecten_Hitte_Risico opwarming oppervlaktewater_Huidig_v10_t0_uit	Heat release from water bodies current		
	GIS	PKS_Klimaateffecten_Hitte_Risico opwarming oppervlaktewater_2050 WH_v9_t0_uit	Heat release from water bodies predicted for 2050WH scenario		
	GIS	Paalrot	Areas with conditions causing pile rot and their severity		
	GIS	Bodemdaling 2016-2050 - huidig	Areas affected by subsidence current to 2050 current prediction		
	GIS	Bodemdaling 2016-2050 (aanvullend) - 2050 WH	Areas affected by additional subsidence anticipated in 2050WH scenario	Climate Adaptation Services, 2020 (further detail to original source in brackets in description)	Climate geodata. Referenced in Chapter 6.
	GIS	Potentieel maximaal neerslagtekort (gemiddeld) - huidig	Areas affected by precipitation deficit (average) current (KNMI)		
	GIS	Potentieel maximaal neerslagtekort (gemiddeld) - 2050 WH	Areas affected by precipitation deficit (average) as predicted in 2050WH scenario (KNMI)		
	GIS	PKS_Klimaateffecten_Wateroverlast_Gemiddelde Hoogste Grondwaterstand_2050 WH_v16_t0_uit	Average high groundwater table height in regions as predicted in 2050WH scenario		
	GIS	PKS_Klimaateffecten_Wateroverlast_Gemiddelde Hoogste Grondwaterstand_Huidig_v17_t0_uit	Average high groundwater table height in regions current		
TIFF/RASTER	GIS	M_25GN1	Amsterdam DSM file - centrum		
	GIS	R5_25GN1	Amsterdam DTM file - centrum		
	GIS	R5_25EZ1	Amsterdam DTM file - centrum	https://downloads.pdok.nl/ahn3-downloadpage/	
	GIS	M5_25EZ1	Amsterdam DTM file - centrum		
	GIS	R5_25DN1	Amsterdam DTM file - new west		
	GIS	M5_25HN1	Amsterdam DTM file - new west		
	GIS	PKS_Gevoelige functies en ruimtelijke kenmerken_Hitte_Stedelijk hitte eiland effect_nvt_v2_t0_uit	Areas affected by urban heat island (UHI) effect current (RIVM)		

	GIS	PKS_Gevoelige functies en ruimtelijke kenmerken_Hitte_Hittekaart gevoelstemperatuur_nvt_v1_t0_uit	Areas affected by wind chill temperature (PET)	Climate Adaptation Services, 2020 (further detail to original source in brackets in description)	Climate geodata. Referenced in Chapter 6.
	GIS	PKS_Klimaateffecten_Hitte_Hittestress door warme nachten_Huidig_v12_t0_uit	Duration of continuous days with heat stress at night current		
	GIS	PKS_Klimaateffecten_Hitte_Hittestress door warme nachten_2050 WH_v11_t0_uit	Duration of continuous days with heat stress as predicted for 2050WH scenario		
	GIS	Laagste grondwaterstand - extreem droge zomer - huidig	Areas with groundwater level change in extreme drought summer current		
	GIS	Laagste grondwaterstand - extreem droge zomer - 2050 WH	Areas with groundwater level change in extreme drought summer as predicted in 2050WH scenario		
	GIS	PKS_Overstromingskenmerken_Overstroming_Overstromingsdiepte | grote kans_nvt_v2_t0_uit	Areas with large chance of fluvial fooding according to depth current		
	GIS	PKS_Overstromingskenmerken_Overstroming_Overstromingsdiepte | middelgrote kans_nvt_v3_t0_uit	Areas with average chance of fluvial flooding according to depth current		
	GIS	PKS_Overstromingskenmerken_Overstroming_Plaatsgebonden overstromingskans 2050 >20cm_nvt_v7_t0_uit	Areas with chance of flooding probabilities up to 2050 of depths of more than 20cm		
	GIS	PKS_Gevoelige functies en ruimtelijke kenmerken_Wateroverlast_Waterdiepte bij intense neerslag - 1:100 jaar_nvt_v1_t0_uit	Regions according to water depth during intense flooding 1:100 year event current		
	GIS	PKS_Gevoelige functies en ruimtelijke kenmerken_Wateroverlast_Waterdiepte bij intense neerslag - 1:1000 jaar_nvt_v2_t0_uit	Regions according to water depth during intense flooding 1:1000 year event current		
	GIS	PKS_Klimaateffecten_Wateroverlast_Dagen met ≥15 mm_2050 WH_v20_t0_uit	Regions according to days with more than 15mm per hour precipitation events as predicted in 2050WH scenario (KNMI)		
	GIS	PKS_Klimaateffecten_Wateroverlast_Dagen met ≥15 mm_Huidig_v21_t0_uit	Regions according to days with more than 15mm per hour precipitation events current		
JPG	INDD	as downloaded	Rokin Image pre-infill	https://archief.amsterdam/beeldbank/detail/b75ce048-b109-57d3-4589-b18356533303	Insight into construction methods over time. Referenced in Chapter 4.
	INDD	as downloaded	Rokin Image pre-infill	https://archief.amsterdam/beeldbank/detail/3834a9b3-f73d-dbcd-dbeb-6f2762b9105f	
	INDD	as downloaded	Amerikahaven and Coenhaven (1954)	https://archief.amsterdam/inventarissen/scans/30184/26.7.4/start/0/limit/10/highlight/5	
	INDD	as downloaded	Ijburg quay wall design (2002)	https://archief.amsterdam/inventarissen/scans/30669/3.7.4.18/start/0/limit/10/highlight/2	
	INDD	as downloaded	Ijburg quay wall design (2002)	https://archief.amsterdam/inventarissen/scans/30669/3.7.4.18/start/0/limit/10/highlight/3	
	INDD	as downloaded	Ijburg quay wall design (2002)	https://archief.amsterdam/inventarissen/scans/30669/3.7.4.18/start/0/limit/10/highlight/4	

	INDD	as downloaded	Ijburg gabion wall design (2002)	https://archief.amsterdam/inventarissen/scans/30669/3.7.4.18/start/0/limit/10/highlight/5	
	INDD	as downloaded	Map of Amsterdam by Anthonisz Cornelis (1544)	https://archief.amsterdam/beeldbank/detail/cf078ee0-cef9-44c5-f844-c144459c7629	
	INDD	as downloaded	'Amstelodami Celeberrimi Hollandiae Emporii Delineatio Nova', first edition by the heirs J. Jansz van Waesberge. Hameleers cat. 82	https://archief.amsterdam/beeldbank/detail/70759182-8527-11e4-9c4e-9354c913ef6f	
	INDD	as downloaded	SUDS garden	https://blogs.nottingham.ac.uk/blue-greencities/2017/09/01/malmo/	
	INDD	as downloaded	SUDS stream	https://climate-adapt.eea.europa.eu/metadata/case-studies/urban-storm-water-management-in-augustenborg-malmo	
	INDD	as downloaded	SUDS channel detail	https://climate-adapt.eea.europa.eu/metadata/case-studies/urban-storm-water-management-in-augustenborg-malmo	
	INDD	as downloaded	Boompjes promenade	https://rotterdammakeithappen.nl/en/media-objects/boompjeskade-2/	Case study images shown in Apendix F.
	INDD	as downloaded	"Room for the River" measures	https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/ruimte-voor-de-rivieren/index.aspx	
	INDD	as downloaded	Examples of BAF calculation from an example plot	https://www.berlin.de/sen/uvk/en/nature-and-green/landscape-planning/baf-biotope-area-factor/calculation-examples/	
	INDD	as downloaded	Courtyard garden at Friedelstrasse 49	https://www.berlin.de/sen/uvk/_assets/natur-gruen/landschaftsplanung/bff-biotopflaechenfaktor/foto13.jpg	
	INDD	as downloaded	News headline from CNN travel	https://edition.cnn.com/travel/article/amsterdam-collapsing/index.html	
	INDD	as downloaded	News headline from NOS news	https://nos.nl/artikel/2339738-deel-amsterdamse-bruggen-en-kades-staat-op-instorten.html	Images of websites used for illustrating societal relevance in Introduction.
	INDD	as downloaded	News headline from Dutch News	https://www.dutchnews.nl/news/2019/02/amsterdams-bridges-and-canal-sides-need-urgent-repair-work/	

B. INTERVIEW & MEETING LIST

Semi-Structured Interview List (Refer to Appendix C for interview notes)

Name	Position	Organisation	Interview Date
Ally Altman	Senior Specialist - Bridge and quay wall programme	Gemeente Amsterdam	28/05/2020
Timothy Augustuszoon	Specialist Construction/Advisor - Bridge and quay wall programme	Gemeente Amsterdam	29/05/2020
Albert Jongsma	Project manager - Bridge and quay wall programme	Gemeente Amsterdam	10/06/2020
Marleen Cervelli	Technical manager - Bridge and quay wall programme	Gemeente Amsterdam	24/06/2020

Meeting List

Name	Position	Organisation	Meeting Date
Henk Wolfert	Head of AMS Institute Living Lab Quay Walls	AMS Institute	29/10/2019
Mellany Doldersum	Program Secretary, Trekker Living Lab Lifetime extension	Gemeente Amsterdam	5/02/2020
Laura Hakvoort	Municipal officer, renewal programme	Gemeente Amsterdam	5/02/2020
Henk Wolfert	Head of AMS Institute Living Lab Quay Walls	AMS Institute	26/02/2020
Mart-Jan Hemel	Research Fellow (LL Quay Walls)	AMS Institute	26/02/2020
Pantelis Karamitopoulos	Research Fellow (LL Quay Walls)	AMS Institute	26/02/2020
Yonne Jaeger	Municipal intern - Bridge and quay wall programme (lifetime extension)	Gemeente Amsterdam	4/03/2020
Mart-Jan Hemel	Research Fellow (LL Quay Walls)	AMS Institute	28/07/2020
Pantelis Karamitopoulos	Research Fellow (LL Quay Walls)	AMS Institute	28/07/2020

C. INTERVIEW QUESTIONS AND NOTES

APPENDIX
SEMI-STRUCTURED INTERVIEWS

Semi structured interviews were undertaken with municipal officers working in the "Quay wall and bridge" programme within the Municipal Engineer's Office responsible for the renovation of the quay wall. The purpose of the interviews was to identify how the municipality of Amsterdam is approaching the challenge wall renovation with respect to: roles and teams, specific local threats, extent of integration with climate change adaptation efforts, awareness of NBS concept, potential for co-benefits alongside renovation. Finally, a last question was added for "snowball" identification of other interviewees. Table 1 summarises the connection between topics, concepts, and the questions asked during the interview.

	TOPICS	KEY WORDS	QUESTIONS
CHALLENGE DESCRIPTION	Actors and groups involved in quay wall renovation	Roles and expertise re: quay walls	• *What is your working role with respect to the quay walls?* • *What are the other roles relating to the day to day maintenance and/or future design of the quay walls?*
	Drivers of quay wall renovation	Lifetime threats acceptable threats	• *What, in your experience, are the biggest challenges with maintaining the quay walls?*
OPPORTUNITIES	Climate change impacts to city and wall	Additional design, operation, or maintenance requirements as a result of flood or drought or heat	• *Given the changing climate of the city, what changes have had to be made to the design, operation, and/or maintenance of the quay walls?* • *Are you aware of "Nature-based Solutions"?*
	Opportunity for co-benefits during renovation	Dependent/affected infrastructures specific co-benefits of quay walls (current and proposed)	• *What, in your opinion, are the opportunities for integrating other city improvements alongside the renovation of the walls?*
ORGANISATION	Stakeholders of the quay wall renovation	Inter-departmental input into the quay wall roles of departments with input	• *How much inter-departmental collaboration is there with forming solution for the renovation of the quay walls?* • *Are there particular departments that you believe could add value to the design of the quay walls?* • *Who would you recommend that I speak to regarding the quay wall renovation?*

Table 1: Quay wall renovation interview topics, concepts, and questions

The notes taken during the interviews are in bullet point format summarising what interviewees said during the call and categorised according to topics because at times questions were answered prior to them being asked due to the natural progression of the conversation.

APPENDIX
SEMI-STRUCTURED INTERVIEWS

INTERVIEW 1:

Name:	Ally Altman	Date & place of interview:	28/5/2020 Zoom Online Meeting
Role: Municipal Department:	Specialist Advisor Senior Specialist - Bridge and quay wall programme	Time:	14:30 – 15:30

Actors and groups:

- Advisor and reviewer of drawings based on professional background as a structural engineer, not part of the full-time team. Focused on reviewing proposals for new quay walls or testing the existing quay walls from the perspective of engineering design.
- His department not involved with the maintenance of the walls, this is handled by the V&OR (Verkeer en Openbare Ruimte – Traffic and Open Space) department. The V&OR is responsible for the daily maintenance and inspections of the quay wall.

Drivers & current challenges:

- The old quay walls are between 80-100 years old and constructed from masonry with wood piles. The newer walls were built in the 50s and 60s and use concrete piles instead.
- Timber piles are the biggest challenge for the quay wall renovation – when they are weak the whole structure is weak.
- The masonry wall provides strength and is a vertical load on the structure.
- The weight and the material of the quay walls are the two main challenges for the design of the quay walls.
- New designs are based on the current design loads that are required and the V&OR determines the loading that is required.
- In some areas of the quay wall in the city centre the design loading is for 500kg within a range of 3m of the quay wall.
- Older areas in the city are designed for less loads because they will have less traffic.
- The new walls are designed with a masonry facing only.
- Another challenge is building around the monumental trees as they are protected by law and the works to the wall will damage them – currently it is impossible to replace the quay wall and keep existing trees (incl. monumental trees).
- In Utrecht the quay walls there were damaged by roots but in Amsterdam this has not been observed to be the case.

Climate change adaptation connection:

- Some connection has been made with Rainproof Amsterdam and Waternet

- In future for climate change adaptation there needs to be consideration of open space use and the amount of space available for access (e.g. fire engine).
- There are already changes like the 'Autoluw' where there is less heavy traffic in the centre and a potential to have more transportation on the water instead.

Opportunities for co-benefits:

- Opportunistic benefits like consolidating underground services is based on what is being done and how long it takes to incorporate.
- Having less car spaces in the new quay wall areas is a potential benefit to how the area in the city centre is used.
- There are also things to learn from the quay walls in Utrecht where the walls were on a sand base and had to be renovated in the last few years.
- Collaboration study between V&OR, TU Delft, and TNO was done to investigate masonry as a material and its properties.

Stakeholders:

- There is already some connection between the Engineer's Office, V&OR, other municipalities, and the scientific department which is undertaking research into the wall.
- Waternet is important stakeholder/partner as they are concerned with the water quality, canal width, depth, water traffic, and bridge clearance height, sewage and stormwater, etc.
- They influence the design quite a lot because they need to grant permission.

*will email names and contact details of people to talk to

APPENDIX
SEMI-STRUCTURED INTERVIEWS

INTERVIEW 2:

Name:	Timothy Augustuszoon	Date & place of interview:	29/5/2020 Zoom Online Meeting
Role: Municipal Department:	Specialist Construction/Advisor Bridge and quay wall programme	Time:	11:30-12:30

Actors and groups:

- Civil engineer concerned with the construction, design, and recalculation of the walls and bridges.
- Some of the walls are over 200 years old and those including the other old walls means that it is not possible to do all of them at once and so prioritisation is needed as well as prolonging the lifespan of the existing walls.
- Prioritisation of the walls involves identifying which walls are close to collapsing and then assessing what can be done to the prolong their lifespan.
- This can be done by decreasing the traffic load, emergency constructions to reinforce them like the sheet pile and sand currently used in the city.
- The reinforcement structures are made by driving large circular hollow sections into the ground and then constructing beam structure for the sheet pile → is used for the walls that are very high risk and generally these structures are built to be used for 5-10 years.
- Maintenance is done by measuring how much the wall has moved over a period of time – displacement.
- Cleaning is done by a different department – Dagelijk beheer or daily management – and they clear 1-3 times over a period of 5 years. When the walls are being cleaned then cracks and displacement that is noticed is also reported. Plants are also removed from the walls during this time.

Drivers & current challenges:

- The biggest concern for the walls is maintaining safety levels
- The challenge is that the quay walls are old and that there are no drawings to show what calculations were made or what the performance requirements were based on.
- A lot of guessing and visual appraisal of how the quay walls were constructed.
- Another unknown is the state of the piles and how to know what condition they are in.
- New quay walls need to retain their monumental status – need to have the same visual appearance
- Loading is different in current times and new construction methods are better suited to it – sheet pile.
- For old quay walls the challenge is to estimate what live and dead loads are possible in the design
- For new quay walls the challenge is the staging of the walls – when will they be built.
- There is no minimum or maximum length practically in the replacement of the walls – the main concern is the surroundings

- Try to maintain a 6m clear zone from the face of the building for access wherever possible.

Climate change adaptation connection:

- There is more freedom in the new quay walls to integrate other benefits like those for climate change adaptation.
- For the current walls it is more challenging because they are susceptible to rising and falling groundwater levels that affects the piles.
- In the new walls it is possible to plant more trees.
- Not aware of NBS.

Opportunities for co-benefits:

- The engineer's office is not so integrated with other departments to identify all the possible opportunities for the quay wall renovation
- Speak to Albert Jongsma who oversees the programme
- Take a look at the underground parking that has been built together with new quay walls in de Pijp.
- Charging stations and new parking signals are being added to the quay wall renovation.

Stakeholders:

- Anna Marie Koestra is the person to speak to re: collaboration between departments.
- Innovation team is good to speak to for the new quay walls.
- Gemeente Rotterdam is also a good resource as they have been advising on the new designs.

APPENDIX
SEMI-STRUCTURED INTERVIEWS

INTERVIEW 3:

Name:	Albert Jongsma	Date & place of interview:	10/6/2020 Telephone call
Role:	Project manager - Bridge and quay wall programme	Time:	PM
Municipal Department:	Bridge and quay wall programme		

Actors and groups:

- Began in the programme looking at the contract for renovation in 2015 when more was known about the state of the quay walls.
- Has since been working on the plans on how to renovate the quay walls to the point where it is at now in the municipality (big team).
- Role is to manage/oversee all of the renovation team connected to the quay walls.

Drivers & current challenges:

- The challenge now is to find ways to reduce the disruption to the waterside during construction. The old manner of construction was to perform the construction on a platform over the water and the demolish the road and wall from that point.
- There are 60 kilometres currently in the programme for renovation in the short term including Singel and Herengracht.
- Another challenge is balancing all of the stakeholders that need to be consulted in the process.
- The first and most important challenge to the city (not the renovation process) is that the technical state of the wall is so bad that it needs to be made to a good level – this is the first priority.
- The decision for what exactly is done during renovation is guided by the first priority and then what other purposes can be added.
- Draining the canal to perform he works is also risky because it lowers the water table under the foundations of the buildings.
- There are three KPIs for the renovation at present:
    - I. Money measured as m2
    - II. People that are affected/benefit from the quay wall renovation as m2
    - III. Strategies that increase benefits to the city measured by m2
- Climate and energy benefits have yet to be fully investigated but is happening now with the municipality working on a dashboard where these decisions can be made and weighted.

Climate change adaptation connection:

- The second priority for the renovation are benefits that can be had alongside the renovation (includes climate change adaptation)

APPENDIX
SEMI-STRUCTURED INTERVIEWS

Opportunities for co-benefits:

- In the past the quay wall only had one purpose – to be a barrier for the shipping activities that took place over land and water but now it can be more
- There are currently plans to investigate what is possible but these have not yet started in earnest.
- Currently there are 3 pilot projects that have been awarded and will take place over the next year and a half – pilot projects will look into new methods for renovation
- There is also a second investigation happening to see how disruption can be minimised in the waterfronts and what other purposes can be accommodated during renovation

APPENDIX
SEMI-STRUCTURED INTERVIEWS

INTERVIEW 4:

Name:	Marleen Cervelli	Date & place of interview:	24/6/2020 Zoom Call
Role:	Project manager - Bridge and quay wall programme	Time:	09:00 – 10:00
Municipal Department:	Technical manager - Bridge and quay wall programme		

Actors and groups:

- Is a technical manager using IPM (integral project management) approach.
- Different roles for project delivery and is responsible for the design of the supporting structures.
- Works together with the project managers who are responsible for the finance, risk, and quality requirements that are set by the city.
- The 'omschrivings beheeer' (descriptions management) department works will all the stakeholders and also conducts the coordination that is required with Waternet.

Drivers & current challenges:

- Different types of reinforcement are used depending on which functions can be cleared – the road or the water.
- The reinforcement works are designed to ensure the safety of the wall and the future construction and have a 6 week lead time from when the rack has been identified as needing support. Working to reduce the time.
- There are different aspects of the renovation process that are being worked on: improving the process of renovation, obtaining licenses in a better way, and identifying standardised solutions that can speed up the process.
- Need to find a new way to make it quicker, technically.
- An example of the coordination that is required is in the cables with Liander who manage the underground gas pipes which were made of iron and are very fragile now to the disturbances caused by renovation. Typically a 10m easement is required by this is not always the case an therefore changes need to be made.
- Waternet is responsible for the sewage pipes, nautical control, and harmonising the water level so that it remains at around 0.4 NAP
- The displacement that is caused by the reinforcement platforms has meant that the design of these platforms has had to change so that the FSL of the ground is set -100mm below the WL so that it can act as an overflow area.
- The lifespan of these platform structures is now being designed to 10-20 years long because of what is known about how much longer they may be required.

- Monumental trees are also a challenge because the crown of the tree does not allow for easy access for installing the sheet pile boundary needed for the platforms – currently this is a challenge that is being looked into.

Climate change adaptation connection:

- The specific challenges from climate change are not part of the reinforcement brief.

Opportunities for co-benefits:

- For some platforms where the biodiversity planting has been done this is done by another department and measures like these assist with providing some benefits to the local residences in addition to the technical solution of the platform.

Stakeholders:

- The renewal team works with the construction team to also strategically size the platforms so that they are 2-3m in width typically – become a working platform in future.
- Teams are also created with one person from each other separate measures/stages teams so that there is some coordination between them and that the solutions that are being proposed at every stage lead to the best solution.
- The pressure from the city is also there with the media coverage – hundreds of millions of euro are needed for the renovation and despite coronavirus the works must continue to ensure the liveability, economy, and water activities that are part of the city.
- Greening team that looks at environmental management could also be good to speak to.

D. SITE VISIT PHOTOS

QUAY WALL WALK - FEBRUARY 2020

Nieuwe Herengracht, Valkenburg, Centrum

Car-parking areas removed from the street and converted into garden bed. Resident on the street said that this was being done because the wall sagging in a different way and it therefore did not need the sheet pile platform. Existing trees were kept on the street along with their concrete edges. New soil level raised approx. 100mm from the level of the road. Seedlings planted extensively in the soil.

QUAY WALL WALK - FEBRUARY 2020

Nieuwe Herengracht, Valkenburg, Centrum

Localised grading issues not part of the renovation type with water ponding along edge of newly constructed kerb. Further north the solution has been to cut down the existing trees and construct a platform to support the wall from the water side. Heavy the steel members used between the wall and the sheet pile edges.

QUAY WALL WALK - FEBRUARY 2020

Nieuwe Herengracht, Valkenburg, Centrum

Sheet pile used for retaining but does not need to be completely waterproof - plastic liner used to create barrier between backfilled area and sand. A valid question painted (by others) on the stump of the removed tree.

QUAY WALL WALK - JULY 2020

Nieuwe Herengracht, Valkenburg, Centrum

Later in the year the same street has - in some places - successfully established summer garden. In other areas plants are not as vigorous. Across canal the timber posts used for boats can be seen along the edge which slopes down from Wertheimpark. Some plants have been installed in the reinforcement platform further north. Appears to be some kind of seedling or climbing plant.

Nieuwe Herengracht, Valkenburg, Centrum

Trees that were cut down earlier in the year leave open and unshaded sections in the street in summer months.

Oudezijds Achterburgwal, Burgwallen Oost, Centrum

Wall is being rebuilt in this location and has taken months to complete. The work platform can be seen in the canal and the extent of demolition that is required to replace the wall extends to the building line. No car access possible and inconvenient for bicycles. Foot traffic is unpleasant during and after the rain - no paving on top of the soil.

QUAY WALL WALK - FEBRUARY 2020

Oudezijds Achterburgwal, Oude Kerk, Centrum

Archival photos used on construction fences. Bottom left image of the boat used to take refuse from the site. Right image shows top of newly constructed wall. The wall appears to be constructed from a thick concrete wall on to which the stone capping is placed. Brick cladding mortared onto concrete wall. Backfill on site appears to be a mix of coarse aggregates and soil.

QUAY WALL WALK - FEBRUARY 2020

Oudezijds Achterburgwal, Oude Kerk, Centrum

Top left: Sand fill is stored in bags until used - uncertain as to what depth it is used. Bottom left: existing wall to the south has a small platform cantilevering out to the water - precedent for having protrusions over the water in central areas. Right: new wall structure visible this time with what appears to be a steep frame or step-down between the wall and the brick cladding.

QUAY WALL WALK - JULY 2020

Oudezijds Achterburgwal, Oude Kerk, Centrum

Later in the year the wall in finished and the wall is complete - a subtle but obvious difference between the new replaced wall and the old walls can be seen in the top left where the left side wall was not replaced and the right side having the new wall. The top edge of the old wall on the left tilts back and forth along the length of the wall whereas the new wall on the right maintains the same alignment throughout. Road width remains the same with a narrow footpath along the side of the buildings causing tourists to walk on the road. Waterfront edge is occupied with bicycle parking and some young trees. Panorama below shows the wall that has not been recently replaced where bollards have been placed in some locations to prevent cars from parking along the water's edge.

QUAY WALL WALK - JULY 2020

Oudezijds Achterburgwal, Oude Kerk, Centrum

Recently renovated side of the street has limited car parking and the width of the space is sized for a small city car rather than larger vans or buses.

QUAY WALL WALK - JULY 2020

Oudezijds Achterburgwal, Oude Kerk, Centrum

A bridge has been closed for access and further north a temporary bridge has been built.

QUAY WALL WALK - FEBRUARY 2020

Groenburgwal, Zuiderkerkbuurt, Centrum




The canal in this section is narrow and the quay walls are supported here by a steel frame that spans over the surface of the water – it is not possible to cross the water by boat anymore. The steel structure uses steel columns that rise beyond the top of the pedestrian surface and these are protected by ad hoc timber boxes. It is observed that vehicles are still permitted to park on top of the wall (top right).

Groenburgwal, Zuiderkerkbuurt, Centrum

The structure is constructed from standard steel sections.

Gelderskade, Burgwallen Oost, Centrum

In the Nieuwmarkt area a reinforcement platform has been completely backfilled with grasses and weeds taking root. The platform is an informal "front yard" for the adjacent houseboat but does not appear to be readily maintained by the houseboat owner. Trash from the street has fallen into the platform and collects because there is no direct access to the platform from the street.

QUAY WALL WALK - FEBRUARY 2020

QUAY WALL WALK - JULY 2020

Gelderskade, Burgwallen Oost, Centrum

Behind the platform the trees have also bee cut down. The platform is approximately 75 metres long in this location.

QUAY WALL WALK - FEBRUARY 2020

Recht Boomssloot, Lastage, Centrum

Another street with the quay walls being replaced on one side. The replacement works are almost complete with most of the finishes complete. This construction sight provides insight into the subsurface preparation under garden bed areas and paving at the edge of the waterfront. Structural cell products appear to be used with risers for water and/or air visible at certain points. On the other side of the street the trees have been cut down as part of the works (presumably to allow working access and space for large machinery on the platform).

Recht Boomssloot, Lastage, Centrum

Left: a notice from the municipality about the renovation works and the anticipated start date of 2020-21 for the un-renovated side of the street. Middle photos show the structural cell product and risers. Plastic-based liners have been installed under the cell units. Right: further west the same street has some works taking place and the existing trees are protected from trunk damage - but not necessarily root damage.

QUAY WALL WALK - JULY 2020

Recht Boomssloot, Lastage, Centrum

The street is now complete and the garden bed areas beginning to establish. Car parking along the street does not appear to be possible - only bicycle parking. Bottom right photo shows the drainage grate indicating that the stormwater system has been installed closer to the building line rather than towards the garden bed areas or canal.

QUAY WALL WALK - JULY 2020

Recht Boomssloot, Lastage, Centrum

Further west some small renovation works are now complete. Bicycle parking added in lieu of - I assume - spaces for parallel car parking that is still maintained further down the street.

QUAY WALL WALK - FEBRUARY 2020

Entrepotdok, Kadijken, Centrum

Reinforcement platform installed in this location required a number of house boats to be moved while the platform was being built. In this location the boat owners (I assume) have appropriated the platform for vegetable growing and additional yard space for storage.

QUAY WALL WALK - FEBRUARY 2020

Singel, Felix Meritisbuurt, Centrum

Reinforcement platform that, in warmer months, was the site of a biodiversity planting initiative. By February most of the annuals have died back.

QUAY WALL WALK - FEBRUARY 2020

Herengracht, Felix Meritisbuurt, Centrum

In this location the reinforcement platform has been left alone with no additional planting.

QUAY WALL WALK - JUNE 2020

Ruysdaelkade, Frans Halsbuurt, Zuid-Oost

The underground parking installed under the canal in De Pijp was mentioned a number of times during meetings and interviews with researchers and municipal officers. This underground parking (pictured) has created a wide waterfront area that is currently used mainly for bicycle parking and boat access.

QUAY WALL WALK - JUNE 2020

Ruysdaelkade, Frans Halsbuurt, Zuid-Oost

Where on-street parking has been removed the municipality has placed small planters to limit the number of cars that can park in these areas. Notable that temporary planters are preferred over more permanent measures like removing the paving altogether.

QUAY WALL WALK - JUNE 2020

Quellijnstraat, Frans Halsbuurt, Zuid-Oost

On a perpendicular street to the underground parking, the results of the carparks being replaced with other functions is visible. There is more bicycle parking, informal garden bed areas - some of which appear to be taken care of by residents - and children's play equipment.

QUAY WALL WALK - JULY 2020

Oudezijds Voorrburgwal, Oude Kerk, Centrum

A reinforcement platform has been installed in the canal but as with the platform in Nieuwmarkt, fenced off to prohibit public access.

E. COMBINED CLIMATE CHANGE AND QUAY WALL RENOVATION IMPACT SCORES

Classification Table

	Score Code	Data description (time)	unit	notes	range	SCALE OF IMPACT WHERE 1 = MOST IMPACT: 1	2	3
Quay wall impact score	QW1	**Area of quay wall as part of neighbourhood**	%	Total of BGT quay wall data of top surface of quay wall structures (m2) as a percentage of the total m2 of the neighbourhood the wall is located in.	tertile 3 classes	6.19	0.45	0.21
Quay wall impact score	QW2	**Population density**	people/ km2	Gemeente Amsterdam open data.	tertile 3 classes	33,236 P/KM2	12,560 P/KM2	5,036 P/KM2
Climate change - drought	D1	**Drought - groundwater level drop summer (current)**	m	KEA data used and based on the National Water Model	ordinal	up to 8m	1.5-2	<1.5
Climate change - drought	D2	**Precipitation deficit trend**	mm	KEA data on the anticipated change in precipitation deficit between 2020 and 2050	ordinal	120	90	60
Climate change - drought	D3	**Groundwater level drop (2050WH)**	m	KEA data used and based on the National Water Model	ordinal	drop or increase	no change	
Climate change - pluvial flooding	F1	**Water depth 1:100 year pluvial flood (current)**	mm	KEA data used and based on the depth used in the text by Stone et al. Waterfront scale data generalised for neighbourhood scale using maximum value.	ordinal	>200	<200	
Climate change - pluvial flooding	F2	**Water depth 1:1000 year pluvial flood (current)**	mm	KEA data used and based on the depth used in the text by Stone et al. Waterfront scale data generalised for neighbourhood scale using maximum value.	ordinal	>200	<200	
Climate change - pluvial flooding	F3	**Increase number of days with 15mm or greater of rain (2020-2050WH)**	days	KEA data used	ordinal	4 more	2 more	
Climate change - fluvial flooding	F4	**Water depth 1:100 year fluvial flooding (current)**	mm	KEA data used and based on the depth used in the text by Stone et al.	ordinal	>200	<200	
Climate change - fluvial flooding	F5	**Chance of >200mm deep flooding in 1:100 event (2050WH)**	probabi lity	KEA data used and based on the depth used in the text by Stone et al.	ordinal	more than moderately high chance	small chance and below	
Climate change - heat	H1	**Waterfront areas with high heat stress levels (current)**	C	KEA data used and with classifications from the RIVM for heat stress levels - waterfront data generalised to a neighbourhood scale and uses the maximum value	ordinal	>41C	<41C	
Climate change - heat	H2	**Duration of heat release by water bodies (current)**	days	KEA data used and waterfront data generalised to the neighbourhood scale taking the maximum value	ordinal	>10 days	<10 days	
Climate change - heat	H3	**Duration of high night time temperatures (current)**	days	KEA data used	ordinal	>1 week	<1 week	
Climate change - heat	H4	**Duration of high night time temperatures (2050WH)**	days	KEA data used	ordinal	>1 week	<1 week	

Impact scores for neighbourhoods with a majority of buildings more than 100 years old

			INDIVIDUAL SCORES (refer to table A for codes)																
Buurt code	Buurt	Stadsdeel	QW1	QW2	D1	D2	D3	D32	H1	H2	H3	H4	F3	F2	F1	F5	F4	Quay Wall Rank	Climate Change Score
A01d	Spuistraat Noord	A	1	1	1	2		1	1	1	1	1	1	1	1			2	11
E14a	De Wittenbuurt Noord	E	1	1	1	1		1	1	1	2	1	1	1	1			2	11
A06h	Passeerdersgrachtbuurt	A	1	1	1	2		1	1	1	2	1	1	1	1			2	12
A06j	Marnixbuurt Zuid	A	1	1	1	2		1	1	1	2	1	1	1	1			2	12
A07c	Leidsebuurt Noordoost	A	1	1	1	2		1	1	1	2	1	1	1	1			2	12
E14b	De Wittenbuurt Zuid	E	1	1	1	1		1	2	1	2	1	1	1	1			2	12
A06e	Zaagpoortbuurt	A	1	1	1	2		1	1	1	2	1	1	1	1			2	12
A04d	Lastage	A	1	1	1	2		1	1	1	2	1	1	1	1		1	2	13
K24c	Frans Halsbuurt	K	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A00a	Kop Zeedijk	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A02a	Langestraat e.o.	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A04h	Zuiderkerkbuurt	A	1	1	1	2		1	2	1	2	1	1	1	1			2	13
A05c	Haarlemmerbuurt West	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A06a	Driehoekbuurt	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A06c	Bloemgrachtbuurt	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A06d	Marnixbuurt Noord	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A06g	Elandsgrachtbuurt	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A07e	Weteringbuurt	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A07g	Utrechtsebuurt Zuid	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
E17a	Da Costabuurt Noord	E	1	1	1	2	2		1	1	2	1	1	1	1			2	13
E18a	Bellamybuurt Noord	E	1	1	1	2	2		1	1	2	1	1	1	1			2	13
E19a	Da Costabuurt Zuid	E	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A06l	Anjeliersbuurt Zuid	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A00c	Burgwallen Oost	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A05b	Haarlemmerbuurt Oost	A	1	1	1	2	2		1	1	2	1	1	1	1			2	13
A04e	Nieuwmarkt	A	1	1	1	2		1	1	1	2	1	1	1	1		2	2	14
E13a	Zeeheldenbuurt	E	1	1	1	1	2		2	1	2	1	1	1	1		1	2	14
E19c	Lootsbuurt	E	1	1	1	2	2		2	1	2	1	1	1	1			2	14
A05f	Planciusbuurt Noord	A	1	1	1	2	2		2	1	2	1	1	1	1			2	14
A09i	Kadijken	A	1	1	1	2	2		2	1	2	1	1	1	1		1	2	15
K24a	Hemonybuurt	K	1	2	1	2	2		2	1	2	1	1	1	1		2	3	16
A04f	Uilenburg	A	2	1	1	2	2		2	1	2	1	1	1	1		2	3	16
M27a	Swammerdambuurt	M	1	2	1	2	2		2	1	2	1	1	1	1		2	3	16
M30b	Transvaalbuurt Oost	M	1	2	1	2	2		2	1	2	1	1	1	1		2	3	16
M56a	Linnaeusparkbuurt	M	1	2	1	2	2		2	1	2	1	2	1	1		1	3	16
M27b	Weesperzijde Midden/Zuid	M	1	2	1	2	2		1	1	2	1	1	1	1		2	3	15
A04b	Scheepvaarthuisbuurt	A	2	1	1	2	2		2	1	2	1	1	1	1		1	3	15
A04c	Rapenburg	A	2	1	1	2	2		2	1	2	1	1	1	1		1	3	15
E13b	Spaarndammerbuurt Noordoost	E	1	2	1	2	2		2	1	2	1	1	1	1		1	3	15
N61b	Vogelbuurt Zuid	N	1	2	1	1	2		2	1	2	1	2	1	1		1	3	15
K24b	Gerard Doubuurt	K	1	2	1	2	2		2	1	2	1	1	1	1			3	14
A03d	Amstelveldbuurt	A	2	1	1	2	2		2	1	2	1	1	1	1			3	14
A03e	Rembrandtpleinbuurt	A	2	1	2	2		1	2	1	2	1	1	1	1			3	14
A04g	Valkenburg	A	1	2	1	2	2		2	1	2	1	1	1	1			3	14
A08b	Sarphatistrook	A	2	1	1	2	2		2	1	2	1	1	1	1			3	14
E21a	Cremerbuurt West	E	1	2	1	2	2		2	1	2	1	1	1	1			3	14
A01c	Nieuwendijk Noord	A	2	1	1	2	2		2	1	2	1	1	1	1			3	14
E16b	Frederik Hendrikbuurt Zuidoost	E	1	2	1	2	2		2	1	2	1	1	1	1			3	14
A06k	Anjeliersbuurt Noord	A	1	2	1	2	2		2	1	2	1	1	1	1			3	14
A00e	BG-terrein e.o.	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
A02b	Leliegracht e.o.	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
A02c	Felix Meritisbuurt	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13

A02d	Leidsegracht Noord	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
A03a	Spiegelbuurt	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
A03c	Van Loonbuurt	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
A06f	Marnixbuurt Midden	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
A07d	Leidsebuurt Zuidoost	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
A07f	Den Texbuurt	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
A08a	Weesperbuurt	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
A05g	Planciusbuurt Zuid	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
A03g	Leidsegracht Zuid	A	2	1	1	2	2		1	1	2	1	1	1	1			3	13
K45a	Schinkelbuurt Noord	K	1	2	1	2	2		2		2	1	1	1	1			3	13
A01b	Hemelrijk	A	2	1	1	2		1	1	1	2	1	1	1	1			3	12
A01f	Spuistraat Zuid	A	2	1	1	2	2		1	1	1	1	1	1	1			3	12
A07a	Leidsebuurt Noordwest	A	2	1	1	2	2		1	1	1	1	1	1	1			3	12
E14d	Fannius Scholtenbuurt	E	1	2	1	1	2		1	1	2	1	1	1	1			3	12
E14f	Buyskade e.o.	E	1	2	1	1	2		1	1	2	1	1	1	1			3	12
E16a	Frederik Hendrikbuurt Noord	E	1	2	1	2		1	1	1	2	1	1	1	1			3	12
K24d	Hercules Seghersbuurt	K	1	2	1	2		1	1	1	1	1	1	1	1			3	11
K47j	Duivelseiland	K	1	2	1	2		1	1	1	1	1	1	1	1			3	11
E13d	Spaarndammerbuurt Zuidwest	E	1	3	1	1	2		1		2	1	1	1	1			4	11
A03f	Reguliersbuurt	A	2	2	1	2		1	1	1	1	1	1	1	1			4	11
A00b	Oude Kerk e.o.	A	2	2	1	2		1	1	1	1	1	1	1	1			4	11
A07b	Leidsebuurt Zuidwest	A	3	1	1	2	2		1	1	1	1	1	1	1			4	12
A00d	Nes e.o.	A	2	2	1	2	2		1	1	1	1	1	1	1			4	12
E13g	Westergasfabriek	E	3	1	1	1		1	2	1	2	1	1	1	1		1	4	13
K25c	Lizzy Ansinghbuurt	K	1	3	1	2	2		2		2	1	1	1	1			4	13
A01h	Kalverdriehoek	A	2	2	1	2	2		1	1	2	1	1	1	1			4	13
A03b	Gouden Bocht	A	3	1	1	2	2		2	1	1	1	1	1	1			4	13
A06i	Groenmarktkadebuurt	A	3	1	1	2	2		1	1	2	1	1	1	1			4	13
E14e	Westerstaatsman	E	1	3	1	2		1	2	1	2	1	1	1	1			4	13
E18b	Bellamybuurt Zuid	E	1	3	1	2	2		1	1	2	1	1	1	1			4	13
E20a	Helmersbuurt Oost	E	1	3	1	2	2		2	1	1	1	1	1	1			4	13
E20c	Cremerbuurt Oost	E	1	3	1	2		1	2	1	2	1	1	1	1			4	13
K46b	Valeriusbuurt West	K	1	3	1	2	2		2		2	1	1	1	1			4	13
K47f	Hondecoeterbuurt	K	1	3	1	2	2		2		2	1	1	1	1			4	13
E13f	Spaarndammerbuurt Noordwest	E	1	3	1	2	2		1	1	2	1	1	1	1			4	13
A09a	Marine-Etablissement	A	3	1	1	2		1	2	1	2	1	1	1	1		1	4	14
K24e	Sarphatiparkbuurt	K	1	3	1	2	2		2	1	2	1	1	1	1			4	14
A04i	Waterloopleinbuurt	A	2	2	1	2	2		2	1	2	1	1	1	1			4	14
A07h	Frederikspleinbuurt	A	2	2	1	2	2		2	1	2	1	1	1	1			4	14
E20b	WG-terrein	E	1	3	1	2	2		2	1	2	1	1	1	1			4	14
E21b	Vondelparkbuurt West	E	1	3	1	2	2		2	1	2	1	1	1	1			4	14
K47a	Johannnes Vermeerbuurt	K	2	2	1	2	2		1	1	2	1	1	1	2			4	14
M28a	Oosterparkbuurt Noordwest	M	1	3	1	2	2		2	1	2	1	1	1	1			4	14
M28b	Oosterpark	M	3	1	1	2	2		2	1	2	1	1	1	1			4	14
M29a	Dapperbuurt Noord	M	1	3	1	2	2		2	1	2	1	1	1	1			4	14
M31a	Noordwestkwadrant Indische buurt Noord	M	1	3	1	2	2		2	1	2	1	1	1	1			4	14
A09e	Czaar Peterbuurt	A	1	3	1	2	2		2	1	2	1	1	1	1			4	14
K45b	Schinkelbuurt Zuid	K	2	2	1	2	2		2	1	2	1	1	1	1			4	14
E22b	Vondelparkbuurt Midden	E	2	2	1	2	2		2	2	2	1	1	1	1			4	15
K25a	Willibrordusbuurt	K	1	3	1	2	2		2	1	2	1	1	1	1		2	4	16
E22a	Vondelparkbuurt Oost	E	2	3	1	2		1	1	1	2	1	1	1	1			5	12
K46a	Valeriusbuurt Oost	K	2	3	1	2	2		2		2	1	1	1	1			5	13
K47b	P.C. Hooftbuurt	K	2	3	1	2		1	2	1	2	1	1	1	1			5	13
A08e	Alexanderplein e.o.	A	2	3	1	2		1	2	1	2	1	1	1	1			5	13
A08d	Plantage	A	3	2	1	2	2		2	1	2	1	1	1	1			5	14
K46c	Willemsparkbuurt Noord	K	2	3	1	2	2		2	1	2	1	1	1	1			5	14
M34a	Zeeburgereiland Noordwest	M	3	3	1	2	2		2	1			2	1	1		1	6	13

Impact scores for neighbourhoods with a majority of buildings built between 1920 and 1970

			INDIVIDUAL SCORES (refer to table A for codes)																
Buurt_code	Buurt	Stadsdeel	QW1	QW2	D1	D2	D3	D32	H1	H2	H3	H4	F3	F2	F1	F5	F4	Quay Wall Rank	Climate Change Score
F81e	Osdorp Zuidoost	F	2	3	1	2	2		2	1	2	1	1	1	1		1	5	15
F82b	Osdorp Midden Zuid	F	1	3	1	2	2		2	1	2	1	2	1	1		1	4	16
E37e	Erasmusparkbuurt Oost	E	1	1	1	1	2		2		2	1	1	1	1			2	12
E13c	Spaarndammerbuurt Zuidoost	E	1	1	1	1	2		2	1	2	1	1	1	1			2	13
F86e	Johan Jongkindbuurt	F	2	2	1	2	2		2	1	2	1	1	1	1		1	4	15
F87c	Delflandpleinbuurt Oost	F	2	2	1	2	2		2	1	2	1	1	1	1	1		4	15
F87d	Delflandpleinbuurt West	F	2	2	1	2	2		2	1	2	1	1	1	1	1	1	4	16
K25d	Cornelis Troostbuurt	K	1	3	1	2	2		2	1	2	1	1	1	1			4	14
F83a	De Punt	F	1	1	1	2	2		2	1	2	1	2	1	1	1	1	2	17
T94c	Bijlmermuseum Noord	T	1	1	3	2	2		2	1	2	1	1	1	1		2	2	18
E15b	Markthallen	E	3	2	1	1	2		1	1	2	1	1	1	1			5	12
E37a	Bedrijventerrein Landlust	E	3	1	1	2	2		2	1	2	1	1	1	1		1	4	15
E37c	Bosleeuw	E	1	3	1	2	2		2	1	2	1	1	1	1			4	14
K44e	Legmeerpleinbuurt	K	1	2	1	2		1	2		2	1	1	1	1			3	12
E40a	Geuzenhofbuurt	E	1	2	1	1	2		1	1	2	1	1	1	1			3	12
E75b	Filips van Almondekwartier	E	1	2	1	2		1	2		2	1	1	1	1			3	12
E41a	John Franklinbuurt	E	1	3	1	1		1	2		2	1	1	1	1			4	11
E42a	Balboaplein e.o.	E	1	3	1	1	2		2		2	1	1	1	1			4	12
E42b	Columbusplein e.o.	E	1	3	1	1	2		1	1	2	1	1	1	1			4	12
E42d	Orteliusbuurt Zuid	E	1	3	1	1	2		2	1	2	1	1	1	1			4	13
E75d	Van Brakelkwartier	E	1	2	1	2		1	1	1	2	1	1	1	1			3	12
E37d	Landlust Zuid	E	1	2	1	1	2		2	1	2	1	1	1	1			3	13
F76a	Buurt 3	F	2	3	1	2	2		2	1	2	1	1	1	1		2	5	16
F76b	Buurt 2	F	2	2	1	2	2		2	1	2	1	1	1	1			4	14
F77a	Slotermeer Zuid	F	2	2	1	2	2		2	1	2	1	1	1	1			4	14
F77c	Buurt 4 Oost	F	2	3	1	2	2		2	1	2	1	1	1	1			5	14
F77d	Buurt 5 Noord	F	1	3	1	2	2		2	1	2	1	1	1	1			4	14
F77f	Buurt 5 Zuid	F	2	3	2	2	2		2	1	2	1	1	1	1			5	15
F78a	Buurt 6	F	2	3	2	2		1	2	1	2	1	1	1	1			5	14
F78b	Buurt 7	F	2	3	1	2	2		2	1	2	1	1	1	1			5	14
E43a	Paramariboplein e.o.	E	1	2	1	2	2		1	1	2	1	1	1	1			3	13
F78d	Buurt 9	F	1	3	1	2	2		2	1	2	1	1	1	1			4	14
F81a	Wildeman	F	1	3	1	2	2		2	1	2	1	1	1	1	1	1	4	16
F81b	Meer en Oever	F	1	3	1	2	2		2		2	1	1	1	1		1	4	14
M57b	Nieuwe Oosterbegraafplaats	M	3	2	1	2		1	2	1	2	1	1	1	1		1	5	14
N60c	Bloemenbuurt Noord	N	2	1	1	1		1	2	1	2	1	2	1	1			3	13
N65b	Tuindorp Oostzaan Oost	N	2	1	1	2		1	2	1	2	1	1	1	1			3	13
K48a	Bertelmanpleinbuurt	K	1	2	1	2	2		2		2	1	1	1	1			3	13
N62a	Tuindorp Nieuwendam West	N	2	2	1	1	2		2	1	2	1	2	1	1			4	14
N62b	Tuindorp Nieuwendam Oost	N	2	3	2	1	2		2	1	2	1	2	1	1			5	15
E38c	Erasmusparkbuurt West	E	2	1	1	2		1	2	1	2	1	1	1	1			3	13
N73e	Zwarte Gouw	N	3	3	3	1		1	2	1			2	1	1		1	6	13
N69l	De Kleine Wereld	N	2	1	1	1		1	2	1	2	1	2	1	1			3	13
E75c	De Wester Quartier	E	1	2	1	2	2		2		2	1	1	1	1			3	13
N65c	Terrasdorp	N	2	2	1	2	2		2	1	2	1	1	1	1			4	14
N69a	Rode Kruisbuurt	N	3	2	1	1	2		2	1	2	1	2	1	1			5	14
N73b	Schellingwoude Oost	N	3	2	1	1		1	2	1	2	1	2	1	1	1	1	5	15
M58i	Amstelkwartier Zuid	M	3	3	1	2	2		2		2	1	1	1	1			6	13
N73d	Durgerdam	N	3	3	3	1		1	2	1			2	1	1	1	1	6	14
F88c	Nieuwe Meer	F	3	2	1	2		1	2	1			1	1	1		1	5	11
K44b	Westlandgrachtbuurt	K	1	3	1	3	2		2	1	2	1	1	1	2			4	16
K44c	Aalsmeerwegbuurt West	K	1	3	1	3	2		2	1	2	1	1	1	1			4	15
K44a	Surinamepleinbuurt	K	1	2	1	2	2		2	1	2	1	1	1	1			3	14
K47e	Banpleinbuurt	K	2	3	1	2	2		2		2	1	1	1	1			5	13
E39d	Kolenkitbuurt Noord	E	1	2	1	2	2		2	1	2	1	1	1	1			3	14
K47i	Vondelpark Oost	K	3	1	1	2		1	1	1	2	1	1	1	1			4	12
E43b	Postjeskade e.o.	E	1	2	1	2	2		2	1	2	1	1	1	1			3	14
K48b	Marathonbuurt Oost	K	2	3	1	2	2		2		2	1	1	1	1			5	13
K48c	Marathonbuurt West	K	1	3	1	2	2		2		2	1	1	1	1			4	13
K49a	Diepenbrockbuurt	K	3	2	1	2	2		2	1	2	1	1	1	1			5	14
K49b	Beethovenbuurt	K	2	3	1	2	2		2		2	1	1	1	1			5	13
K49c	Hiltonbuurt	K	3	2	1	2	2		2		2	1	1	1	1			5	13
K49f	Minervabuurt Zuid	K	1	3	1	2	2		2	1	2	1	1	1	1			4	14
N60b	Bloemenbuurt Zuid	N	2	1	1	1	2		2	1	2	1	2	1	1			3	14

K52b	Scheldebuurt West	K	1	3	1	2		1	2		2	1	1	1	1			4	12
K53a	IJselbuurt West	K	1	3	1	2	2		2		2	1	1	1	1			4	13
N64a	Buiksloterdijk West	N	2	1	1	1	2		2	1	2	1	2	1	1			3	14
K54a	Kromme Mijdrechtbuurt	K	1	3	1	2	2		2	1	2	1	1	1	1		2	4	16
K54b	Rijnbuurt Oost	K	2	3	1	2		1	2	1	2	1	1	1	1		2	5	15
K54c	Rijnbuurt Midden	K	2	2	1	2		1	2	1	2	1	1	1	1			4	13
K54d	Rijnbuurt West	K	1	3	1	2	2		1		2	1	1	1	1			4	12
K54e	Zorgvlied	K	3	1	1	2	2		2	1			1	1	1			4	11
K90a	Gelderlandpleinbuurt	K	2	2	1	2	2		2	1	2	1	1	1	1			4	14
K90c	Buitenveldert Midden Zuid	K	2	2	1	2	2		2	1	2	1	1	1	1			4	14
K90d	Buitenveldert Zuidwest	K	2	2	1	2	2		2	1	2	1	1	1	1		1	4	15
K91b	Buitenveldert Oost Midden	K	2	2	1	2		1	2	1	2	1	1	1	1			4	13
K91c	Buitenveldert Zuidoost	K	2	3	1	2	2		2	1	2	1	1	1	1			5	14
N65a	Tuindorp Oostzaan West	N	2	1	1	2	2		2	1	2	1	1	1	1			3	14
M32a	Noordoostkwadrant Indische buurt	M	1	3	1	2		1	2	1	2	1	2	1	1		2	4	16
M55d	Don Bosco	M	1	3	1	2	2		2	1	2	1	1	1	1		2	4	16
M55e	Frankendael	M	3	1	3	2	2		2	1	2	1	1	1	1		1	4	17
K47g	Harmoniehofbuurt	K	2	1	1	2	2		2	1	2	1	1	1	1			3	14
M55h	Tuindorp Frankendael	M	2	3	3	2		1	2	1	2	1	1	1	1		1	5	16
M56b	Middenmeer Noord	M	1	3	1	2	2		2	1	2	1	2	1	1		1	4	16
K52a	Wielingenbuurt	K	1	2	1	2	2		2	1	2	1	1	1	1			3	14
N64d	Nieuwendammerdijk Oost	N	3	3	2	1		1	2	1	2	1	2	1	1		1	6	15
F85b	Emanuel van Meterenbuurt	F	3	3	1	2	2		2	1	2	1	1	1	1		1	6	15
B10h	Westhaven Zuid	B	3	2	1	3	2		2	1	2	1	1	1	1		1	5	16
E37f	Gibraltarbuurt	E	1	3	1	2	2		2	1	2	1	1	1	1			4	14
N69k	Plan van Gool	N	2	1	1	1	2		2	1	2	1	2	1	1			3	14
E38d	Robert Scottbuurt Oost	E	1	3	1	2	2		2	1	2	1	1	1	1			4	14
F89a	Louis Crispijnbuurt	F	2	3	1	2	2		2	1	2	1	1	1	1		1	5	15
F89b	Jacques Veldmanbuurt	F	2	2	1	2	2		2	1	2	1	1	1	1		1	4	15
F78c	Buurt 8	F	1	2	2	2	2		2	1	2	1	1	1	1			3	15
N60a	Van der Pekbuurt	N	2	1	1	1	2		2	1	2	1	2	1	1		1	3	15
K90i	Buitenveldert West Midden	K	3	1	1	2		1	2	1	2	1	1	1	1		1	4	14
M55i	Van der Kunbuurt	M	2	2	1	2	2		2	1	2	1	1	1	1		2	4	16
B10c	Petroleumhaven	B	3	2	1	3	2		2	1	2	1	1	1	1		1	5	16
E39a	Robert Scottbuurt West	E	1	3	1	2	2		1		2	1	1	1	1			4	12
K44d	Aalsmeerwegbuurt Oost	K	1	3	1	2	2		2	1	2	1	1	1	1			4	14
K44f	Bedrijventerrein Schinkel	K	3	2	1	3	2		2	1	2	1	1	1	1		1	5	16
K48d	Olympisch Stadion e.o.	K	2	3	1	2	2		2	1	2	1	1	1	1			5	14
K48f	Van Tuyllbuurt	K	1	3	1	2	2		2	1	2	1	1	1	1			4	14
M29c	Oostpoort	M	2	2	1	2	2		2	1	2	1	1	1	1		1	4	15
M55f	Tuindorp Amstelstation	M	2	3	1	2	2		2	1	2	1	1	1	1		1	5	15
N61c	Vogelbuurt Noord	N	3	2	1	1		1	2	1	2	1	2	1	1			5	13
N63a	Blauwe Zand	N	2	3	1	1		1	2	1	2	1	2	1	1			5	13
N64c	Nieuwendammmerdijk West	N	2	2	1	1		1	2	1	2	1	2	1	1			4	13
M30a	Transvaalbuurt West	M	1	2	1	2	2		1	1	2	1	1	1	1		2	3	15
M55g	De Wetbuurt	M	2	1	1	2	2		2	1	2	1	1	1	1		1	3	15
E40c	Pieter van der Doesbuurt	E	1	3	1	1	2		2		2	1	1	1	1			4	12
E75a	Kortenaerkwartier	E	1	3	1	2		1	1	1	2	1	1	1	1			4	12
M56c	Middenmeer Zuid	M	1	2	1	2		1	2	1	2	1	2	1	1		1	3	15
F82c	Zuidwestkwadrant Osdorp Noord	F	1	2	1	2	2		2	1	2	1	2	1	1		1	3	16
K53b	IJselbuurt Oost	K	1	2	1	2	2		2	1	2	1	1	1	1		2	3	16
T95c	Gaasperplas	T	3	3	1	2		1	2	1	2	1	1	1	1	1	1	6	15
F85c	Jacob Geelbuurt	F	2	2	1	2		1	2	1	2	1	1	1	1		1	4	14
K26a	Diamantbuurt	K	1	3	1	2	2		2	1	2	1	1	1	1		2	4	16
K26b	Burgemeester Tellegenbuurt Oost	K	1	3	1	2	2		2		2	1	1	1	1			4	13
K26c	Burgemeester Tellegenbuurt West	K	1	3	1	2	2		2		2	1	1	1	1			4	13
K59a	Prinses Irenebuurt	K	2	2	1	2	2		2	1	2	1	1	1	1			4	14
K59b	Beatrixpark	K	3	1	1	2	2		2	1	2	1	1	1	1	1		4	15
M57a	Betondorp	M	2	2	1	2	2		2	1	2	1	1	1	1		1	4	15
M58e	Amstelglorie	M	3	1	1	2	2		2	1			1	1	1		2	4	13
M56d	Sportpark Middenmeer Zuid	M	3	3	1	2	2		2	1	2	1	2	1	1		1	6	16
M58j	Amstelkwartier West	M	3	2	1	2		1	2	1	2	1	1	1	1		2	5	15
N68b	Werengouw Noord	N	3	2	1	1		1	2	1	2	1	2	1	1			5	13
N68c	Werengouw Midden	N	1	3	1	1		1	2	1	2	1	2	1	1			4	13
N68f	Werengouw Zuid	N	2	3	2	1	2		2	1	2	1	2	1	1		2	5	17
T95b	Gaasperpark	T	3	1	1	2		1	2	1	2	1	1	1	1	1	1	4	15
K90j	Zuiderhof	K	3	3	1	3	2		2	1	2	1	1	1	1		1	6	16
T98a	Dorp Driemond	T	3	1	1	2	2		2	1	2	1	1	1	1	1	1	4	16

Impact scores for neighbourhoods with a majority of buildings built between 1970-2020

Buurt_code	Buurt	Stadsdeel	INDIVIDUAL SCORES (refer to table A for codes) QW1	QW2	D1	D2	D3	D32	H1	H2	H3	H4	F3	F2	F1	F5	F4	Quay Wall Rank	Climate change score
A01a	Stationsplein e.o.	A	3	1	1	2	2		2	1	1	1	1	1	1		1	4	14
A04a	Oosterdokseiland	A	3	2	1	2	2		2	1	2	1	1	1	1		1	5	15
A05a	Westerdokseiland	A	2	1	1	2	2		2	1	2	1	1	1	1		1	3	15
A05d	Westelijke eilanden	A	1	1	1	2	2		2	1	2	1	1	1	1			2	14
A09b	Kattenburg	A	1	1	1	2	2		2	1	2	1	1	1	1		1	2	15
A09c	Wittenburg	A	1	2	1	2	2		2	1	2	1	1	1	1		1	3	15
A09d	Oostenburg	A	2	2	1	2	2		1	1	2	1	1	1	1			4	13
A09f	Het Funen	A	1	2	1	2		1	2	1	2	1	1	1	1			3	13
A09h	Kazernebuurt	A	1	3	1	2		1	2	1	2	1	1	1	1			4	13
B10a	Coenhaven/Mercuriushaven	B	3	2	1	3	2		2	1	2	1	1	1	1		1	5	16
B10b	Alfa-driehoek	B	3	1	1	3	2		2	1	2	1	1	1	1			4	15
B10d	Westhaven Noord	B	3	3	1	3	2		2	1	2	1	1	1	1		1	6	16
B10e	Vervoerscentrum	B	3	2	1	3	2		2	1	2	1	1	1	1			5	15
B10f	Amerikahaven	B	3	3	1	3	2		2	1	2	1	1	1	1	1	1	6	17
B10g	Afrikahaven	B	3	3														6	0
E12a	Houthavens West	E	3	3	1	2	2		2	1	2	1	1	1	1		1	6	15
E12b	Houthavens Oost	E	3	2	1	1		1	2	1	2	1	1	1	1		1	5	13
E13h	Overbraker Binnenpolder	E	3	3	1	2	2		2	1	2	1	1	1	1	1	1	6	16
E14c	Staatsliedenbuurt Noordoost	E	1	1	1	1	2		2	1	2	1	1	1	1			2	13
E15a	Ecowijk	E	1	1	1	2		1	2	2	2	1	1	1	2			2	15
E15c	Bedrijvencentrum Westerkwartier	E	3	3	1	2	2		2	1	2	1	1	1	1			6	14
E15d	Marcanti	E	1	1	1	1	2		2	1	2	1	1	1	1			2	13
E16c	Frederik Hendrikbuurt Zuidwest	E	1	1	1	2	2		1	1	2	1	1	1	1			2	13
E19b	Borgerbuurt	E	1	2	1	2	2		1	1	2	1	1	1	1			3	13
E36a	Woon- en Groengebied Sloterdijk	E	3	3	1	2		1	2	1	2	1	1	1	1	1	1	6	15
E36b	Bedrijventerrein Sloterdijk I	E	3	3	1	2		1	2	1	2	1	1	1	1		1	6	14
E39b	Laan van Spartaan	E	1	1	1	2	2		2	1	2	1	1	1	1			2	14
E39c	Kolenkitbuurt Zuid	E	1	2	1	2	2		2		2	1	1	1	1			3	13
E41d	Mercatorpark	E	1	3	1	2		1	1	2	2	1	1	1	1			4	13
F11c	Sloterdijk III Oost	F	3	2	1	2	2		2	1	2	1	1	1	1		1	5	15
F11d	Sloterdijk III West	F	3	3	1	2		1	2	1	2	1	1	1	1			6	13
F11e	De Heining	F	3	3														6	0
F11f	Teleport	F	3	2	1	2	2		2	1	2	1	1	1	1			5	14
F11h	Bretten Oost	F	3	3	1	2	2		2	1	2	1	1	1	1			6	14
F11j	Bretten West	F	3	1	1	2		1	2	1			1	1	1			4	10
F77b	Noordoever Sloterplas	F	2	2	1	2	2		2	1	2	1	1	1	1		1	4	15
F77e	Sloterpark	F	3	3	1	2	2		2	1	2	1	1	1	1	1	1	6	16
F78e	Eendrachtspark	F	3	2	1	2	2		2	1	2	1	1	1	1			5	14
F79a	Osdorper Binnenpolder	F	3	3	1	2		1	2	1	2	1	1	1	1	1	1	6	15
F79b	Buurt 10	F	2	2	1	2		1	2	1	2	1	1	1	1		1	4	14
F80a	Ookmeer	F	3	3	1	2	2		2	1	2	1	1	1	1			6	14
F80b	Osdorper Bovenpolder	F	3	3	1	2	2		2	1	2	1	1	1	1	1	1	6	16
F80c	Bedrijvenpark Lutkemeer	F	3	1	1	2		1	2	1	2	1	2	1	1	1	1	4	16
F81c	Osdorpplein e.o.	F	2	3	1	2	2		2	1	2	1	1	1	1	1	1	5	16
F81d	Calandlaan/Lelylaan	F	3	3	1	2	2		2	1	2	1	1	1	1	1	1	6	16
F82a	Osdorp Midden Noord	F	1	3	1	2		1	2	1	2	1	2	1	1			4	14
F82d	Zuidwestkwadrant Osdorp Zuid	F	1	2	1	2		1	2	1	2	1	2	1	1	1	1	3	16
F83b	Bedrijvencentrum Osdorp	F	3	1	1	2		1	2	1	2	1	2	1	1	1	1	4	16
F84a	Middelveldsche Akerpolder	F	2	1	1	2	2		2	1	2	1	2	1	1	1	1	3	17
F84b	De Aker West	F	2	1	1	2	2		2	1	2	1	2	1	1	1	1	3	17
F84c	De Aker Oost	F	2	2	1	2		1	2	1	2	1	2	1	1	1	1	4	16

F85a	Oostoever Sloterplas	F	3	2	1	2		1	2	1	2	1	1	1	1	1	1	5	15
F86a	Overtoomse Veld Noord	F	1	3	1	2	2		2	1	2	1	1	1	1		1	4	15
F86b	Overtoomse Veld Zuid	F	1	3	1	2	2		2	1	2	1	1	1	1		1	4	15
F86c	Rembrandtpark Noord	F	3	1	1	2		1	2	1	2	1	1	1	1			4	13
F86d	Rembrandtpark Zuid	F	3	1	1	2	2		2	1	2	1	1	1	1			4	14
F86f	Lucas/Andreasziekenhuis e.o.	F	2	3	1	2	2		2	1	2	1	1	1	1			5	14
F87a	Koningin Wilhelminaplein	F	2	2	1	2	2		2	1	2	1	1	1	1		1	4	15
F87b	Andreasterrein	F	2	2	1	2	2		2	1	2	1	1	1	1			4	14
F87e	Riekerhaven	F	3	2	1	2	2		2	1	2	1	1	1	1	1	1	5	16
F87f	Schipluidenbuurt	F	2	2	1	2	2		2	1	2	1	1	1	1		1	4	15
F88a	Riekerpolder	F	3	2	1	2		1	1	1	2	1	1	1	1	1	1	5	14
F88b	Park Haagseweg	F	2	2	1	2		1	2	1	2	1	1	1	1		1	4	14
F88d	Sloterweg e.o.	F	3	2	1	2		1	2	1	2	1	1	1	1	1	1	5	15
F88e	Nieuw Sloten Noordwest	F	2	2	1	2		1	2	1	2	1	2	1	1		1	4	15
F88f	Nieuw Sloten Noordoost	F	2	2	1	2		1	2	1	2	1	1	1	1		1	4	14
F88g	Belgiëplein e.o.	F	1	3	1	2		1	2	1	2	1	2	1	1			4	14
F88h	Nieuw Sloten Zuidwest	F	2	1	1	2		1	2	1	2	1	2	1	1		1	3	15
F88i	Nieuw Sloten Zuidoost	F	2	3	1	2		1	2	1	2	1	1	1	1		1	5	14
F88j	Dorp Sloten	F	3	2	1	2		1	2	1	2	1	2	1	1	1	1	5	16
F89c	Staalmanbuurt	F	2	3	1	2	2		2	1	2	1	1	1	1		1	5	15
F89d	Medisch Centrum Slotervaart	F	3	3	1	2		1	2	1	2	1	1	1	1		1	6	14
K23a	Zuidas Noord	K	3	2	1	2	2		2	1	2	1	1	1	1			5	14
K23b	RAI	K	3	3	1	2	2		2	1	2	1	1	1	1			6	14
K23c	VU-kwartier	K	3	1	1	2		1	1	1	2	1	1	1	1			4	12
K23d	Zuidas Zuid	K	2	2	1	2	2		2	1	2	1	1	1	1			4	14
K23e	Vivaldi	K	3	2	1	2	2		1	1	2	1	1	1	1			5	13
K46d	Vondelpark West	K	3	1	1	2	2		2	1	2	1	1	1	1			4	14
K47h	Museumplein	K	3	3	1	2	2		1	1	2	1	1	1	1			6	13
K48e	IJsbaanpad e.o.	K	3	1	1	2		1	2	1	2	1	1	1	1		1	4	14
K52h	Kop Zuidas	K	3	3	1	2	2		2	1	2	1	1	1	1			6	14
K90e	Amsterdamse Bos	K	3	2	1	3		1	2	1	2	1	1	1	1		1	5	15
K91a	De Klenckebuurt	K	2	2	1	2	2		1	1	2	1	1	1	1			4	13
K91d	Amstelpark	K	3	1	1	2		1	2	1	2	1	1	1	1			4	13
M31c	Zuidwestkwadrant Indische buurt	M	1	3	1	2	2		2	1	2	1	1	1	2		1	4	16
M32b	Zuidoostkwadrant Indische buurt	M	1	3	1	2	2		2	1	2	1	2	1	1		1	4	16
M32c	Zeeburgerdijk Oost	M	3	1	1	2	2		2	1	2	1	2	1	1		1	4	16
M32d	Flevopark	M	3	1	1	2	2		2	1	2	1	2	1	1	1	1	4	17
M33a	Oostelijke Handelskade	M	3	1	1	2	2		2	1	2	1	2	1	1		1	4	16
M33b	Rietlanden	M	2	2	1	2		1	2	1	2	1	2	1	1		1	4	15
M33c	Java-eiland	M	3	1	1	2		1	2	1	2	1	2	1	1		1	4	15
M33d	KNSM-eiland	M	3	3	1	2	2		2	1	2	1	2	1	1		1	6	16
M33e	Sporenburg	M	2	2	1	2	2		2	1	2	1	2	1	1		1	4	16
M33f	Borneo	M	2	1	1	2	2		2		2	1	2	1	1		1	3	15
M33g	Entrepot-Noordwest	M	2	1	1	2	2		2	1	2	1	2	1	1		2	3	17
M33h	Architectenbuurt	M	2	2	1	2	2		2	1	2	1	2	1	1		2	4	17
M33i	Bedrijvengebied Veelaan	M	3	1	1	2	2		2	1	2	1	2	1	1			4	15
M33j	Bedrijvengebied Cruquiusweg	M	3	3	1	2	2		2	1	2	1	2	1	1		1	6	16
M33k	Bedrijvengebied Zeeburgerkade	M	3	1	1	2	2		2	1	2	1	2	1	1			4	15
M34c	Zeeburgereiland Zuidoost	M	3	2	2	2	2		2	1			2	1	1		1	5	14
M34d	Zeeburgereiland Zuidwest	M	3	2	1	2	2		2	1	2	1	2	1	1	1	1	5	17
M34e	Nieuwe Diep/Diemerpark	M	3	3	1	2		1	2	1			2	1	1	1	1	6	13
M34g	Zeeburgereiland Noordoost	M	3	2	1	2		1	2	1			2	1	1		1	5	12
M35a	Steigereiland Noord	M	3	3		2			2		2	1	2	1	1	1	1	6	13
M35b	Steigereiland Zuid	M	2	2	1	2		1	2	1	2	1	2	1	1		1	4	15
M35c	Haveneiland Zuidwest/Rieteiland We	M	2	2		2			2		2	1	2	1	1	1	1	4	13
M35e	Haveneiland Noordwest	M	3	3		2			2		2	1	2	1	1	1	1	6	13
M35f	Haveneiland Noordoost	M	2	2		2			2		2	1	2	1	1		1	4	12
M50g	Centrumeiland	M	3	3		2			2		2	1	1	1	1	1	1	6	12

M51b	Haveneiland Oost	M	2	2	3	2		1	2		2	1	2	1	1		1	4	16
M51c	Haveneiland Noord	M	2	2		2			2		2	1	2	1	1	1	1	4	13
M55b	De Eenhoorn	M	1	3	1	2	2		1	1	2	1	1	1	1		1	4	14
M55c	Julianapark	M	2	1	1	2	2		2	1	2	1	1	1	1		1	3	15
M56e	Sportpark Middenmeer Noord	M	3	2	1	2	2		2	1	2	1	2	1	1		1	5	16
M56f	Park de Mees	M	2	1	1	2	2		2	1	2	1	2	1	1		1	3	16
M56g	Sportpark Voorland	M	3	1	1	2		1	2	1	2	1	2	1	1		1	4	15
M56h	Science Park Noord	M	2	2	1	2	2		2	1	2	1	2	1	1		1	4	16
M56i	Science Park Zuid	M	3	2	1	2	2		2	1	2	1	2	1	1	1	1	5	17
M57c	Drieburg	M	3	1	1	2	2		2	1	2	1	1	1	1		1	4	15
M58b	Weespertrekvaart	M	3	1	1	2	2		2	1	2	1	1	1	1			4	14
M58f	Overamstel	M	3	3	1	2	2		2	1			1	1	1	1		6	12
M58g	Amstelkwartier Noord	M	2	2	1	2		1	2	1	2	1	1	1	1		2	4	15
M58h	De Omval	M	3	1	1	2	2		2	1	2	1	1	1	1		2	4	16
N61a	IJplein e.o.	N	2	1	1	1	2		1	1	2	1	2	1	1		1	3	14
N61d	Vliegenbos	N	3	1	1	1		1	2	1	2	1	2	1	1			4	13
N64b	Buiksloterdijk Oost	N	3	1	1	1	2		2	1	2	1	2	1	1			4	14
N65d	De Bongerd	N	2	2	1	2	2		2	1	2	1	1	1	1			4	14
N66b	Oostzanerdijk	N	3	3	1	2		1	2	1	2	1	1	1	1			6	13
N66c	Walvisbuurt	N	3	1	1	2		1	2	1	2	1	1	1	1			4	13
N66d	Twiske West	N	2	1	1	2		1	2	1	2	1	1	1	1			3	13
N66e	Noorder IJplas	N	3	3	1	2		1	2	1			1	1	1		1	6	11
N66f	Molenwijk	N	2	1	1	2		1	2	1	2	1	1	1	1			3	13
N66g	Circus/Kermisbuurt	N	2	1	1	2	2		2	1	2	1	1	1	1			3	14
N67a	Kadoelen	N	3	1	1	2		1	2	1	2	1	1	1	1		2	4	15
N67b	Twiske Oost	N	2	1	2	2		1	2	1	2	1	1	1	1			3	14
N68a	Markengouw Noord	N	2	1	1	1		1	2	1	2	1	2	1	1			3	13
N68d	Markengouw Midden	N	2	2	1	1		1	2	1	2	1	2	1	1			4	13
N68e	Markengouw Zuid	N	2	3	1	1		1	2	1	2	1	2	1	1			5	13
N69c	Loenermark	N	2	1	1	1	2		2	1	2	1	2	1	1			3	14
N69j	Buikslotermeerplein	N	3	1	3	1	2		2	1	2	1	2	1	1			4	16
N69m	Buikslotermeer Noord	N	2	2	1	1		1	2	1	2	1	2	1	1			4	13
N70a	Banne Zuidwest	N	2	3	1	2	2		2	1	2	1	1	1	1		2	5	16
N70b	Banne Zuidoost	N	2	2	1	1	2		2	1	2	1	1	1	1			4	13
N70c	Banne Noordwest	N	2	1	1	2		1	2	1	2	1	1	1	1			3	13
N70d	Banne Noordoost	N	2	1	1	2		1	2	1	2	1	1	1	1			3	13
N70e	Buiksloterbreek	N	3	3	1	2	2		2	1	2	1	1	1	1		2	6	16
N70f	Marjoleinterrein	N	2	3	1	2	2		2	1	2	1	1	1	1			5	14
N71c	Papaverweg e.o.	N	3	2	1	2	2		2	1	2	1	1	1	1		1	5	15
N71e	Cornelis Douwesterrein	N	3	2	1	3		1	2	1	2	1	1	1	1		1	5	15
N71f	NDSM terrein	N	3	3	1	3		1	2	1	2	1	1	1	1		1	6	15
N71g	Buiksloterham	N	3	3	1	2	2		2	1	2	1	1	1	1		1	6	15
N71h	Overhoeks	N	3	2	1	2	2		2	1	2	1	1	1	1		1	5	15
N72a	Bedrijventerrein Hamerstraat	N	3	3	1	1		1	2	1	2	1	2	1	1		1	6	14
N72b	Zamenhofstraat e.o.	N	3	3	1	1		1	2	1	2	1	2	1	1		1	6	14
N72c	Bedrijventerrein Nieuwendammerdijk	N	3	3	2	1	2		2	1	2	1	2	1	1		1	6	16
N73a	Schellingwoude West	N	3	3	2	1	2		2	1			2	1	1		1	6	13
N73c	Schellingwoude Noord	N	3	1	1	1		1	2	1			2	1	1			4	10
N73f	Ransdorp	N	3	3	3	1		1	2	1			2	1	1		2	6	14
N73g	Holysloot	N	3	3	1	1		1	2	1			2	1	1	1	1	6	12
N73h	Zunderdorp	N	3	3	1	1	2		2	1	2	1	2	1	1		2	6	16
N73i	Noorderstrook West	N	3	3	1	1		1	2	1			2	1	1			6	10
N73j	Noorderstrook Oost	N	3	1	1	1		1	2	1			2	1	1			4	10
N74a	Nintemanterrein	N	3	2	1	1	2		2	1	2	1	2	1	2			5	15
N74b	Elzenhagen Zuid	N	3	1	1	1	2		2	1	2	1	2	1	1			4	14
N74c	Elzenhagen Noord	N	3	2	1	1		1	2	1	2	1	2	1	1			5	13
T92a	Hoofdcentrum Zuidoost	T	3	2	1	1		1	1	1	1	1	1	1	1	1	1	5	12
T92b	Amstel III deel A/B Noord	T	3	2	1	1		1	1	1	2	1	1	1	1	1	1	5	13

T92c	Amstel III deel C/D Noord	T	3	3	2	1		1	2	1	2	1	1	1	1	1	1	6	15
T92d	Amstel III deel A/B Zuid	T	3	1	1	1		1	2	1			1	1	1	1	1	4	11
T92e	Amstel III deel C/D Zuid	T	3	1	2	1		1	2	1			1	1	1	1	1	4	12
T92f	AMC	T	3	3	1	1		1	2	1			1	1	1	1	1	6	11
T92g	Hoge Dijk	T	3	2	1	1		1	2	1			1	1	1	1	1	5	11
T93a	Velserpolder West	T	2	1	1	2		1	2	1	2	1	1	1	1		1	3	14
T93b	Venserpolder Oost	T	2	1	1	2		1	2	1	2	1	1	1	1			3	13
T93c	D-buurt	T	2	3	1	2		1	2	1	2	1	1	1	1		2	5	15
T93d	F-buurt	T	1	2	1	2	2		2	1	2	1	1	1	1		2	3	16
T93e	Amsterdamse Poort	T	3	1	1	2	2		1	1	2	1	1	1	1		1	4	14
T93f	Hoptille	T	2	3	1	2	2		2	1	2	1	1	1	1		1	5	15
T93h	Hakfort/Huigenbos	T	2	1	1	2		1	2	1	2	1	1	1	1		2	3	15
T93i	Huntum	T	3	1	2	2	2		2	1	2	1	1	1	1		1	4	16
T93j	Vogeltjeswei	T	2	2	3	2	2		2	1	2	1	1	1	1		2	4	18
T93k	Bijlmerpark West	T	3	1	1	2	2		2	1	2	1	1	1	1		1	4	15
T94a	E-buurt	T	2	3	1	2		1	2	1	2	1	1	1	1		2	5	15
T94b	G-buurt West	T	2	2	3	2	2		2	1	2	1	1	1	1		2	4	18
T94d	Kortvoort	T	2	2	1	2	2		2	1	2	1	1	1	1		2	4	16
T94e	Kelbergen	T	3	3	1	2	2		2	1	2	1	1	1	1	1	2	6	17
T94g	K-buurt Zuidoost	T	2	3	1	2		1	2	1	2	1	1	1	1		2	5	15
T94h	K-buurt Zuidwest	T	2	3	2	2	2		2	1	2	1	1	1	1		2	5	17
T94i	Grunder/Koningshoef	T	1	3	3	2	2		2	1	2	1	1	1	1		2	4	18
T94j	G-buurt Oost	T	3	1	1	2	2		2	1	2	1	1	1	1		1	4	15
T94k	Kantershof	T	3	1	1	2	2		2	1	2	1	1	1	1		1	4	15
T94l	Bijlmerpark Oost	T	3	2	1	2	2		2	1	2	1	1	1	1		2	5	16
T94m	G-buurt Noord	T	1	2	1	2	2		2	1	2	1	1	1	1		2	3	16
T94n	Bijlmermuseum Zuid	T	2	2	3	2	2		2	1	2	1	1	1	1		2	4	18
T95a	L-buurt	T	3	2	1	2		1	2	1	2	1	1	1	1	1	1	5	15
T96a	Holendrecht West	T	2	2	1	2		1	2	1	2	1	1	1	1		1	4	14
T96b	Reigersbos Noord	T	2	3	1	2		1	2	1	2	1	1	1	1	1	1	5	15
T96c	Holendrecht Oost	T	3	1	1	2		1	2	1	2	1	1	1	1		1	4	14
T96d	Gaasperdam Noord	T	2	2	1	2		1	2	1	2	1	1	1	1		1	4	14
T96e	Gaasperdam Zuid	T	2	2	2	2		1	2	1	2	1	1	1	1		1	4	15
T96f	Reigersbos Midden	T	2	1	1	2		1	2	1	2	1	1	1	1	1	1	3	15
T96g	Reigersbos Zuid	T	3	1	1	2		1	2	1	2	1	1	1	1	1	1	4	15
T97a	Gein Noordwest	T	2	1	1	2		1	2	1	2	1	1	1	1		1	3	14
T97b	Gein Zuidwest	T	2	1	1	2		1	2	1	2	1	1	1	1	1	1	3	15
T97c	Gein Noordoost	T	2	2	1	2		1	2	1	2	1	1	1	1	1	1	4	15
T97d	Gein Zuioost	T	3	2	1	2		1	2	1	2	1	1	1	1	1	1	5	15
T98b	Landelijk gebied Driemond	T	3	2	1	2	2		2	1	2	1	1	1	1	1	1	5	16

CASE STUDY PROJECTS

CITY-SCALE STRATEGIES:

1. Biotope Area Factor (BAF) requirement, Berlin, Germany

City information:

Land area: 891.8km2

Population: 3.769 million

Urban climate change effects: increase heat, decrease summer precipitation, increase risk river floods, increase in energy demand for cooling.

NBS Description:

The BAF requirement was created to address four challenges in the city: soil sealing; falling groundwater due to low infiltration combined with efficient man-made drainage networks; low humidity and heat; decreasing habitat areas for plants and animals.

Climate Challenges:

- Climate regulation
- Water flow regulation

Background, aims, and objectives:

The BAF requirement is a regulation and planning standard that has been implemented in Berlin, Germany since 1994. It was created to increase Green Infrastructure outcomes in inner city areas to combat environmental quality challenges caused by years of urban development in the city (GrowGreen, 2019).

The objective of the BAF is to solve its challenges with respect to water and heat by requiring minimum areas of biotope (spaces with ecological functions) while maintaining current land use in inner city areas.

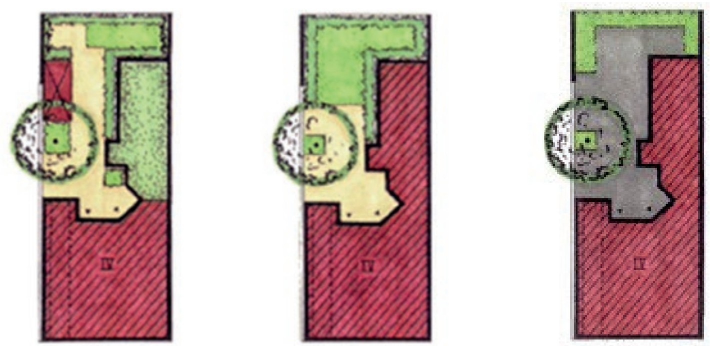
There are four objectives of the BAF requirement (City of Berlin, 2020):

1. Improving and maintaining the microclimate and air quality
2. Improving and maintaining soil functions and the hydrological cycle
3. Creating and enhancing the quality of plant and animal habitats
4. Improving amenity in residential areas

NBS Outcomes:

The BAF requirement is an ecological parameter than is used to ensures a minimum amount of ecologically performing area in new urban developments in the inner areas of Berlin. When planning permits are submitted to the government, the BAF factor is calculated as a percentage of the total site area to permeable and/or green spaces. The calculation is not only based on area but also the ecological functions provided by the surface types. Surface types that are fully permeable and planted are weighted higher and therefore count more towards achieving the BAF requirement.

As a policy instrument, the BAF requirement does not bear the costs of converting urban spaces to ecologically valuable areas, instead where it incurs costs is in the evaluation and enforcement of the requirement. Anticipated benefits to human health and wellbeing are directly linked to the improvement of the natural environment via restoring soil functions and increasing vegetated areas. In outer areas, the BAF calculation is voluntary.



Surface treatment types for a typical urban plot. Image credit: City of Berlin, 2020.

Weighting factors for surface treatment types (City of Berlin, 2020)

Weighting factor 0,0 per m²	Sealed surfaces
Weighting factor 0,3 per m²	Partially sealed surfaces
Weighting factor 0,5 per m²	Semi-open surfaces Surfaces with vegetation, unconnected to the soil below Vertical greenery with connection to the ground Extensive roof greening
Weighting factor 0,7 per m²	Surfaces with vegetation, unconnected to the soil below Vertical greenery without connection to the ground Semi-intensive roof greening
Weighting factor 1,0 per m²	Surfaces with vegetation, connected to the soil below
Weighting factor 0,2 per m²	Rainwater infiltration per m² of roof area
(Weighting factor 0,8 per m²)	Intensive roof greening

https://www.berlin.de/sen/uvk/en/nature-and-green/landscape-planning/baf-biotope-area-factor/calculating-the-baf/

Spatial consequences:

Example of BAF courtyard implemented in Berlin. Image credit: City of Berlin, 2020.

The BAF requirement applies to 16% of Berlin's land area which is equivalent to approximately 142.6km2.

Although there are cases where the BAF requirement has been applied voluntarily (Kopetzki, 2014), there are no measurements for sites where the BAF has been applied voluntarily.

Impacts to human health and wellbeing:

- There are no measurements on the benefits to human health and wellbeing since the introduction of the BAF requirement.
- Initial review by the EU and EEA's Climate-ADAPT platform observe that there have been improvements to the residential environment and quality of life of residents living near BAF areas and that reduced vulnerability to heat and water stress are expected (Kopetzki, 2014).

Lessons learned:

- Flexibility in the BAF approach has increased success in its adoption because developers can choose from a variety of surface types to suit their development functions.
- Collaboration between city government departments ensured that the BAF requirement was implemented in a coordinated way.
- Compulsory requirements are only as effective as the area that they are applicable to – a higher area covered by the requirement would significantly increase benefits across the city.
- Cost-effectiveness is not guaranteed when it causes significant institutional change and enforcement.

2. Green Infrastructure and Biodiversity Plan 2020, Barcelona, Spain

City information:

Land area: 101.9km2

Population: 5.575 million

Projected and observed climate change effects: increased heat and associated heat-related mortality, decrease in precipitation, increased risk of droughts and biodiversity loss, increase energy demand for cooling.

NBS Description:

Barcelona's 'Biodiversity Plan' is a long-term plan that aims to increase the connectivity and areas of green infrastructure in the city to improve health and wellbeing in the city while balancing the negative climate effects of the city (Barcelona City Council, 2020). The plan includes five strategic goals that within them contain actions to achieve the goal.

Climate Challenges:

- Climate regulation
- Water flow regulation

Background, aims, and objectives:

Rapid urbanization and poorly integrated traffic infrastructures have increased scarcity and fragmentation of green spaces in the city. This has disrupted the ecosystem services that natural areas provide including those that can mitigate the effects of the city's climate change and air pollution challenges.

The aim of the Biodiversity Plan is to create a city that has a connected and expanding green infrastructure that enhances and preserves the natural heritage and biodiversity for the long-term benefit of its citizens and climate change resilience goals (IUCN, 2016).

Visualisation of Green Infrastructure concept. Image credit: City of Barcelona, 2020.

There are eight areas of improvement identified:

1. Natural heritage: preservation and creation of habitats.
2. Territory: provision, access, adequacy, and connectivity of green spaces for citizens.
3. Structure and ecological services: ecological enhancement.
4. Quality of life: multi-functional spaces that increase citizen health and wellbeing.
5. Cultural heritage: preservation and perpetuation of historical and local green spaces and assets.

6. Communication and education: increasing public participation and educational activities and material.
7. Management and maintenance: improving processes and quality standards and aiming for efficient use of resources.
8. Commitment: promoting multi-level involvement, increasing knowledge, and leveraging networks.

NBS Outcomes:

The plan contains five strategic goals that describe the importance of natural heritage and green infrastructure for climate resilience as well as the importance of education and capacity building in society. These goals are expanded into ten strategic lines with accompanying actions:

Summary of strategic lines and actions (Barcelona City Council, 2020):

Strategic line	Summary of actions
1. Preserving the city's natural heritage	Create protocols and action plans to improve upon, prevent, and control threats to the city's natural heritage (eg: invasive species). Includes consolidating conservation programmes.
2. Planning green infrastructure to ensure connectivity and strike a balance in distribution	Identify green infrastructure areas and increase area and connections between green areas especially in outer areas of the city.
3. Designing the city and its green spaces taking into account environmental services and integrating criteria to enhance biodiversity	Creation of charters and measures that increase permeability and biodiversity. Increase efficiency in water usage and maintenance practices.
4. Creating new sources for nature and increasing the presence of green infrastructure and biodiversity	Increase and restore green areas in the city by utilising unused plots, increase soil area for plants, and seeking opportunities to add plants in and on buildings.
5. Managing parks and gardens and other green spaces with sustainability and efficiency criteria, fostering biodiversity	Increase efficiency in watering and maintenance regimes. Create measures for repairing and maintaining green spaces after weather-related incidents.
6. Preserving and enhancing the value of cultural heritage, especially in historical gardens	Identify historic gardens, create management plans, and identify and protect trees of historical and cultural significance.
7. Improving knowledge for the Management and conservation of green infrastructure and biodiversity	Increase data collection via sensing, mapping, and monitoring green spaces with the aim of collecting applied knowledge. Collaborate with knowledge institutes.
8. Spreading knowledge of green infrastructure and biodiversity and their values, fostering training	Raising awareness and education levels via communications, programs, citizen activities, and information centres.
9. Fostering green spaces as places for health and enjoyment as well as promoting citizen involvement in their creation and in the conservation biodiversity	Increase number of and access to community and private spaces that can provide opportunities for urban agriculture, play, and recreation.
10. Strengthening local leadership, networking and the commitment to the conservation of green infrastructure and biodiversity	Build capacity in government departments, increase networking and agreements with organisations and stakeholders, create tools for conservation and establish environmentally friendly procurement protocol.

Visualisation of citizens' reactions to green infrastructure. Image credit: Barcelona City Council, 2020.

CASE STUDY PROJECTS

Spatial consequences:

The Biodiversity Plan was issued to the public in 2020 (this year) and therefore it is too early to assess what the spatial consequences have been. According to a local government officer who presented the plan at a conference on Nature-based Solutions in March 2020, spatial interventions will be staged with the aim of measuring and contributing to a cumulative area target (Appendix CX).

Furthermore it is unlikely that large scale sites will be converted for urban greening as it has been identified that more resources should be invested into maintenance of existing green areas (IUCN, 2016).

Impacts to human health and wellbeing:

- The plan describes anticipated benefits to human health and wellbeing but does explicitly mention the desire to measure increased benefits to humans.

Lessons learned:

- Political support and willingness is necessary for the adoption of long-term and city-scale plans – strategies need to be able to connect to and bring together multiple scales, stakeholders, and sectors.
- Citizen awareness and participation is necessary for conservation or improvement plans to be supported and adopted in the long term.
- High-density urban environments like Barcelona struggle to maintain green areas due to their popularity and intensive use by citizens. This limits the abilities of the city to add more green spaces of similar quality.

3. Green Capital proposal, London, U.K.

City information:

Land area: 1,572km2

Population: 8.982 million

Projected and observed climate change effects: Increase in heavy precipitation events, increase in river flow, increased risk of river and coastal flooding, increased damage risk from winter storms, increase in multiple climactic hazards.

NBS Description:

The Green Capital proposal connects governments and business and land owners with expertise to add green infrastructure to the city to benefit the ecological function of the city and citizen health and wellbeing – all while improving the value of assets or gains in productivity to businesses.

Climate Challenges:

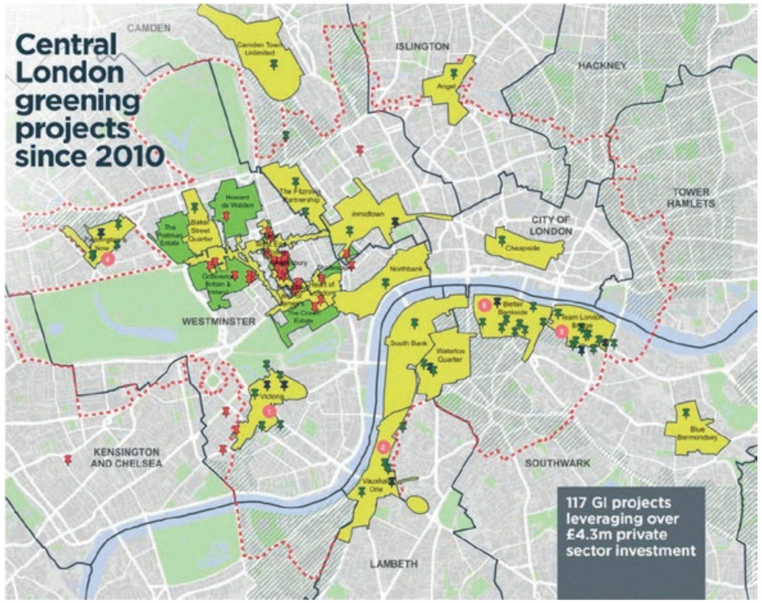
- Climate regulation
- Water flow regulation

Background, aims, and objectives:

The Green Capital proposal was created alongside multiple government initiatives aiming to make London climate-proof. The proposal is focused on the increased amount of green infrastructure spaces to provide additional habitats for animals, biodiversity, and citizen health and wellbeing outcomes.

As a business-driven initiative, the Green Capital proposal approaches the challenge of climate action in an entrepreneurial way – businesses are encouraged to propose improvements to Green Infrastructure to benefit their business interests rather than wait for spatial planning changes or public projects to start. As such the five objectives of the proposal (adopted from another government taskforce for Green Infrastructure) are supported by four reasons for businesses to invest in the proposal:

Objective	Business case
1. Promote healthy living by increasing physical activity, reducing stress, and removing pollutants. 2. Strengthen resilient living by keeping the city dry and cool and its air clean. 3. Encourage Active Living by increasing levels of walking and cycling. 4. Create living landscapes by conserving the most special landscapes, habitats and species. 5. Enhance living space by providing a range of outdoor spaces for cultural, civic, learning and community activities like productive landscapes.	Green Infrastructure has the potential to benefit businesses by: • attracting customers by linking green infrastructure benefits with their products, services or corporate social responsibility • maximising spending by increasing dwell-time • motivating staff by increasing wellbeing and making links to wider environmental concerns such as air quality, flooding, climate change • adding value by building partnerships with local authorities and community groups



Green Capital project map. Image credit: Mayor of London, 2016.

NBS Outcomes:

The Green Capital proposal is based on the need to adapt to climate change and to do so in ways that also stimulate investment and returns for both the city and private businesses. To do this, the Mayor of London's office, Nature England (a public body), and the not-for-profit "Cross River Partnership" have created "Business Improvement Districts" (BIDs) groups that rely on mainly private investment for the implementation of green infrastructure in the city (Mayor of London, 2016). To date there have been 15 BID projects implemented and the Cross River Partnership has since identified 1 million areas of additional small scale greening projects that could be integrated into the city (C40 Cities Climate Leadership Group, 2016).

Steps towards achieving the stated goals have are evidenced in the small number of NBS projects in London that have, in addition to increasing biodiversity, contributed to climate change mitigation (via sequestration) and reducing heat stress and flood risks (Somarakis, Stagakis, & Chysoulakis, 2019).

Spatial consequences:

Two of the five case study projects are 'vertical greening' or 'green wall' projects that do not change the function of materiality of the ground surface. In this respect, the BID projects can have significant spatial consequence on building facades as well as the ground plane.

The remaining three projects focus on adding green area without significantly changing existing functions and occur at ground level and vary from a few hundred metres of streetscape to pocket parks.

Impacts to human health and wellbeing:

- There was no stated goal to quantify nor measure health and wellbeing outcomes.

Lessons learned:

- Using public-private partnerships like those of the Green Capital BIDs is successful in communicating the benefits of green infrastructure to businesses by providing them with a business case for acting sustainably while receiving economic gains.
- BID groups and projects work well in contexts where building regulations are flexible and can be used to stimulate interest and support for urban greening.
- High amounts of capacity are required from city governments to undertake and manage the public-private agreements and working groups of BID groups and projects.
- Although there is potential of achieving cumulative benefits over multiple small projects, it is not feasible to depend on business groups to deliver city-wide benefits. Given small size and range of BID projects, it will take many thousands more to fulfil the 9,292 hectares that the City of London has aspired to as part of its infrastructure plans by 2050 (Mayor of London, 2016).

4. Retrofitting SUDS in Augustinborg, Malmo, Sweden

City information:

City land area: 332.6km2

Population: 3,470

Project site area: 0.334km2

Projected and observed climate change effects: Increase in heavy precipitation events, increase in river flow, increased risk of river and coastal flooding, increased damage risk from winter storms, increase in multiple climactic hazards.

NBS Description:

Augustenborg is a neighbourhood that was prone to flood risk and challenges involving community building and social cohesion. Retrofitting SUDS in the neighbourhood was recommended to reduce the flood risk of the neighbourhood while also increasing climate change adaptation and improving citizen wellbeing and social cohesion.

Climate Challenges:

- Climate regulation
- Water flow regulation

Background, aims and objectives:

Augustenborg is a neighbourhood in the coastal city of Malmo, Sweden and like the rest of the city is vulnerable to increasing precipitation due to climate change. Sustainable Urban Drainage Systems (SUDS) supported the municipality's aims to make Malmo more socially, environmentally, and economically sustainable.

The aims and objectives of the Augustenborg retrofitted SUDS were to:

Aim	Objective
Enhance sustainable urbanisation	Reduce pressure on stormwater system Reduce costs associated to flood risks Create protected green areas Increase citizen wellbeing by improving visual amenity and providing space for socio-cultural activities
Restoring ecosystems and their functions	Increase infiltration function in the soil Improve quality and quantity of ecosystems
Develop climate change mitigation ability	Carbon sequestration Reduce energy use for water treatment
Develop climate change adaptation ability by improving risk management and resilience	Increase capacity to withstand heavy rainfall events Reduce flood risk Crease stable and resilient ecosystems Maximise water storage abilities in green areas

NBS Outcomes:

An extensive plan for constructing SUDS in the neighbourhood was created with input and participation of citizens. The works were approved and funded by the local government and housing corporation. The constructions of the SUDS started in 1999 and completed in 2000. The drainage system comprised of open water and collection and infiltration areas that were at times integrated into courtyard areas. The water collected by the system was eventually discharged via a conventional underground sewage and stormwater system.

View of permanently inundated SUDS water feature with accompanying community facilities. Image credit: University of Nottingham (https://blogs.nottingham.ac.uk/bluegreencities/2017/09/01/malmo/)

Ephemeral water streams and specialised water drainage channels designed as features in the park. Image credit: Climate-ADAPT (https://climate-adapt.eea.europa.eu/metadata/case-studies/urban-storm-water-management-in-augustenborg-malmo)

Design interventions used:

- Canals with natural edges (i.e. without walls) to detain water until it is discharged to the sewage/stormwater system.
- Concrete channels installed to collect water and discharge it to specific points downstream.
- Planted swales integrated into landscapes and at building downpipe locations.
- Geotextiles laid below all infiltration areas to limit risk of damage to building foundations.

Impacts to climate challenge:

- In 2007 a 50-year probability rainfall event occurred and flooded areas isolated Malmo from the rest of the country. Augustinborg however, was not flooded and this is attributed to the implementation of the SUDs in addition to the conventional drainage system(ThinkNature, 2018).
- No incidence of flooding during monitor period of 2002-2010.
- Carbon emissions and waste generation decreased by 20%.

Lessons learned:

- It was challenging to find space SUDS in the existing built fabric of the city especially with respect to underground assets, emergency vehicle requirements, and citizen concerns about losing recreational space to water storage areas.
- The installation of geotextiles limited the infiltration abilities of the SUDS – full infiltration to the groundwater table was limited by the geotextile and the design which directed flow to conventional sewage systems.
- Nuisance due to construction was a factor for some residents.
- Nutrient levels in open water areas need to be monitored to prevent algal blooms. This was solved in Augustenborg via a technical solution.
- Neighbourhood scale tests of SUDS can lead to city-wide adoption as was the case in Augustenborg where the success of the SUDS led to similar systems being used in new developments elsewhere in Malmo.
- Citizens should be encouraged to participate from the beginning of the process so that they can shape the process and direction of the development. For Augustenborg this resulted in high levels of engagement by some locals and minimal opposition to the project.
- The enhanced visual amenity that SUDS provide to neighbourhoods has been linked to decreased unemployment rates and tenancy turnovers (EU Commission, 2015).
- Extensive SUDS projects like Augustenborg can become the focus of international interest creating a demand for educational tours and knowledge exchange.

5. SUDS in Severn-Trent Water Ripple Effect Investigation, Coventry, U.K.

City information:

City land area: 98.64km2

Population: 325,900

Project site area: 1.5km length street

Projected and observed climate change effects: Increase in heavy precipitation events, decrease in snow and ice cover, increase in precipitation and river flow, increased damage risk from winter storms.

NBS Description:

The city of Coventry faces water-related challenges due to its location over a culverted river, increasing water demand, and decreased ability for water to infiltrate locally (AECOM & Severn Trent Water, 2013). Sustainable Urban Drainage Systems are proposed as a solution to the water related challenges while also bringing gains to citizens in the form of health and wellbeing and to water suppliers by reducing costs.

Climate Challenges:

- Water flow regulation

Background, aims, and objectives:

The SUDS proposal for Stoney Road is part of a larger, city-wide investigation into making the water system more resilient to climate change and population growth. The investigation is based on appraisal the inner city area and the identification of ten possible sites for water system improvements. Of the ten, three have scope to include SUDS.

The aims of the investigation are to build resilience in the urban water system by identifying challenges in the context, locating opportunity areas in the city, and providing a business case that can guide the decision making process of the council (AECOM & Severn Trent Water, 2013).

Resilience in the urban water system is analysed against specific climate change risks to form the interventions that are the outcome of the investigation. These water and climate objectives are:

1. Reduce flooding
2. Maintain quality alongside population growth and liveability
3. Maintain supply despite increasing demand
4. Reduce the urban heat island effect and/or its impacts on citizens
5. Improve and maintain water quality in rivers

Outcome:

11 water system related interventions were determined in the investigation including SUDS. Although SUDS are identified as a separate intervention, in reality they are a combination of interventions that are also listed in the report. The 11 interventions are:

i. Green Roofs: reduce surface runoff and increase benefits from green infrastructure.
ii. Water feature storage (in hardscape and softscape areas): additional canals or equivalent features can be designed to be inundated to attenuate flows and prevent flooding.
iii. Green sustainable drainage systems (SUDS) in streets: using raingardens, swales, and tree pits to absorb street runoff and assist with irrigation needs.
iv. Daylighting water courses: removing culverts over natural waterway to add more direct flood management.
v. In-situ river treatment: clean water within the river itself.
vi. Flood resilient development: design buildings and public spaces to withstand flood events without incurring significant damage.
vii. Water efficiency : reduce water consumption where possible to reduce usage, wastewater production, and the associated energy use to treatment.
viii. Rainwater run-off recycling: capture, store, and reuse rainwater where non-potable water is acceptable.
ix. Groundwater abstraction: extract groundwater from areas where the groundwater table is higher and increases flood risk.

x. Underground infrastructure renewal: ageing supply and drainage infrastructure should be replaced to reduce risk of leakage and intrusion of groundwater.

xi. Sewer separation: separate sewage and stormwater when possible to increase capacity of either.

The interventions are then applied to ten locations in Coventry and often with more than one intervention being applied at once. Of the 11 interventions, two relate to changes in underground infrastructure and three to changing behaviours and norms towards water recycling.

Green streets retrofit: Stoney Road before intervention

Green streets retrofit: Stoney Road after intervention

Visualisation of streetscape changed by implementing SUDS and raingardens. Image credit: AECOM, 2013.

Design interventions used:

- Raingardens with infiltration and/or detention capabilities
- Elsewhere, design interventions included: hardscape or softscape features that could be temporarily inundated in high rainfall events; designing new buildings and spaces to accommodate flooding; in-situ water treatment in rivers; and green roofs.

Impacts to climate challenge:

- Benefits were not measured.
- The proposal remains as such and if the SUDS would have been constructed this would alter approximately 1.5km of roads. The addition of planted retention areas and street trees would have also benefited the visual amenity and environmental quality of the roads (CIRIA, Demonstrating the multiple benefits of SuDS – A business case (Phase 2)).
- Based on the recommendations of AECOM and Severn Trent Water (2013), the new street trees would remove 15.8 tonnes of pollutants from the air over a period of 40 years.
- Increased physical activity and reducing risk of mortality due to the urban heat island effect are also cited.

Lessons learned:

- Making a business case for SUDS is important for demonstrating the value of passive and/or natural forms of water drainage in the city.
- Purported gains in jobs due to green infrastructure can also be offset by job losses due to changes made to the operation of the water system. Additionally, job creation is dependent on the council being unable to shift additional workload onto existing employees.

6. <u>Boompjes Promenade & "Room for the River", Rotterdam, The Netherlands</u>

City information:

City land area: 325.8km2

Population: 820,000

Project site area: 600 metres length

Projected and observed climate change effects: Increase in heavy precipitation events, decrease in snow and ice cover, increase in precipitation and river flow, increased damage risk from winter storms.

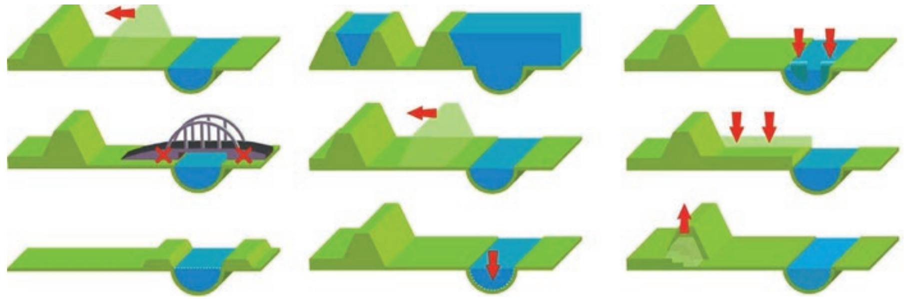
NBS Description:

The Boompjeskade in Rotterdam addresses flood risk (from precipitation) by increasing the amount of permeable and planted areas on the street and in doing so create an attractive urban area for citizens to enjoy.

Climate Challenges:

- Water flow regulation
- Background, aims, and objectives:

The Boompjeskade is located on the waterfront of the Nieuwe Maas river and acts as one of the dikes protecting the city and in the last decade the urban waterfront was renovated as part of the "Room for the River" initiative by Rijkswaterstaat (Frantzeskaki, 2019). The aim of the "Room for the River" is to alleviate the pressure on rivers to drain increasing amounts of water so that risks to life and property are reduced.



Diagrams of typical water management strategies along the dikes. Image credit: RWS, 2020.

As a national-level initiative the specific objectives of each project will differ based on the location and context of the water-related challenge. There are nine overall measures proposed (Rijkswaterstaat, 2020):

1. Dike relocation: moving dikes inland to increase the size of floodplains.
2. High water channel: create an overflow channel by building additional dikes in parallel.
3. Crib lowering and longitudinal dams: increase ease of drainage in the river.
4. Obstruction removal: entails reducing bridge landings and removing obstructions like jetties to the water.
5. Depoldering: increase flow in and out of polders during high tide.
6. Excavating flood plains: removing the top layer of soil or sediment in the floodplain.
7. Water storage: Allow for excess water storage in the rivers when the storm surge barriers are closed.
8. Riverbed excavation: dredging the bottom of riverbeds to increase depth and therefore capacity of the river.
9. Dike improvement: reinforce or increase height of existing dikes.

NBS Outcomes:

In Rotterdam the renovation of the Boompjes area created an opportunity to adapt the "Room for the River" measures to an urban setting. Boompjes is a dike that is integrated into the urban fabric (RCI, 2013) therefore decreasing the amount of sealed, impervious surfaces increases its ability to absorb additional water.

Photograph of Boompjes area after project completion. Image credit: RCI, 2013.

Design interventions used:

- Extensive sloped lawn and garden areas that increase permeability of the total surfaces in the area.

Impacts to climate:

- Benefits were not measured.

Lessons learned:

- Flood protection infrastructure can also function as recreational spaces for citizens.
- Boompjeskade benefits from being approximately 20 metres wide from the edge of the water to the top of the steps that join the pedestrian level above.

7. ZOHO Raingardens, Rotterdam, The Netherlands

City information:

City land area: 325.8km2

Population: 820,000

Project site area: 0.63km2

Projected and observed climate change effects: Increase in heavy precipitation events, decrease in snow and ice cover, increase in precipitation and river flow, increased damage risk from winter storms.

NBS Description:

Rotterdam's residential areas are also prone to flood risk and drought due to climate change. For the neighbourhood of Zomerhofkwartier (ZOHO, for short), raingardens were proposed as a solution to water related challenges. Raingardens are planted with vegetation that increases biodiversity locally and improves the visual amenity of the neighbourhood.

Climate Challenges:

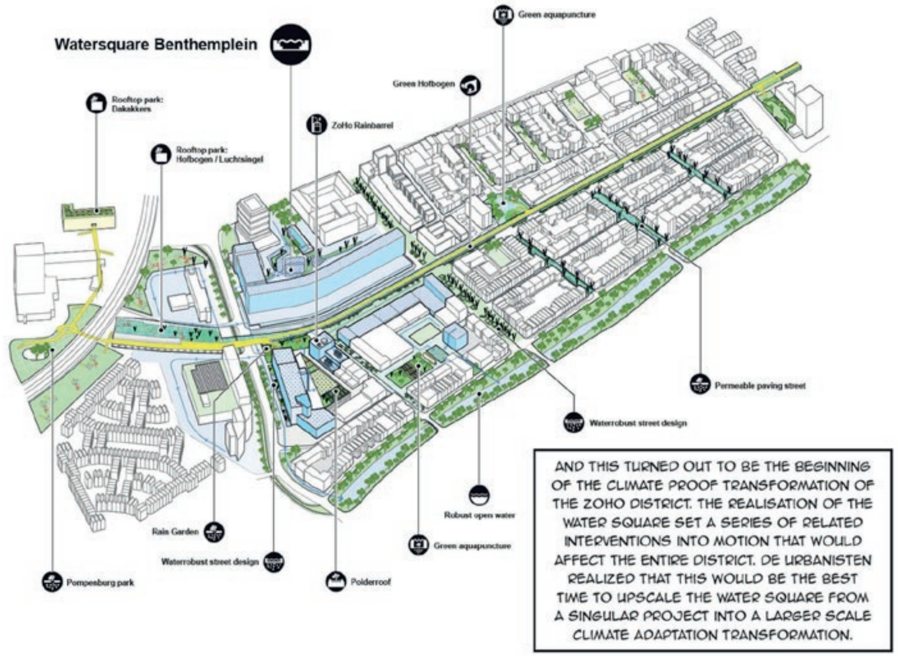
- Water flow regulation
- Climate regulation

Background, aims, and objectives:

The ZOHO raingardens are a part of a larger initiative to explore how Rotterdam's neighbourhoods can become more climate resilient and the raingardens are one of the interventions that can address water-related challenges. The selected neighbourhoods of Zomerhofskwartier and Agniesbuurt are located to the north of the city centre and experience heat, drought, and flood risks.

The aims and objectives of the project were as follows (De Urbanisten, 2016):

Aims	Objectives
Increase (soil) buffer capacity	Reduce total area of impermeable surfaces in the neighbourhood
Decrease effects of drought	Detain and store groundwater to keep groundwater levels high enough to protect building piles
Fighting heat stress	Increase shaded areas with water and vegetation
Reduce soil sealing and reduce car dominance	Remove carparks and replace them with permeable surfaces and where possible convert the spaces in to parks
Experiment with "slow urbanism"	Use bottom up approaches that encourage activation in public gathering places



Visualisation of neighbourhood with locations and measures identified. Image credit: De Urbanisten, 2016.

NBS Outcomes:

A range of solutions were provided for the ZOHO project including extensive green roof "polders", a "water square", rainwater storage solutions, green walls, and raingardens.

Raingardens are a ground-level intervention that is designed to collect rainwater and detain it prior to water either infiltrating to the ground water table, discharged to the stormwater network, or collected in tanks for future reuse.

100 lineal metres of raingarden features were located around three pilot residential blocks and combined in ways that suited the local condition.

Before and after photographs from community workshop implementing swales and gardens in an area of the neighbourhood. Image credit: De Urbanisten, 2016.

Design interventions used:

- Swales with peripheral planting of hydrophytes and other moisture tolerant species
- Planted garden bed trenches alongside buildings
- Depressions for drainage integrated into garden beds

Impacts to climate challenge:

- Benefits were not measured.
- Estimates on the volume of water and experienced decreased temperature were made and using these figures an economic case for the ZOHO proposals was made (van Peijpe, 2016).

Lessons learned:

- Climate adaptation measures should be considered as a part of the housing infrastructure.
- Return on investment time is approximated to be 30 years for all interventions including green roofs, green walls, and stormwater tanks.
- A pilot block is useful for demonstrating the possibilities and benefits of passive drainage and increasing green spaces in the city.
- It is necessary to consider who the beneficiaries and cost bearer of measures so that alternative arrangements can be explored if necessary.

8. The Green Corridor, Antwerp, Belgium

City information:

Land area: 204.5km2

Population: 500,000

Project site area: 380m length

Projected and observed climate change effects: Increase in heavy precipitation events, decrease in snow and ice cover, increase in precipitation and river flow, increased damage risk from winter storms.

NBS Description:

The old city centre neighbourhood of Sint-Andries is vulnerable to flooding and converting parts of the neighbourhood to vegetated and permeable surfaces can increase its resilience to climate change while improving the amenity of the neighbourhood and citizen health and wellbeing.

Climate Challenges:

- Water flow regulation

Background, aims, and objectives:

Sint-Andries is a historic neighbourhood that is particularly subject to climate change because its abundance of hard surfaces amplifies the risks of heat, drought, and flooding. To address this the municipality worked closely with citizens to find a solution that could meet multiple goals.

Consultation with the community identified a desire for more green areas that could be used for recreation and water retention (Frantzeskaki, 2019) and this was integrated into five aims and nine principles in which to achieve the aims (UrbanGreenBlueGrids, 2020):

Aims	Principles
1. Make Sint-Andries a pleasant neighbourhood to live in 2. Convert roofs into multi-functional areas and consider climate adaptation opportunities 3. Increase opportunities for infiltration, detention, and collection of water 4. Increase people's abilities to cope with climate adaptation stresses 5. Stimulate co-creation between different stakeholders in Sint-Andries	1. Sustainability and climate robustness are coherent goals 2. Use a "learning by doing" approach 3. "Maximum support": create an environment that builds support for the project from all parts of society 4. "Social sustainability": inclusion of all members of society and not just the environmentally-conscious 5. "Joining forces": optimise cooperation between all groups and sectors 6. "Learning process in citizen participation": study how cooperation between residents associations and administration can be improved 7. "From neighbourhood to city": scale up experiments in Sint-Andries to the rest of the city 8. "From experiment to policy": promote the adoption of experiment knowledge into government policies 9. "Networking": working together with other EU cities (e.g. Rotterdam) and learn from each other.

NBS Outcomes:

The working groups developed a plan for a "Green Corridor" created from the conversion of a network of streets in the neighbourhood. During community meetings the design of the corridor was created to be climate adaptive while also meeting the desires of the community. Working days were organised where local residents could join in activities to experiment with green interventions in the corridor zone.

Design interventions used:

- Replacing paving stones with garden bed areas
- Experimental rainwater harvesting unit with integrated planting
- Due to the experimental and temporary nature of the "Green Corridor" initiative the outcomes tend towards process-based knowledge rather than spatial outcomes.

Map of affected streets with community "working day" invitation (top). Photographs of types of interventions explored during the event. Image credit: Resilient Europe & Urbact, 2020

Impacts to climate change:

- Benefits were not measured.

Lessons learned:

- Bottom-up approaches were successful for educating citizens about climate change impacts and adaptation.
- Social connections are strengthened by combining social programs with climate resilience initiatives.
- Human resources the for coordinating an initiative of this nature was an identified challenge – finding the right people is important but hard.

9. "The Missing Link" project, Vauxhall, London, U.K.

City information:

Land area: 1,572km2

Population: 8.982 million

Project site area: 1,000m2

Projected and observed climate change effects: Increase in heavy precipitation events, decrease in snow and ice cover, increase in precipitation and river flow, increased damage risk from winter storms.

NBS Description:

The Vauxhall area in London's Southbank is vulnerable to flooding as well as diminished air quality. A small pocket park was proposed to increase permeability in the area by integrating SUDS into the design of the park. This would reduce the risk of localised flooding as well as improving the visual amenity and appeal of local businesses in the area.

Climate Challenges:

- Water flow regulation
- Climate regulation

Background, aims, and objectives:

"The Missing Link" project on Vauxhall Walk in London is one of the Business Interest Districts (BIDs) identified in the Green Capital proposal (Mayor of London, 2016) and, in line with the ambitions of the proposal was a product of a partnership between a private developer, a bank, and local government departments.

The aim of the project was to create a green connection between Vauxhall Park and South Bank to the west. The aims of the project were to create a pleasant environment that encourage people to walk and bicycle in the area while addressing local drainage issues by constructing SUDS as part of an overall greening project.

NBS Outcomes:

The first stage of "The Missing Link" plan was constructed in the southernmost portion of Vauxhall Walk in front of the Tea House Theatre.

Visualisation of proposed "missing link" gardens. Image credit: Mayor of London, 2016.

CASE STUDY PROJECTS

Design measures used:

- Raingardens were installed at ground level and mixed with traditional garden beds
- Permeable walking surfaces in some areas in lieu of traditional impervious paving

Impacts to climate change:

- Benefits were not measured.

Lessons learned:

- Although benefits to climate change were not measured, the pilot project has generated interest in the rest of the area and well received by local businesses with terraces that benefit from the increased attractiveness of the area.
- The success of the project is credited to having a broad partnership of stakeholders, including the local community, to promote consensus about the scheme.
- Financially, the project benefited from early identification of funding partnerships and amounts so that confirmation of the project could be given which then led to confidence in the project being successfully delivered.

REFERENCES

AECOM, & Severn Trent Water. (2013). *The ripple effect - Building resilience of urban water systems to climate change* Retrieved from https://docplayer.net/240510-The-ripple-effect-building-resilience-of-urban-water-systems-to-climate-change-executive-summary-the-case-for-birmingham-and-coventry.html

Barcelona City Council. (2020). *Barcelona Green Infrastructure and Biodiversity Plan 2020*. Barcelona Retrieved from https://ajuntament.barcelona.cat/ecologiaurbana/en/what-we-do-and-why/green-city-and-biodiversity/green-and-biodiversity-plan.

C40 Cities Climate Leadership Group. (2016). *Good Practice Guide - Cool Cities*. Retrieved from http://c40-production-images.s3.amazonaws.com/good_practice_briefings/images/4_C40_GPG_CCN.original.pdf?1456788797

CIRIA. (Demonstrating the multiple benefits of SuDS – A business case (Phase 2)). *2013*. Retrieved from https://www.susdrain.org/files/resources/ciria_guidance/ciria_rp993_literature_review_october_2013_.pdf

City of Berlin. (2020). BAF – Biotope area factor. Retrieved from https://www.berlin.de/sen/uvk/en/nature-and-green/landscape-planning/baf-biotope-area-factor/

De Urbanisten. (2016). Climate proof ZOHO district. Retrieved from https://www.urbanadapt.eu/wp-content/uploads/2016/01/URBANISTEN_climate_adaptive_ZOHO_lr-strippresentatie.pdf

EU Commission. (2015). *Towards an EU Research and Innovation policy agenda for Nature-Based Solutions & Re-Naturing Cities*. Retrieved from Luxembourg:

Frantzeskaki, N. (2019). Seven lessons for planning nature-based solutions in cities. *Environmental science & policy, 93*, 101-111.

GrowGreen. (2019). GrowGreen: Approches to financing nature-based solutions in cities - Draft, November 2019. In L. Baroni, G. Nicholls, & K. Whiteoak (Eds.).

IUCN. (2016). *Nature-based Solutions to address global societal challenges.* Retrieved from Gland, Switzerlans: www.iucn.org/resources/publications

Kopetzki, S. (2014). Berlin Biotope Area Factor – Implementation of guidelines helping to control temperature and runoff. Retrieved from https://climate-adapt.eea.europa.eu/metadata/case-studies/berlin-biotope-area-factor-2013-implementation-of-guidelines-helping-to-control-temperature-and-runoff/#cost_benefit_anchor

Mayor of London. (2016). *Green Capital - Green Infrastructure for a future city*. Retrieved from London: https://www.london.gov.uk/sites/default/files/green_capital.pdf

RCI. (2013). *Rotterdam Climate Change Adaptation Strategy*. Retrieved from Rotterdam: http://www.urbanisten.nl/wp/wp-content/uploads/UB_RAS_EN_lr.pdf

Resilient Europe, & Urbact. (2020). Integrated Action Plan for Urban Resilience. In.

Rijkswaterstaat. (2020). Maatregelen rivierengebied. Retrieved from https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/ruimte-voor-de-rivieren/maatregelen-rivierengebied/index.aspx

CASE STUDY PROJECTS

Somarakis, G., Stagakis, S., & Chysoulakis, N. (2019). *ThinkNature NAture-Based Solutions Handbook*.

ThinkNature. (2018). *NBS case study: Malmo*. Retrieved from https://www.think-nature.eu/wp-content/uploads/2018/08/15a-Case-studies-Malm%C3%B6-NBS-MS-workshop.pdf

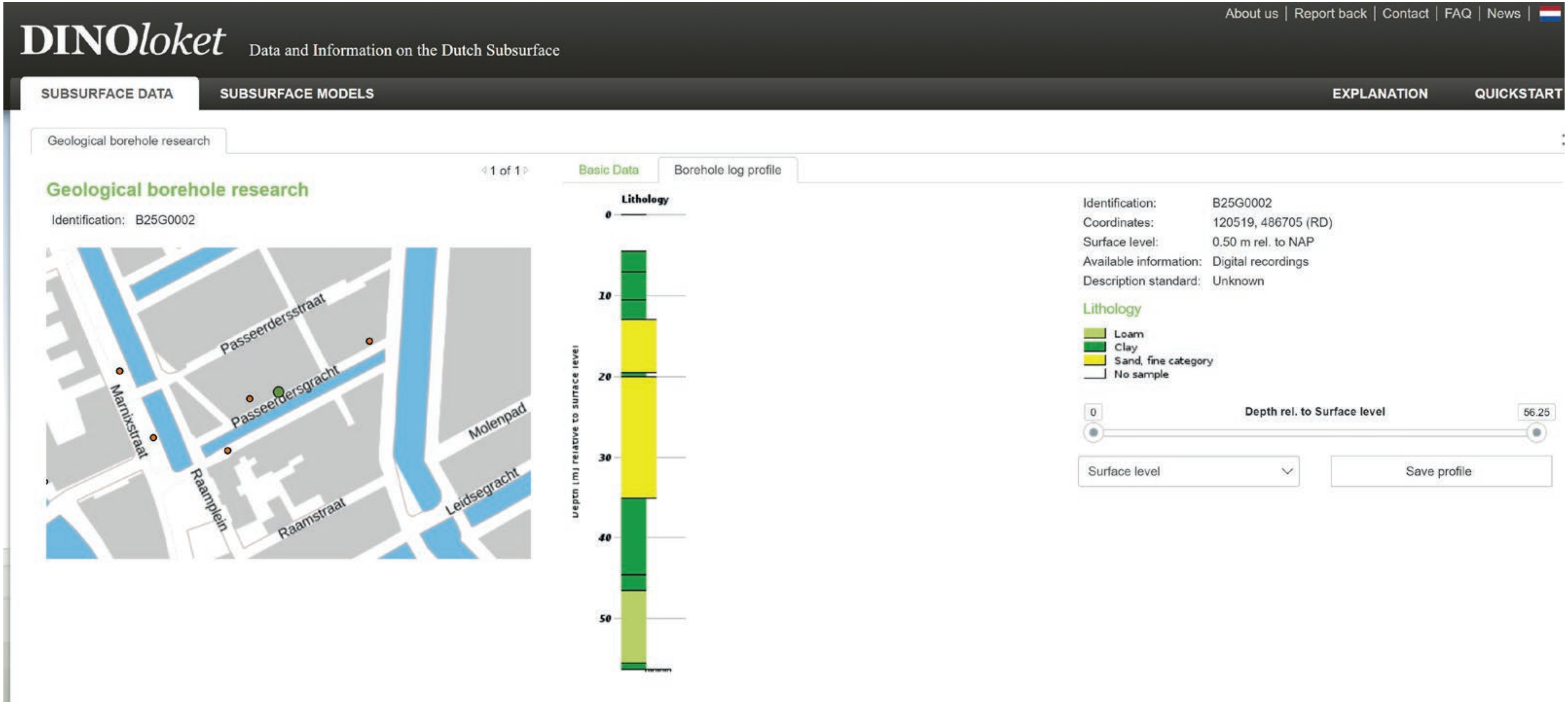
UrbanGreenBlueGrids. (2020). Sint-Andries: working together towards a climate robust neighbourhood. In.

van Peijpe, D. (2016). KLIMAATBLOK AGNIESEBUURT / ZOMERHOFKWARTIER: Impact Project klimaatbestendig inrichten van corporatiebezit op blok- en buurtniveau In.

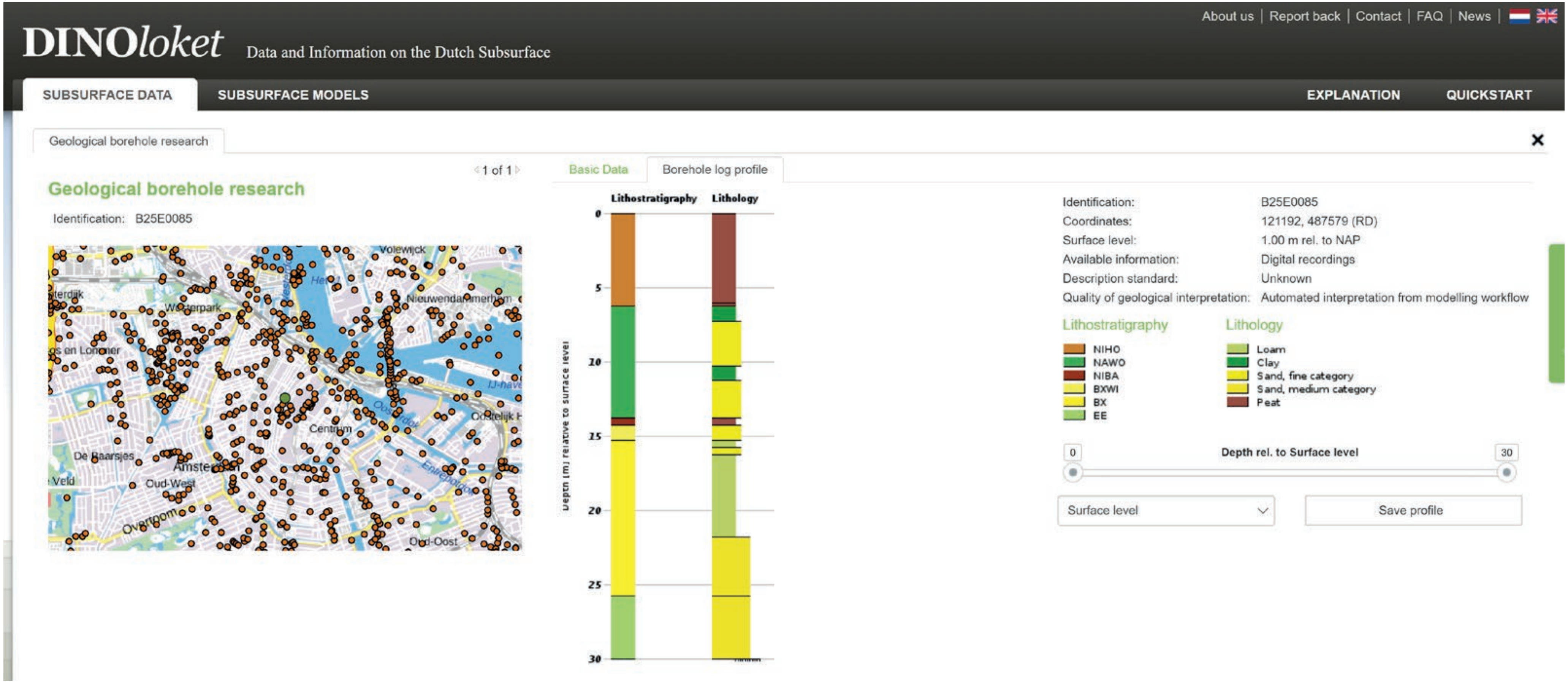
Subsurface data from DINOloket which is an online database created by the Geological Survey of the Netherlands together with the Netherlands Organisation for Applied Scientific Research (TNO).

Reference:
DINOloket. (2020). Subsurface Data. Retrieved from https://www.dinoloket.nl/en/subsurface-data

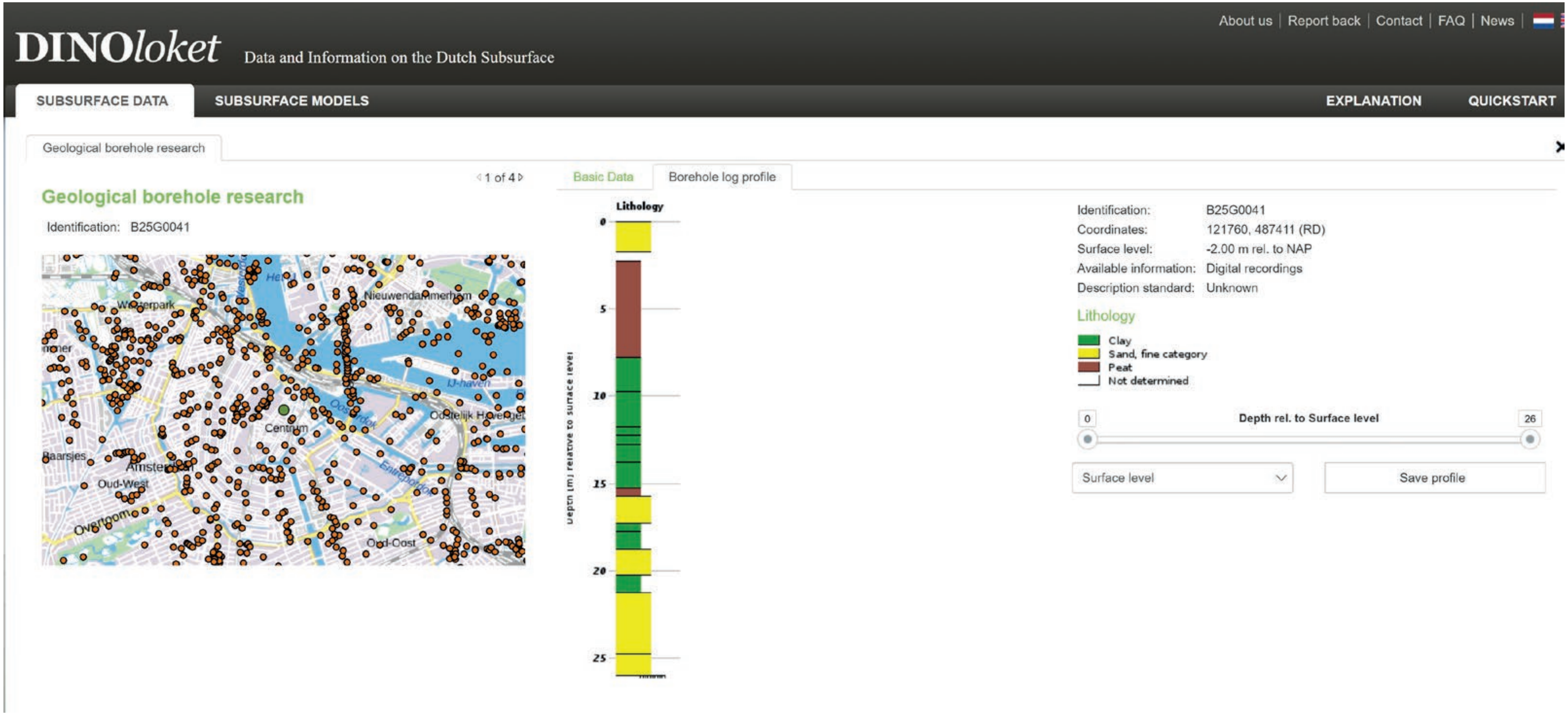
Scenario 1: Passeerdersgracht, Passeerdersgrachtbuurt, Centrum.



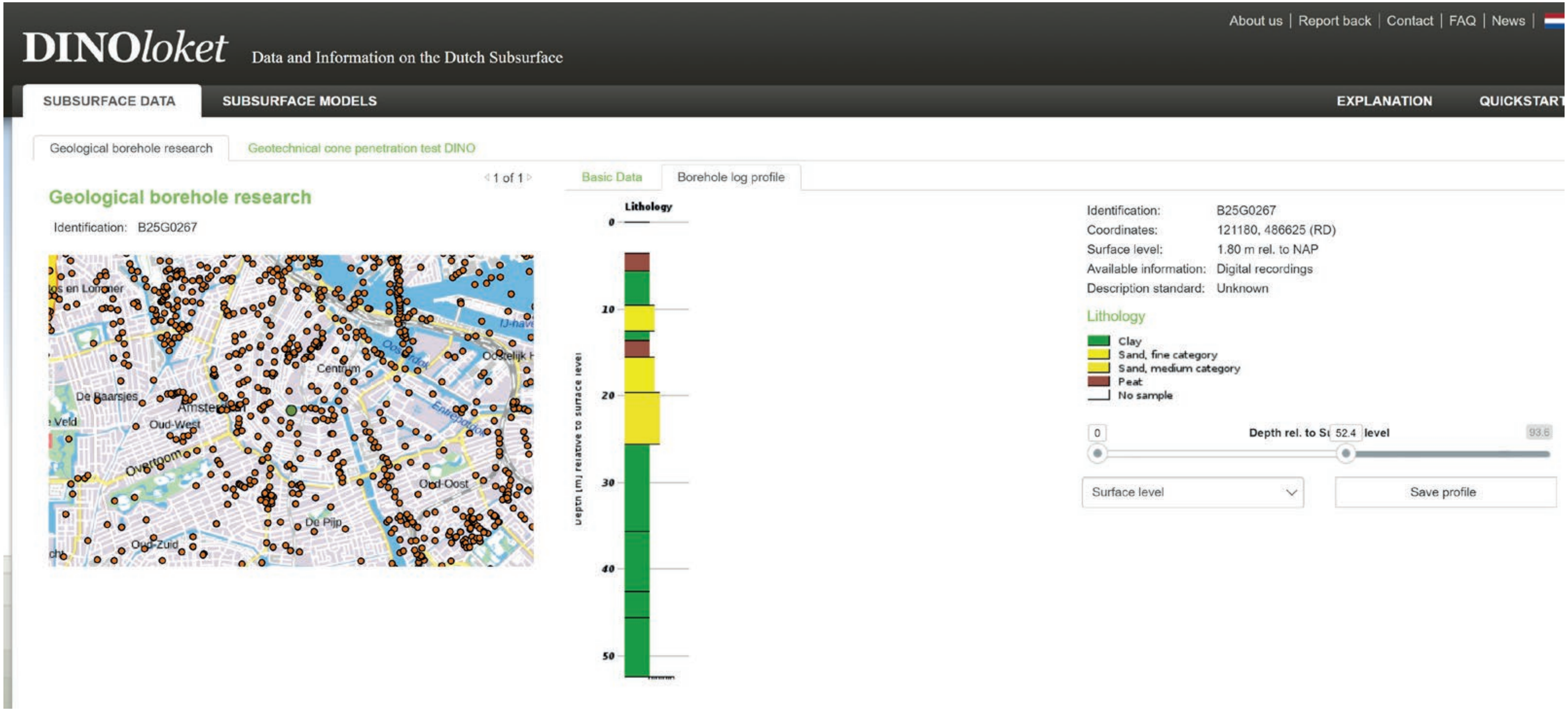
Scenario 2: Singel, Spuistraat Noord, Centrum.



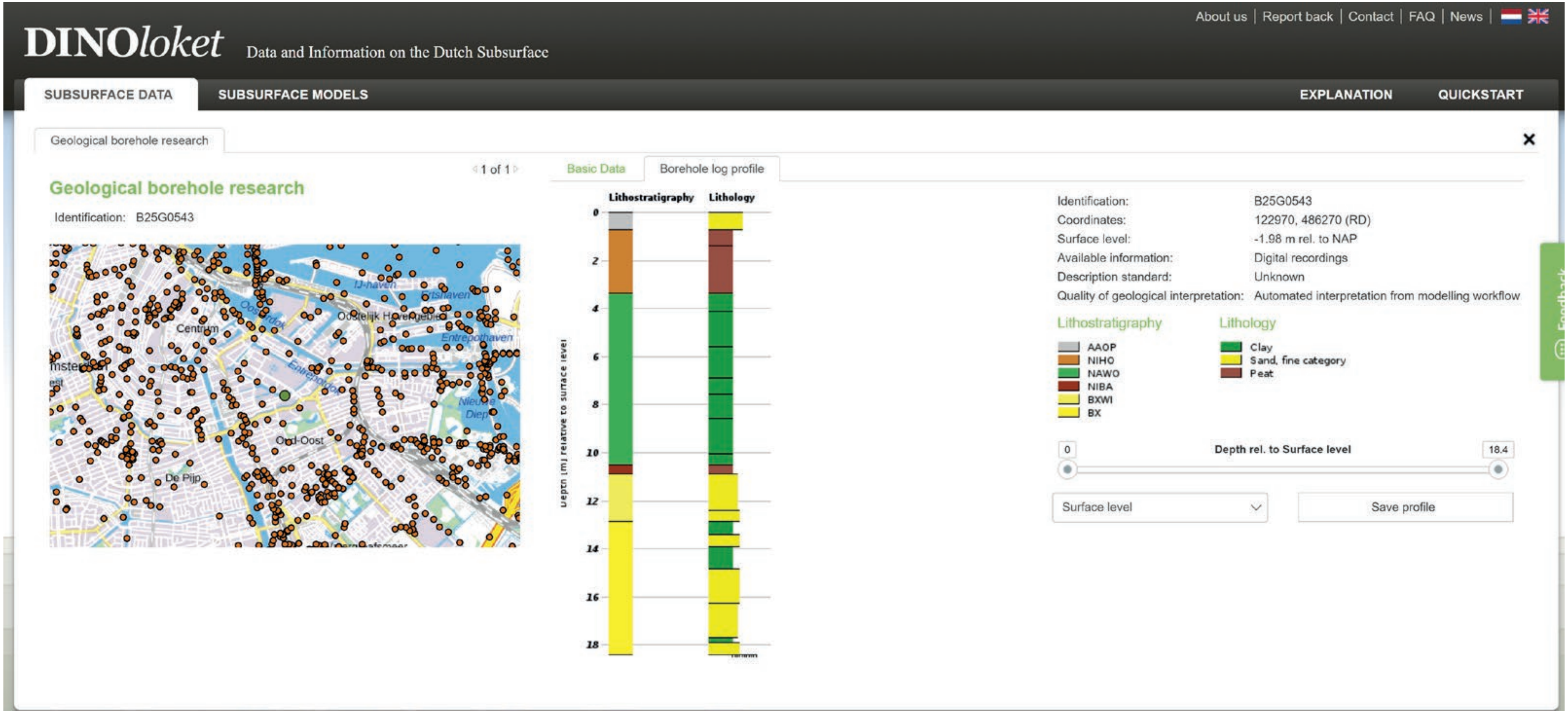
Scenario 3: Oudezijds Voorburgwal, Oude Kerk, Centrum.



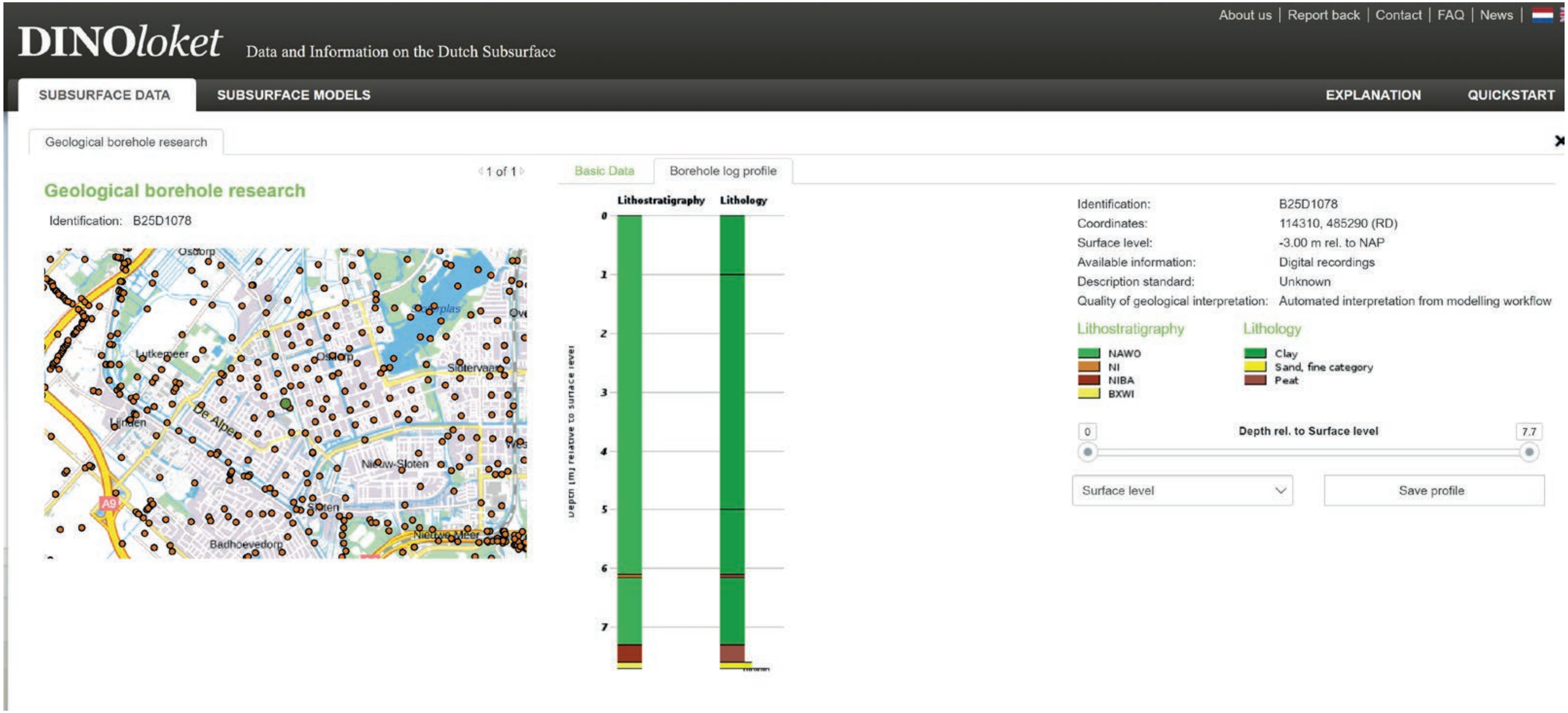
Scenario 4: Singel, Reguliersbuurt, Centrum.



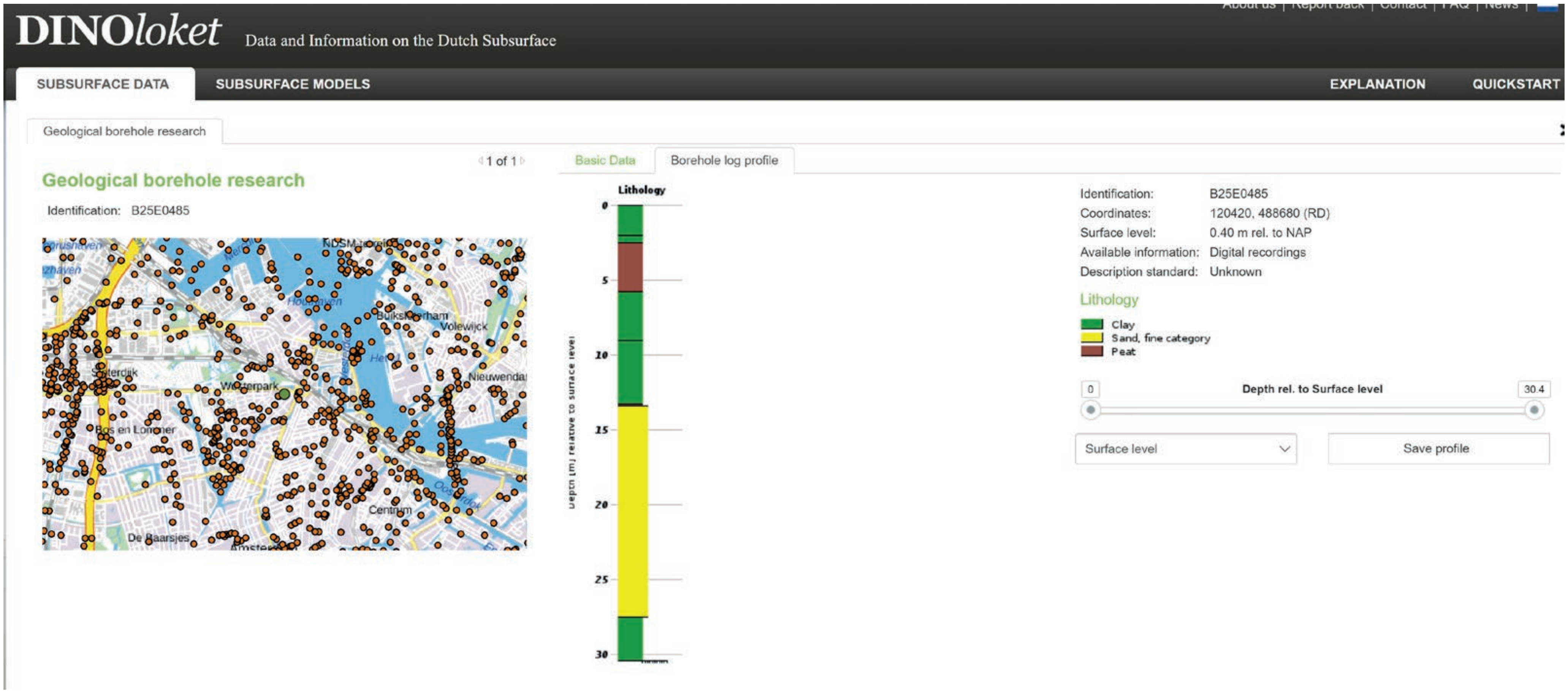
Scenario 5: Plantage Muidergracht, Plantage, Centrum.



Scenario 6: Korte Water, De Punt, Nieuw West.



Scenario 7: De Wittenkade, Staatsliedenbuurt Noordoost, West.



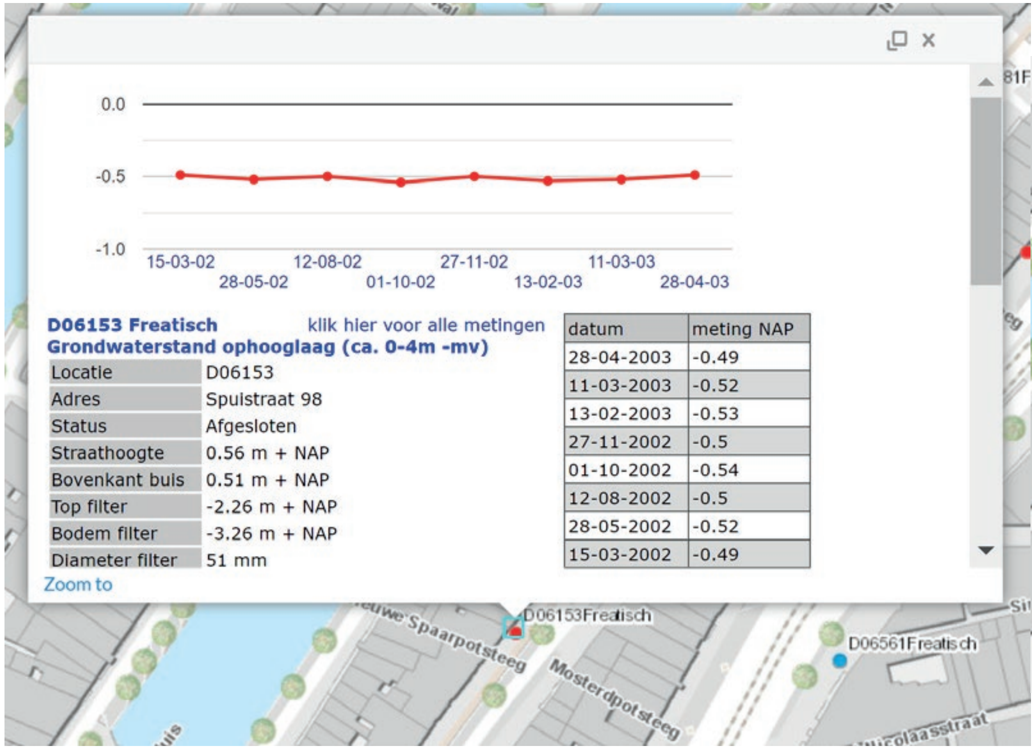
H. WATERNET PEILBUIZEN DATA FOR LANDSCAPE SCENARIO SITES

Groundwater table heights and finished surface levels are taken from the most recent reading of the closest monitoring station to the site. The groundwater monitoring data is taken from Waternet's "Peilbuizen" – monitoring wells – website that contains level measurements taken by Waternet.

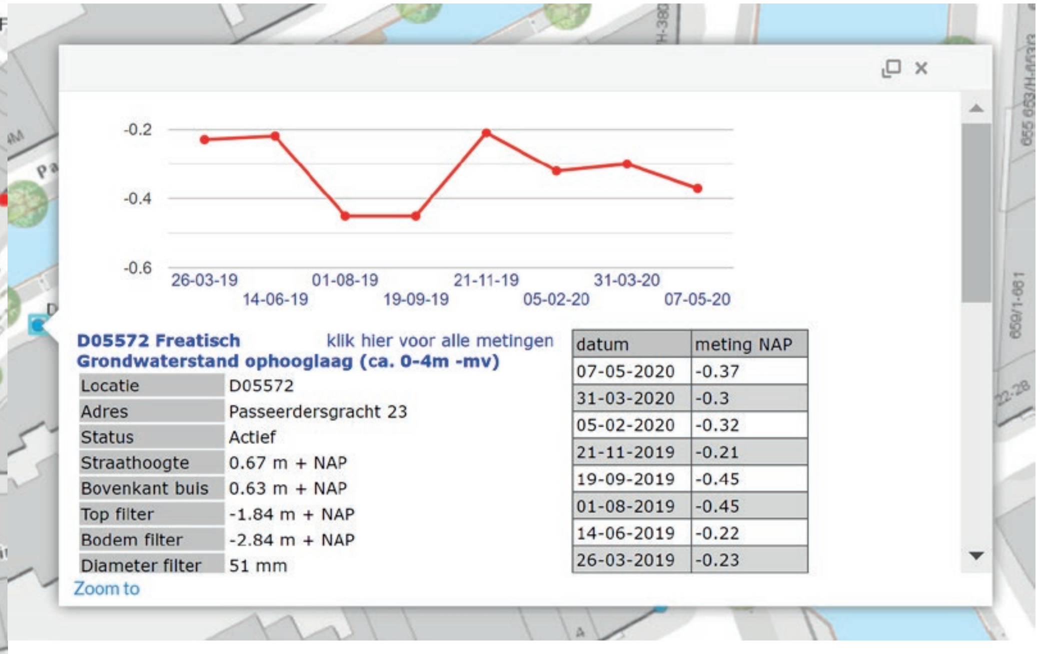
Reference:

Waternet. (2020). Peilbuizen. Retrieved from https://maps.waternet.nl/kaarten/peilbuizen.html

Scenario 1: Passeerdersgracht, Passeerdersgrachtbuurt, Centrum.

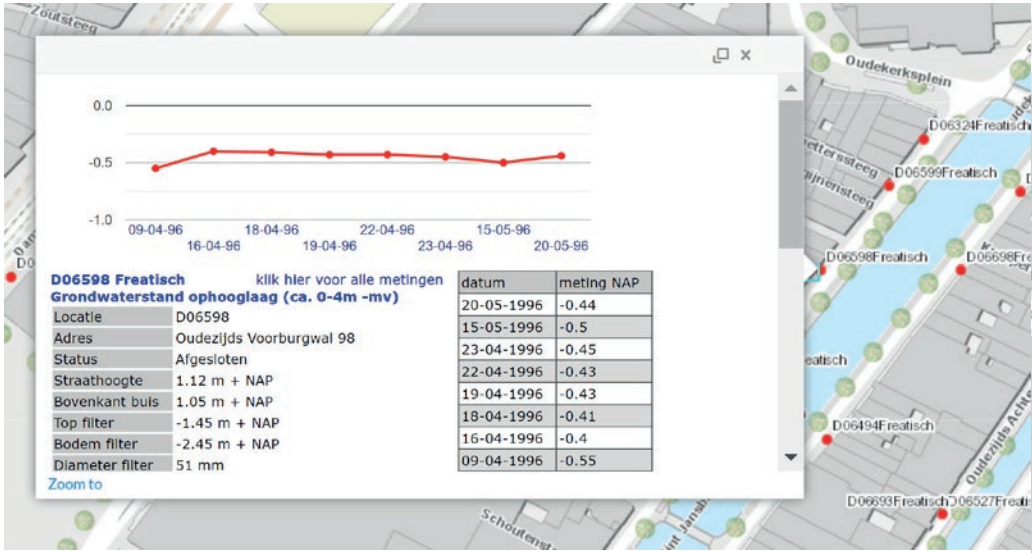


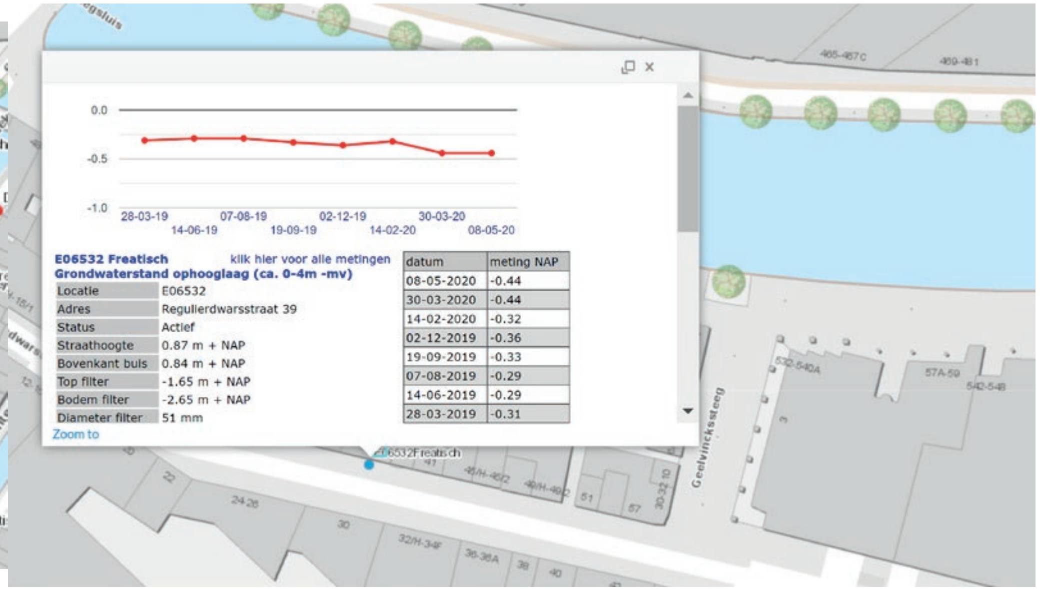
Scenario 2: Singel, Spuistraat Noord, Centrum.



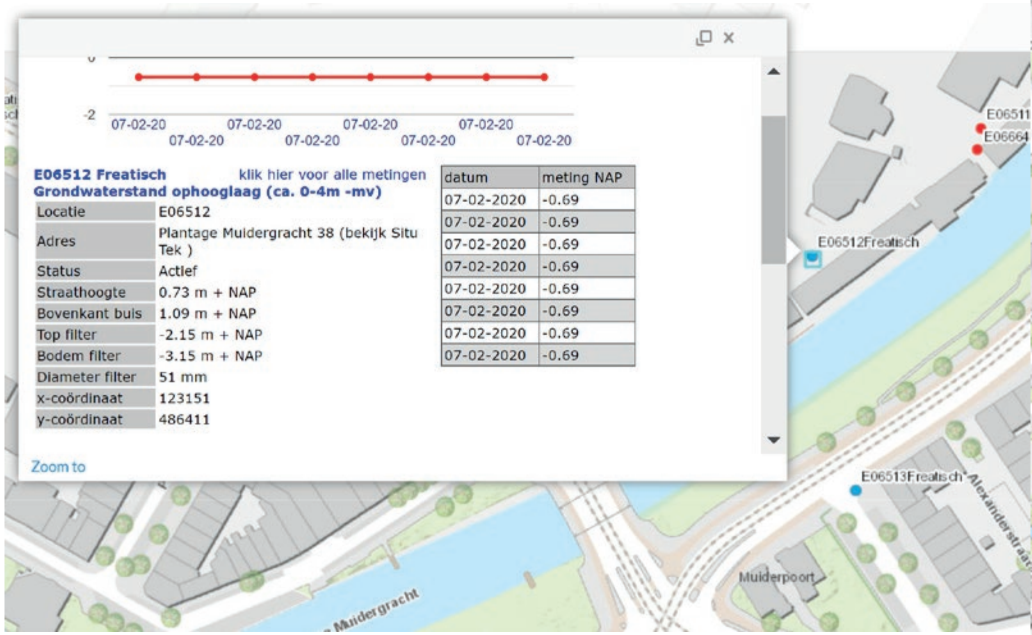
Scenario 3: Oudezijds Voorburgwal, Oude Kerk, Centrum.

Scenario 4: Singel, Reguliersbuurt, Centrum.

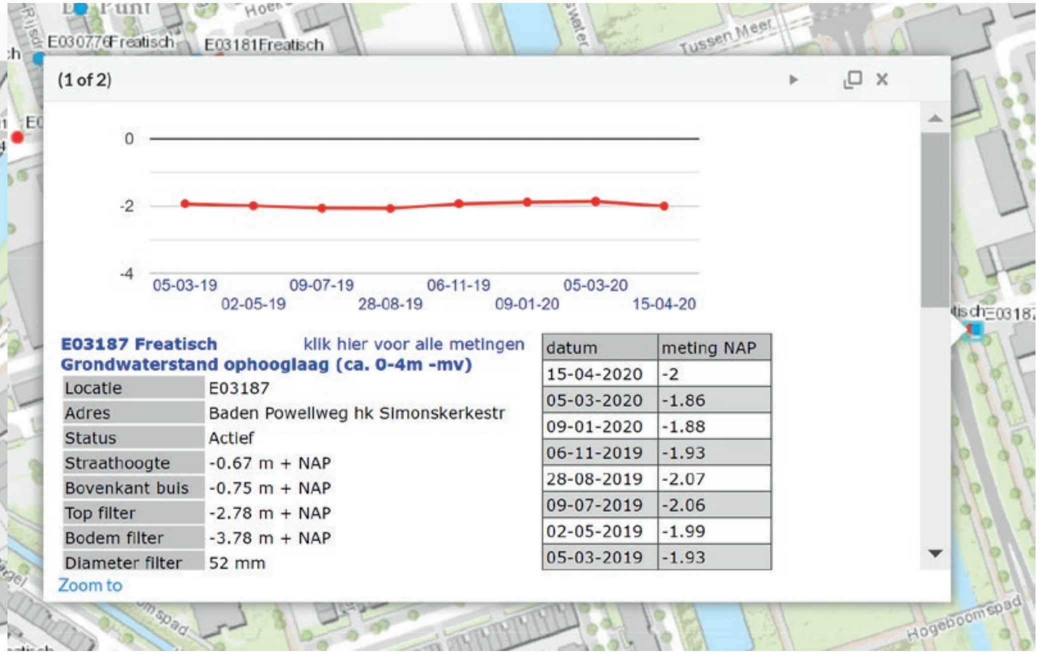




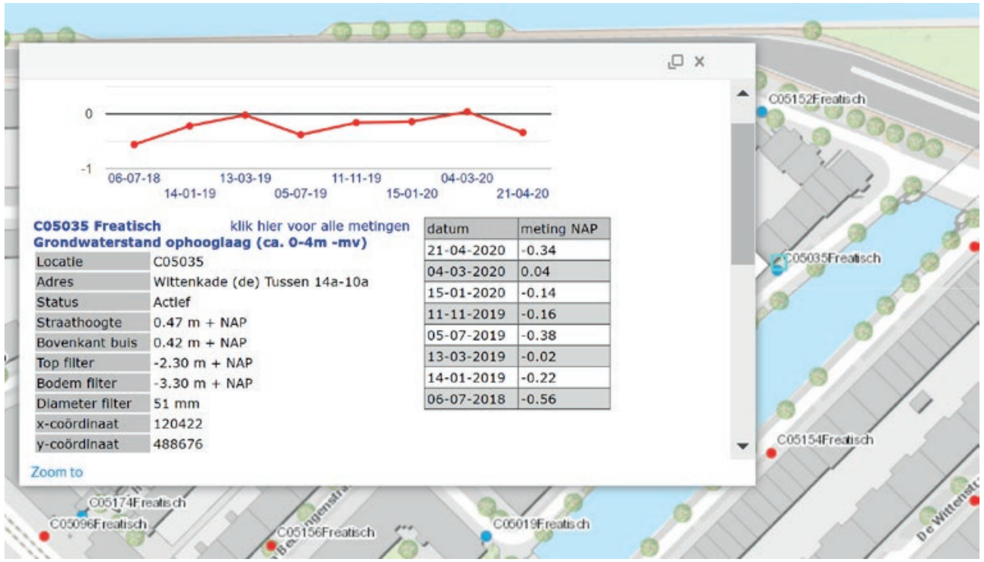
Scenario 5: Plantage Muidergracht, Plantage, Centrum.



Scenario 6: Korte Water, De Punt, Nieuw West.



Scenario 7: De Wittenkade, Staatsliedenbuurt Noordoost, West.



I. LANDSCAPE SCENARIO SITES: COMBINED IMPACT AND VULNERABILITY S CORE

		replace				reinforce				reduce			
		Passeerdersgrachtbuurt		Spuistraat Noord		Reguliersbuurt		Oude Kerk e.o.		De Punt (1970)		Staatsliedenbuurt Noordoost (2020)		Plantage (2020	
		PASSEERDERSGRACHT		SINGEL		SINGEL		OUDESIZJDS BURGWAL		KORTE WATER		DE WITTENKADE			
QW	Pop. Density	1	33236 P/KM2	1	33236 P/KM2	2	12560 P/KM2	2	12560 P/KM2	1	33236 P/KM2	1	33236 P/KM2	3	5036 P/KM2
	% Area quay wall	1	6.19	1	6.19	2	0.45	2	0.45	1	6.19	1	6.19	2	0.45
DROUGHT	GWL drop in summer (trend)	1	up to 8m	1	up to 8m	1	up to 8m	1	up to 8m	1	up to 8m	1	up to 8m	1	up to 8m
	Annual precipitation deficit (current to 2050WH trend)	2	90mm	2	90mm	2	90mm	2	90mm	2	90mm	1	120mm	2	90mm
	Signficant groundwater level change (2050WH)	1	yes	1	yes	1	yes	1	yes	2	no change	2	no change	2	no change
HEAT	PET temperature at waterfront (current)	1	>41C	1	>41C	1	>41C	1	>41C	2	<41C	2	<41C	2	<41C
	No. days heat released from water (current)	1	>10 days	1	>10 days	1	>10 days	1	>10 days	1	>10 days	1	>10 days	1	>10 days
	Continuous days of night time temperatures (Current)	2	<1 week	1	>1 week	1	>1 week	1	>1 week	2	<1 week	2	<1 week	2	<1 week
	Continuous days of night time temperatures (2050WH Scenario)	1	>1 week	1	>1 week	1	>1 week	1	>1 week	1	>1 week	1	>1 week	1	>1 week
FLOOD	Increased number of days with >15mm rain (current)	1	4 more days	1	4 more days	1	4 more days	1	4 more days	2	4 more days	1	4 more days	1	4 more days
	Flood depth during 1:1000 year event (current)	1	>200mm	1	>200	1	>200	1	>200	1	>200	1	>200	1	>200
	Flood depth during 1:100 year event (current)	1	>200mm	1	>200	1	>200	1	>200	1	>200	1	>200	1	>200
	Fluvial flood depth during 1:100 year event (current)	no data	n/a	no data		no data		no data		1	>200	no data		no data	
	Chance of >200mm deep flooding in 1:100 year fluvial event (2050WH)	no data	n/a	no data		no data		no data		1	more than moderately high chance	no data		no data	

J. MEASUREMENTS OF RESULTS FOR LANDSCAPE SCENARIO SITES

		Scenario Site Location & Renovation type	PASSEERDERSGRACHT, Passeerdersgrachtbuurt, Replace				SINGEL, Spuistraat Noord, Replace			
Functional requirements to delay quay wall replacement	**Indicator**	**Measurement**	**New**	**Existing**	**Difference**	**% change**	**New**	**Existing**	**Difference**	**% change**
Reduce heavy loads next to the wall	Removal of materials or functions which involve the use of heavy machinery or objects behind the wall on land side.	M2 area directly next to the wall without carparking or loading areas for heavy vehicles (existing amount shown for comparison)	92	306	214	70%	102	432	330	76%
As above	As above	M2 area with brick or concrete paving (existing amount shown for comparison)	651	791	140	18%	855	1008	153	15%
Reduce fluctuations in groundwater table level	Increase infiltration of water through the soil to recharge ground water table.	M2 area designed to be permeable to water	828	47	781	1762%	1094	95	999	1152%
Regulate temperatures around the quay wall structure	Decrease exposure of wall components and improve cooling abilities of the structure and surfaces adjacent to it.	M2 area containing plants and/or trees	140	47	93	298%	185	95	90	195%
Protect canal bed from erosion	Decrease exposure of canal bed to scouring forces caused by water traffic.	Lineal metres where wall is protected from scouring	new wall	new wall	-	-	new wall	new wall	-	-
Reduce live loads next to the wall	Stabilisation of trees next to quay walls.	Installation of tree root anchors and/or tree guards.	excluded from scope							
Functional requirements for climate adaptation										
Increase infiltration to soil – Drought, Flood	Increase permeability of ground surface and/or drain to areas that are permeable	M2 area designed to be permeable to water	as above							
Increase water storage areas for future re-use or for controlled discharge to stormwater network – Drought, Flood	Construct water storage areas and make necessary connections for storage and/or discharge	M2 area designed to collect and detain water for future reuse or discharge	140	0	140	-	153	0	153	-
Use plants and trees that are able to withstand heat, drought, and flood – All	Location-specific species selection	Species name (if any)	excluded from scope							
Provide additional areas that can be temporarily inundated and drained at a later time – Flood	Plan and construct areas where water can be collected in case of overflow to other areas in the street	M2 area designed to collect and detain water for future reuse or discharge	as above							
Reduce use of materials with high thermal mass - Heat	Remove or replace materials with materials that have better thermal properties	M2 area where brick or concrete paving has been removed	as above							
Increase use of broadleaf vegetation to increase evapotranspiration - Heat	Species selection	Species name (if any)	excluded from scope							
Shade or cover building surfaces to reduce heat absorption and release - Heat	Provide space and necessary supporting structures to shade surfaces from direct sunlight	Number of trees added (m2 area of planted areas calculated above)	0	6	-6	-100%	26	8	18	325%

		Scenario Site Location & Renovation type	OUDESIZJDS VOORBURGWAL, Oude Kerk, Reinforce				SINGEL, Reguliersbuurt, Reinforce					
Functional requirements to delay quay wall replacement	**Indicator**	**Measurement**	**New**	**Existing**	**Difference**	**% change**	**New**	**Existing**	**Difference**	**% change**		
Reduce heavy loads next to the wall	Removal of materials or functions which involve the use of heavy machinery or objects behind the wall on land side.	M2 area directly next to the wall without carparking or loading areas for heavy vehicles (existing amount shown for comparison)	0	120	120	100%	0	0	0	-		
As above	As above	M2 area with brick or concrete paving (existing amount shown for comparison)	11	150	139	93%	562	609	47	8%		
Reduce fluctuations in groundwater table level	Increase infiltration of water through the soil to recharge ground water table.	M2 area designed to be permeable to water	132	36	96	367%	47	0	47	-	0	720
Regulate temperatures around the quay wall structure	Decrease exposure of wall components and improve cooling abilities of the structure and surfaces adjacent to it.	M2 area containing plants and/or trees	84	36	48	233%	49	0	49	-	0	720
Protect canal bed from erosion	Decrease exposure of canal bed to scouring forces caused by water traffic.	Lineal metres where wall is protected from scouring	28	0	28	-	6	0	6	-		
Reduce live loads next to the wall	Stabilisation of trees next to quay walls.	Installation of tree root anchors and/or tree guards.										
Functional requirements for climate adaptation												
Increase infiltration to soil – Drought, Flood	Increase permeability of ground surface and/or drain to areas that are permeable	M2 area designed to be permeable to water										
Increase water storage areas for future re-use or for controlled discharge to stormwater network – Drought, Flood	Construct water storage areas and make necessary connections for storage and/or discharge	M2 area designed to collect and detain water for future reuse or discharge	154	0	154	-	0	0	0	-		
Use plants and trees that are able to withstand heat, drought, and flood – All	Location-specific species selection	Species name (if any)										
Provide additional areas that can be temporarily inundated and drained at a later time – Flood	Plan and construct areas where water can be collected in case of overflow to other areas in the street	M2 area designed to collect and detain water for future reuse or discharge										
Reduce use of materials with high thermal mass - Heat	Remove or replace materials with materials that have better thermal properties	M2 area where brick or concrete paving has been removed										
Increase use of broadleaf vegetation to increase evapotranspiration - Heat	Species selection	Species name (if any)										
Shade or cover building surfaces to reduce heat absorption and release - Heat	Provide space and necessary supporting structures to shade surfaces from direct sunlight	Number of trees added (m2 area of planted areas calculated above)	0	5	0	0%	0	1	0	0%		

Scenario Site Location & Renovation type			KORTE WATER, De Punt, Reinforce				DE WITTENKADE, Staatsliedenbuurt Noordoost, Reduce			
Functional requirements to delay quay wall replacement	**Indicator**	**Measurement**	**New**	**Existing**	**Difference**	**% change**	**New**	**Existing**	**Difference**	**% change**
Reduce heavy loads next to the wall	Removal of materials or functions which involve the use of heavy machinery or objects behind the wall on land side.	M2 area directly next to the wall without carparking or loading areas for heavy vehicles (existing amount shown for comparison) -	0	0	0	-	0	120	120	100%
As above	As above	M2 area with brick or concrete paving (existing amount shown for comparison) 8%	0	0	0	-	38	142	104	73%
Reduce fluctuations in groundwater table level	Increase infiltration of water through the soil to recharge ground water table.	M2 area designed to be permeable to water -	0	720	0	-	200	64	136	313%
Regulate temperatures around the quay wall structure	Decrease exposure of wall components and improve cooling abilities of the structure and surfaces adjacent to it.	M2 area containing plants and/or trees -	0	720	0	-	97	64	0	152%
Protect canal bed from erosion	Decrease exposure of canal bed to scouring forces caused by water traffic.	Lineal metres where wall is protected from scouring	15	0	15	-	21	0	21	-
Reduce live loads next to the wall	Stabilisation of trees next to quay walls.	Installation of tree root anchors and/or tree guards.								
Functional requirements for climate adaptation										
Increase infiltration to soil – Drought, Flood	Increase permeability of ground surface and/or drain to areas that are permeable	M2 area designed to be permeable to water								
Increase water storage areas for future re-use or for controlled discharge to stormwater network – Drought, Flood	Construct water storage areas and make necessary connections for storage and/or discharge	M2 area designed to collect and detain water for future reuse or discharge -	360	0	360	-	200	0	200	-
Use plants and trees that are able to withstand heat, drought, and flood – All	Location-specific species selection	Species name (if any)								
Provide additional areas that can be temporarily inundated and drained at a later time – Flood	Plan and construct areas where water can be collected in case of overflow to other areas in the street	M2 area designed to collect and detain water for future reuse or discharge								
Reduce use of materials with high thermal mass - Heat	Remove or replace materials with materials that have better thermal properties	M2 area where brick or concrete paving has been removed								
Increase use of broadleaf vegetation to increase evapotranspiration - Heat	Species selection	Species name (if any)								
Shade or cover building surfaces to reduce heat absorption and release - Heat	Provide space and necessary supporting structures to shade surfaces from direct sunlight	Number of trees added (m2 area of planted areas calculated above) 0%	6	3	0	200%	0	8	0	0%

		Scenario Site Location & Renovation type	PLANTAGE MUIDERSGRACHT, Plantage, Reduce			
Functional requirements to delay quay wall replacement	**Indicator**	**Measurement**	**New**	**Existing**	**Difference**	**% change**
Reduce heavy loads next to the wall	Removal of materials or functions which involve the use of heavy machinery or objects behind the wall on land side.	M2 area directly next to the wall without carparking or loading areas for heavy vehicles (existing amount shown for comparison)	0	0	0	-
As above	As above	M2 area with brick or concrete paving (existing amount shown for comparison)	0	132	132	100%
Reduce fluctuations in groundwater table level	Increase infiltration of water through the soil to recharge ground water table.	M2 area designed to be permeable to water	143	0	143	-
Regulate temperatures around the quay wall structure	Decrease exposure of wall components and improve cooling abilities of the structure and surfaces adjacent to it.	M2 area containing plants and/or trees	132	11	0	1200%
Protect canal bed from erosion	Decrease exposure of canal bed to scouring forces caused by water traffic.	Lineal metres where wall is protected from scouring	30	0	30	-
Reduce live loads next to the wall	Stabilisation of trees next to quay walls.	Installation of tree root anchors and/or tree guards.				
Functional requirements for climate adaptation						
Increase infiltration to soil – Drought, Flood	Increase permeability of ground surface and/or drain to areas that are permeable	M2 area designed to be permeable to water				
Increase water storage areas for future re-use or for controlled discharge to stormwater network – Drought, Flood	Construct water storage areas and make necessary connections for storage and/or discharge	M2 area designed to collect and detain water for future reuse or discharge	29	0	29	-
Use plants and trees that are able to withstand heat, drought, and flood – All	Location-specific species selection	Species name (if any)				
Provide additional areas that can be temporarily inundated and drained at a later time – Flood	Plan and construct areas where water can be collected in case of overflow to other areas in the street	M2 area designed to collect and detain water for future reuse or discharge				
Reduce use of materials with high thermal mass - Heat	Remove or replace materials with materials that have better thermal properties	M2 area where brick or concrete paving has been removed				
Increase use of broadleaf vegetation to increase evapotranspiration - Heat	Species selection	Species name (if any)				
Shade or cover building surfaces to reduce heat absorption and release - Heat	Provide space and necessary supporting structures to shade surfaces from direct sunlight	Number of trees added (m2 area of planted areas calculated above)	0	2	0	0%

10. REFERENCES

Andersson, E., Borgström, S., & McPhearson, T. (2017). Double Insurance in Dealing with Extremes: Ecological and Social Factors for Making Nature-Based Solutions Last. In N. Kabisch, H. Korn, J. Stadler, & A. Bonn (Eds.), Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice (pp. 51-64). Cham: Springer International Publishing.

Anguelovski, I., Irazábal-Zurita, C., & Connolly, J. J. T. (2019). Grabbed Urban Landscapes: Socio-spatial Tensions in Green Infrastructure Planning in Medellín GRABBED URBAN LANDSCAPES. *International Journal of Urban and Regional Research, 43*(1), 133-156. doi:10.1111/1468-2427.12725

Berents, R., & Straver, H. (2016). Watervisie 2016-2040. In R. e. D. v. d. G. Amsterdam (Ed.). Amsterdam.

Bohemen, H. v. (2012). *(Eco)System Thinking: Ecological Principles for Buildings, Roads and Industrial and Urban Areas.* Dordrecht: Springer.

Brink, A. v. d., Bruns, D., Tobi, H., & Bell, S. (2017). *Research in landscape architecture : methods and methodology*. Abingdon, Oxon ;: Routledge, an imprint of the Taylor & Francis Group.

CBD. (2009a). *Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change.* Retrieved from Montreal, Canada:
CBD. (2009b). *The Ecosystem Approach: Advanced User Guide*. Retrieved from https://www.cbd.int/ecosystem/sourcebook/advanced-guide/

CBD. (2010). Ecosystem Approach - Definition. Retrieved from https://www.cbd.int/ecosystem/description.shtml

CBD. (2012). *Ecosystem Services*. Convention on Biological Diversity, United Nations Environment Programme (UNEP) Retrieved from https://www.cbd.int/undb/media/factsheets/undb-factsheet-ecoserv-en.pdf.

CBS Netherlands. (2017). Amsterdam is expanding, mainly due to immigration. Retrieved from https://www.cbs.nl/en-gb/news/2017/45/amsterdam-is-expanding-mainly-due-to-immigration

Chapin, F. S., Carpenter, S. R., Kofinas, G. P., Folke, C., Abel, N., Clark, W. C., . . . Swanson, F. J. (2010). Ecosystem stewardship: sustainability strategies for a rapidly changing planet. *Trends in Ecology & Evolution, 25*(4), 241-249. doi:https://doi.org/10.1016/j.tree.2009.10.008

Coenen, L., Benneworth, P., & Truffer, B. (2012). Toward a spatial perspective on sustainability transitions. *Research Policy, 41*(6), 968.

Cohen-Shacham, E., Andrade, A., Dalton, J., Dudley, N., Jones, M., Kumar, C., . . . Walters, G. (2019). Core principles for successfully implementing and upscaling Nature-based Solutions. *Environmental Science and Policy, 98*, 20-29. doi:10.1016/j.envsci.2019.04.014

Commissioner, D. P. (2019). *Delta Programme 2019 Continuing the work on the delta: adapting the Netherlands to climate change in time*. Retrieved from https://english.deltacommissaris.nl/documents/publications/2018/09/18/dp2019-en-printversie.

Cork, S., & Chamberlain, N. (2015). *Old Waterfront Walls*. Retrieved from London:
Cross, N. (2006). *Designerly ways of knowing*. In. Retrieved from http://public.eblib.com/choice/publicfullrecord.aspx?p=303690 Retrieved from doi:10.1007/1-84628-301-9.

Davoudi, S., & Sturzaker, J. (2017). Urban form, policy packaging and sustainable urban metabolism. *Resources, Conservation and Recycling, 120*, 55-64. doi:https://doi.org/10.1016/j.resconrec.2017.01.011

de Gijt, J. (2020). *History and background: Quay walls in Amsterdam* Paper presented at the Quay wall mini symposium Online, Amsterdam.
De Urbanisten. (2016). Climate proof ZOHO district. Retrieved from https://www.urbanadapt.eu/wp-content/uploads/2016/01/URBANISTEN_climate_adaptive_ZOHO_lr-strippresentatie.pdf

Deppisch, S. (2017). Cities and Urban Regions Under Change—Between Vulnerability, Resilience, Transition and Transformation. In S. Deppisch (Ed.), *Urban Regions Now & Tomorrow: Between vulnerability, resilience and transformation* (pp. 1-15). Wiesbaden: Springer Fachmedien Wiesbaden.

EU Commission. (2013). *Green Infrastructure (GI) — Enhancing Europe's Natural Capital*. Brussels Retrieved from https://eur-lex.europa.eu/resource.html?uri=cellar:d41348f2-01d5-4abe-b817-4c73e6f1b2df.0014.03/DOC_1&format=PDF.

EU Commission. (2015). *Towards an EU Research and Innovation policy agenda for Nature-Based Solutions & Re-Naturing Cities*. Retrieved from Luxembourg:

Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., & Vandewoestijne, S. (2017). Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. *Environ Res, 159*, 509-518. doi:10.1016/j.envres.2017.08.032

Feddes, F., & Mader, D. H. (2012). *A millennium of Amsterdam : spatial history of a marvellous city*. Bussum: THOTH.

Frantzeskaki, N. (2019). Seven lessons for planning nature-based solutions in cities. *Environmental science & policy, 93*, 101-111.

Gemeente Amsterdam. (2019). *Actieplan bruggen en kademuren* Amsterdam: Gemeente Amsterdam Retrieved from https://assets.amsterdam.nl/publish/pages/935382/actieplan_programma_bruggen_en_kademuren_juli_2019.pdf.

Gemeente Amsterdam. (2020). Agenda Amsterdam Autoluw. Retrieved from https://www.amsterdam.nl/parkeren-verkeer/agenda-amsterdam-autoluw/#h2c3c7e43-8e83-49c0-b41e-18372113b085

Gerber, A., Kurath, S., Schurk, H., & Zuger, R. (2018). *Handbook of Methods for Architecture and Urban Design*. Zurich.

Gijt, J. G. d. (2010). *A history of quay walls : techniques, types, costs and future.* s.n.], [S.l. WorldCat.org database.

Goldbohm, P. C. R., Wolfert, A. R. M., de Gijt, J. G., de Bruijne, M. L. C., & van Heesch, M. A. (2018). Beneficial Inner-City Quay Walls? *Journal of Advanced Civil and Environmental Engineering, 1*(1), 1-8. doi:http://dx.doi.org/10.30659/jacee.1.1.1-8

Grant, G. (2016). *The water sensitive city*. Chichester, West Sussex, United Kingdom: Wiley Blackwell.

Haase, D., Kabisch, S., Haase, A., Andersson, E., Banzhaf, E., Baró, F., . . . Wolff, M. (2017). Greening cities – To be socially inclusive? About the alleged paradox of society and ecology in cities. *Habitat International, 64*, 41-48. doi:https://doi.org/10.1016/j.habitatint.2017.04.005

Heaviside, C., Macintyre, H., & Vardoulakis, S. (2017). The Urban Heat Island: Implications for Health in a Changing Environment. *Current environmental health reports, 4*(3), 296-305. doi:10.1007/s40572-017-0150-3

Hijdra, A., Arts, J., & Woltjer, J. (2014). Do We Need to Rethink Our Waterways? Values of Ageing Waterways in Current and Future Society. *Water Resources Management : An International Journal - Published for the European Water Resources Association (EWRA), 28*(9), 2599-2613. doi:10.1007/s11269-014-0629-8

ICOMOS. (2009). The Canal Area of Amsterdam (Netherlands),No 1349. Retrieved from https://whc.unesco.org/document/152438

IUCN. (2016). *Nature-based Solutions to address global societal challenges.* Retrieved from Gland, Switzerlans: www.iucn.org/resources/publications

Ivens, L. (2020). *Strategie Klimaatadaptatie Amsterdam*. Amsterdam: Gemeente Amsterdam.

Jacobs, C., Klok, L., Bruse, M., Cortesão, J. o., Lenzholzer, S., & Kluck, J. (2020). Are urban water bodies really cooling? *Urban Climate, 32*.

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., . . . Bonn, A. (2016). Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society, 21*(2). doi:10.5751/ES-08373-210239

Kabisch, N., Korn, H., Stadler, J., & Bonn, A. (2017). Nature-Based Solutions to Climate Change Adaptation in Urban Areas—Linkages Between Science, Policy and Practice. In N. Kabisch, H. Korn, J. Stadler, & A. Bonn (Eds.), *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice* (pp. 1-11). Cham: Springer International Publishing.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., & Cerdà, A. (2018). The superior effect of nature based solutions in land management for enhancing ecosystem services. *Science of The Total Environment, 610-611*, 997-1009. doi:https://doi.org/10.1016/j.scitotenv.2017.08.077

Klimaateffectatlas. (2020). Climate Effect Atlas Website. Retrieved from https://www.klimaateffectatlas.nl/en/

KNMI. (2014). *KNMI '14 : climate scenarios for the Netherlands : a guide for professionals inclimate adaption*. De Bilt: KNMI.

Kronenberg, J. (2015). Why not to green a city? Institutional barriers to preserving urban ecosystem services. *Ecosystem Services, 12*, 218-227. doi:https://doi.org/10.1016/j.ecoser.2014.07.002

Levin-Keitel, M., Mölders, T., Othengrafen, F., & Ibendorf, J. (2018). Sustainability Transitions and the Spatial Interface: Developing Conceptual Perspectives. *Sustainability, 10*(6), 1880.

Li, D., Liao, W., Rigden, A. J., Liu, X., Wang, D., Malyshev, S., & Shevliakova, E. (2019). Urban heat island: Aerodynamics or imperviousness? *Science advances, 5*(4), eaau4299. doi:10.1126/sciadv.aau4299

Ligtvoet, W., van Oostenbrugge, R., Knoop, J., Muilwijk, H., & Vonk, M. (2015). *Adaptation to climate change in the Netherlands - Studying related risks and opportunities*. Retrieved from The Hague: https://www.pbl.nl/sites/default/files/downloads/PBL-2015-Adaptation-to-climage-change-1632.pdf

Locatelli, B. (2011). *Synergies between adaptation and mitigation in a nutshell*. Retrieved from www.jstor.org/stable/resrep01900

Mayor of London. (2016). *Green Capital - Green Infrastructure for a future city*. Retrieved from London: https://www.london.gov.uk/sites/default/files/green_capital.pdf

Mens, M. J. P. (2015). *System Robustness Analysis in Support of Flood and Drought Risk Management*. [Amsterdam]: IOS Press.

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Allaire, M., & Matthew, R. A. (2018). What Is Nuisance Flooding? Defining and Monitoring an Emerging Challenge. *Water Resources Research, 54*(7), 4218-4227. doi:10.1029/2018wr022828

Naafs, S. (2018). *Amsterdam Rainproof*. Gemeente Amsterdam, Waternet, and Water Authority Amstel Gooi and Vecht Retrieved from https://www.rainproof.nl/sites/default/files/rainproof-magazine-engels.pdf.

Nessho¨ver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., . . . Wittmer, H. (2017). The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *The Science of the total environment, 579*, 1215-1227. doi:10.1016/j.scitotenv.2016.11.106

Nijhuis, S. (2020). Design as (re)search strategy. [Online Lecture]. Amsterdam, Netherlands: TU Deflt, Faculty of Architecture and the Built Environment.

Nilon, C. H., Berkowitz, A. R., & Hollweg, K. S. (2003). Introduction: Ecosystem Understanding Is a Key to Understanding Cities. In A. R. Berkowitz, C. H. Nilon, & K. S. Hollweg (Eds.), *Understanding urban ecosystems: a new frontier for science and education*. New York: Springer.

Pauleit, S., Zölch, T., Hansen, R., Randrup, T. B., & Konijnendijk van den Bosch, C. (2017). Nature-Based Solutions and Climate Change – Four Shades of Green. In N. Kabisch, H. Korn, J. Stadler, & A. Bonn (Eds.), *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice* (pp. 29-49). Cham: Springer International Publishing.

Prominski, M. (2012). River, space, design : planning strategies, methods and projects for urban rivers. Retrieved from https://doi.org/10.1515/9783034611732

Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M. R., . . . Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental science & policy, 77*, 15-24.

Richards, D. R., & Edwards, P. J. (2018). Using water management infrastructure to address both flood risk and the urban heat island. *International Journal of Water Resources Development, 34*(4), 490-498. doi:10.1080/07900627.2017.1357538

Richter, C. H., Xu, J., & Wilcox, B. A. (2015). Opportunities and challenges of the ecosystem approach. *Futures, 67*, 40-51. doi:https://doi.org/10.1016/j.futures.2014.12.002

Rijksoverheid. (2016). *Adapting with ambition: National Climate Adaptation Strategy 2016 (NAS)*. The Hague.

Ritzema, H. P., & Van Loon-Steensma, J. M. (2018). Coping with Climate Change in a densely Populated Delta: A Paradigm Shift in Flood and Water Management in The Netherlands. *Irrigation and Drainage, 67*(S1), 52-65. doi:10.1002/ird.2128

RIVM. (2019). *Ontwikkeling Standaard Stresstest Hitte*. RIVM Retrieved from https://www.rivm.nl/bibliotheek/rapporten/2019-0008.pdf.

Roggema, R. (2016). Research by Design: Proposition for a Methodological Approach. *Urban Science, 1*, 2. doi:10.3390/urbansci1010002

Romero-Lankao, P., Gnatz, D. M., Wilhelmi, O., & Hayden, M. (2016). Urban Sustainability and Resilience: From Theory to Practice. *Sustainability, 8*(12), 1224.

Rosenzweig, B. R., McPhillips, L., Chang, H., Cheng, C., Welty, C., Matsler, M., . . . Davidson, C. I. (2018). Pluvial flood risk and opportunities for resilience. *WIREs Water, 5*(6), e1302. doi:10.1002/wat2.1302

Rovers, V., Bosch, P., & Albers, R. (2014). *Climate proof cities : final report*. [Utrecht]: Knowledge for Climate.

Rutherford, J. (2020). *Redeploying urban infrastructure : the politics of urban socio-technical futures*. In. Retrieved from https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=2216591

Schuetze, T., van Bohemen, H., & van Bueren, E. (2012). Conclusions and Solutions. In E. van Bueren, H. van Bohemen, L. Itard, & H. Visscher (Eds.), *Sustainable Urban Environments: An Ecosystem Approach* (pp. 399-413). Dordrecht: Springer Netherlands.

Schäfer, E., & Scheele, U. (2017). Making Infrastructure Climate Resilient: Bridging the Transformation Gap with "Living Labs"? In S. Deppisch (Ed.), *Urban Regions Now & Tomorrow: Between vulnerability, resilience and transformation* (pp. 219-253). Wiesbaden: Springer Fachmedien Wiesbaden.

Shishegar, N. (2013). Street Design and Urban Microclimate: Analyzing the Effects of Street Geometry and Orientation on Airflow and Solar Access in Urban Canyons. *Journal of Clean Energy Technologies, 1*, 52. doi:10.7763/jocet.2013.v1.13

Somarakis, G., Stagakis, S., & Chysoulakis, N. (2019). *ThinkNature NAture-Based Solutions Handbook*.

Steeneveld, G. J., Koopmans, S., Heusinkveld, B. G., van Hove, L. W. A., & Holtslag, A. A. M. (2011). Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands. *Journal of Geophysical Research, 116*(D20). doi:10.1029/2011jd015988

Stone, K., Duinen, R. v., Veerbeek, W., & Dopp, S. (2011). *Sensitivity and vulnerability of urban systems : assessment of climate change impact to urban systems*. Delft: Deltares.

Tjallingii, S. (2012). Water Flows and Urban Planning. In E. van Bueren, H. van Bohemen, L. Itard, & H. Visscher (Eds.), *Sustainable Urban Environments: An Ecosystem Approach* (pp. 91-111). Dordrecht: Springer Netherlands.

UrbanGreenBlueGrids. (2020). Sint-Andries: working together towards a climate robust neighbourhood. In.

van Bohemen, H. (2012). (Eco)System Thinking: Ecological Principles for Buildings, Roads and Industrial and Urban Areas. In E. van Bueren, H. van Bohemen, L. Itard, & H. Visscher (Eds.), *Sustainable Urban Environments: An Ecosystem Approach* (pp. 15-70). Dordrecht: Springer Netherlands.

van Bueren, E. (2012). *Sustainable urban environments : an ecosystem approach*. Springer. Retrieved from http://site.ebrary.com/id/10497172

van Dorst, M. (2012). Liveability. In E. van Bueren, H. van Bohemen, L. Itard, & H. Visscher (Eds.), *Sustainable Urban Environments: An Ecosystem Approach* (pp. 223-241). Dordrecht: Springer Netherlands.

.

von Döhren, Peer, & Haase, Dagmar. (2015). Ecosystem disservices research: A review of the state of the art with a focus on cities. *Ecological Indicators*, 52, 490-497. doi:https://doi.org/10.1016/j.ecolind.2014.12.027

van Timmeren, A. (2012). Climate Integrated Design and Closing Cycles. In E. van Bueren, H. van Bohemen, L. Itard, & H. Visscher (Eds.), *Sustainable Urban Environments: An Ecosystem Approach* (pp. 313-339). Dordrecht: Springer Netherlands.

Wolfert, H. (2020). *Introductory Presentation - AMS Institute quay wall mini symposium*. Paper presented at the Quay wall symposium, Online, Amsterdam.

Woltjer, J., & Al, N. (2008). Integrating Water Management and Spatial Planning: Strategies Based on the Dutch Experience. *JOURNAL- AMERICAN PLANNING ASSOCIATION, 73*(2), 211-222.

Yigitcanlar, T., & Dizdaroglu, D. (2015). Ecological approaches in planning for sustainable cities a review of the literature. *Global Journal of Environmental Science and Management, 1*(2), 159-188. doi:10.7508/gjesm.2015.02.008

This page is intentionally left blank

Noelle Teh

MSc MADE Thesis | August 2020