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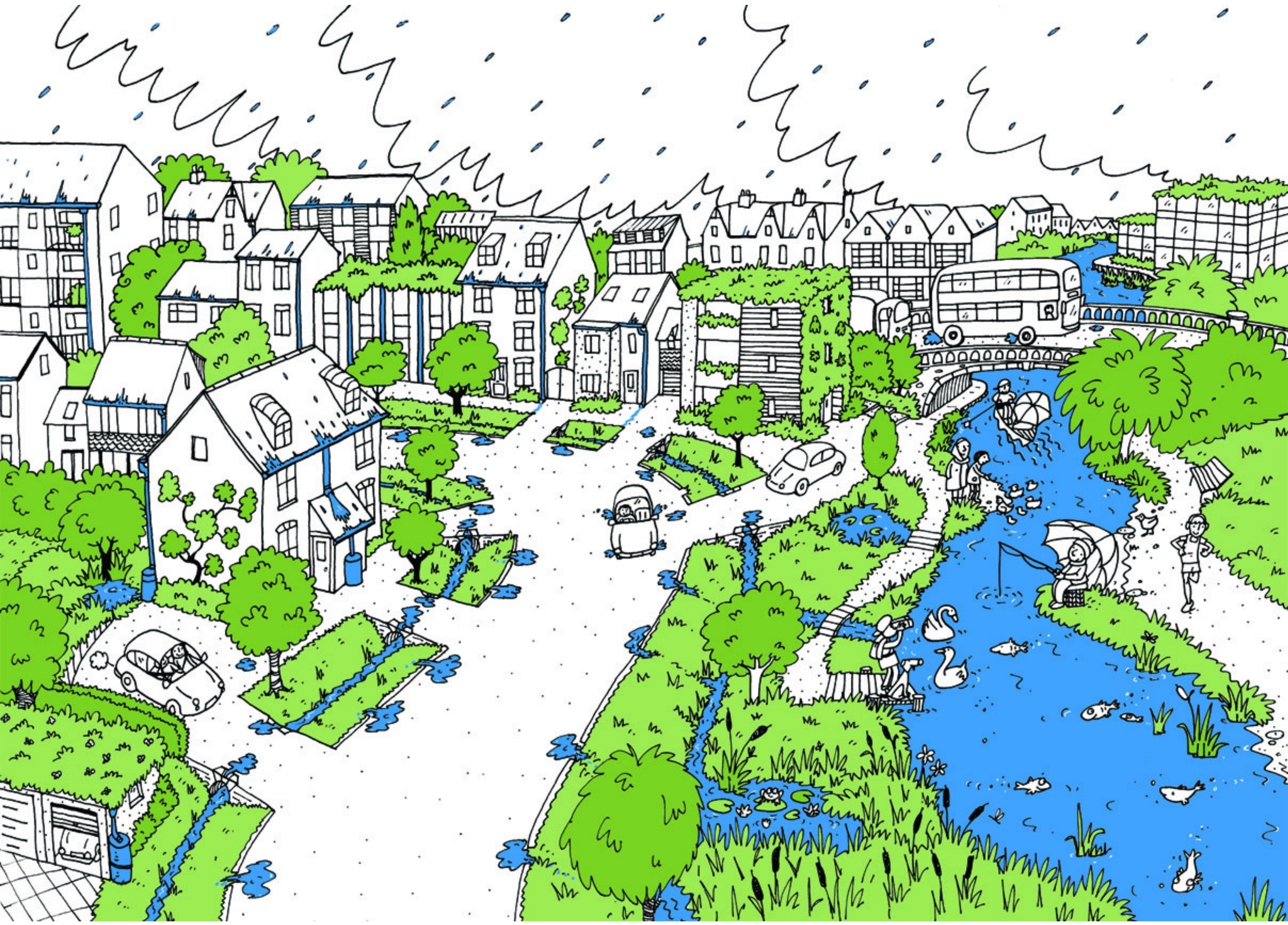
Faculty of Civil Engineering

An assessment framework for SUDS-based storm water management in an urban area



An assessment framework for SUDS-based stormwater management in an urban area

by

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To all reading this thesis, enjoy it!

Laura Vogelzang
Amsterdam, January 27, 2023

Abstract

Globally, there is an ongoing trend to improve the live-ability of cities. Furthermore, the importance of sufficient urban response systems for storm water is growing due to climate change and urbanization. Sustainable Urban Drainage Solutions (SUDSs) are seen as a key tool to tackle multiple urban challenges. This is as their design is multi-objective, focusing on water quantity, water quality, amenity, and biodiversity. However, currently knowledge is lacking amongst decision makers on how SUDS affect the urban environment. Therefore, this research aims to develop an assessment framework for SUDS-based storm water management in the urban landscape to help Dutch municipalities improve their decision making to improve the live-ability of the urban environment.

To evaluate the performance of SUDS, assessment frameworks include Key Performance Indicators (KPIs). KPIs are measurable indicators demonstrating how effective SUDS are in achieving their objectives. This research highlights that there is no universal or even country based standard assessment framework for SUDS. Furthermore, there are few examples of the translation of the scientific assessment methods of SUDS to engineering practice available. The assessment of the full effect of SUDS therefore remains unclear to practitioners.

This research proposes a new framework ("extended framework") to assess the performance of SUDS, building on the existing framework ("conventional framework") which assesses cost and water quantity currently used in engineering practice. The extended framework adds KPIs assessing the remaining three objectives of SUDS design. Firstly, water quality is assessed with the KPIs Site Pollution Index (SPI) and Pollutant Removal Capacity (PRC). Amenity with the KPIs Thermal Comfort Score (TCS) and impervious area. Thirdly, biodiversity is assessed with the KPI Biotope Area Factor (BAF). Furthermore, it improves the assessment of water quantity by replacing the currently used KPI with Expected Annual Damages (EAD). With the choice of KPIs in the extended framework, it is ensured that their assessment methodologies are suitable to engineering practice. Furthermore, by including KPIs that assess the multi-objectiveness of SUDS, the co-benefits are included in the extended framework.

With the application of both frameworks on the municipality of Alkmaar, this research substantiates the positive influence of SUDS on urban areas. The case study shows improving performance for water quantity, water quality, amenity and biodiversity if the number of SUDS increases.

To assess the effect of the extended framework on the decision making process, the MCDA type Compromise Programming (CP) is applied to the results of both frameworks. With the identification of the best choice of design based on the performance results of either the conventional or extended framework, the outcome of the CP method showed that using the extended framework as opposed to the conventional framework sometimes led to different design choices.

It is demonstrated that the extended framework indeed improves the decision making process to improve the live-ability of the urban environment. Even though the extended framework is more time consuming and may result in more costly designs, using this framework to base decision making on is likely to result in better quality of life for humans with a reduced negative impact on the associated natural environment. This framework better equips decision-makers to face emerging urban challenges. However, both frameworks are of use in engineering practice. The ultimate choice of using either one of the frameworks is dependent on the goal of the project, the client, and the amount of time and money available.

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Nomenclature

Abbreviation	Definition
BAF	Biotope Area Factor
CP	Compromise Programming
DPRA	Deltaplan Ruimtelijke Adaptatie
Ecotox EM	Ecotox Evaluation Method
EAD	Expected Annual Damages
Fertility EM	Fertility Evaluation Method
GHG	Green House Gas
GI	Green Infrastructure
HM	Heavy Metals
KRW	Kaderrichtlijn Water
KPI	Key Performance Indicator
LUPI	Land Use Pollution Index
LUST	Land Use Surface Type
LID	Low Impact Developments
NBS	Nature-Based Solution
NDVI	Normalized Difference Vegetation Index
MCDA	Multi Criteria Decision Analysis
Org	Organic pollution
PET	Physiological Equivalent Temperature
PI	Pollution Index
PMI	Pollution Mitigation Index
PRC	Pollutant Removal Capacity
PAH	Polyaromatic Hydrocarbons
PDF	Potentially Disappeared Fraction
SPI	Site Pollution Index
SBA EM	Soil Biological Activity Evaluation Method
SDG	Sustainable Development Goal
SUDS	Sustainable Urban Drainage Solution
SWARD	Sustainable Water industry Asset Resource Decisions
TCS	Thermal Comfort Score
TSS	Total Suspended Solids
UHI	Urban Heat Island
UTCI	Universal Thermal Climate Index
WFD	Water Framework Directive
WSUD	Water Sensitive Urban Design

1 Introduction

Urbanisation and climate change have a significant effect on urban water management, and their influence is growing [1].

Urbanisation accompanied by population growth is leading to increased concentration of people, materials, waste and energy. Quantity and quality of urban water is affected [1], highly complex infrastructure networks arise, the Urban Heat Island (UHI) effect increases cities' heat [2], and biodiversity reduces [3]. Consequently, cities are becoming more vulnerable to flood hazards. Runoff patterns change in both peak runoff as well as speed of runoff due to the increase of impervious surface [1].

Climate change is leading to more extreme weather with multiple effects on urban water management. Firstly, it reduces water available at the source and can worsen the quality of this water. It leads to increased water consumption in urban areas, as it increases the heat via the UHI effect. In terms of urban drainage, climate change poses a huge challenge as it influences the return periods of design storms. Current drainage systems are designed for a certain return period, but the increasing amount of precipitation can cause severe capacity problems like pluvial flooding [1]. This increased frequency and intensity of storms are also an important factor to take into account for future drainage design in order to maintain an acceptable frequency of system overloading [1].

As climate change and urbanisation are becoming more influential on urban development, sufficient urban response systems are of growing importance. It is thus essential for urban water management to be an integral part of urban planning. A promising solution that both integrates urban water management with urban planning and can tackle urban challenges arising from climate change and urbanization is the implementation of Sustainable Urban Drainage Solution (SUDS) [4]. SUDS are multi objective, including four design pillars: water quantity, water quality, amenity, and biodiversity [5]. Implementation in an urban area therefore does not only lead to a reduced flood risk, but results in a wide range of co-benefits, amongst others a reduced UHI effect [6] and protection against drought [7].

There is not enough knowledge amongst decision makers of urban development on the effectiveness of SUDS. Decision makers are questioning how to sufficiently implement possible SUDS types whilst taking into account various spatial and other constraints. This is because when designing an urban area, not only the management of the storm water needs to be addressed, but a wide range of other factors play an important role too, like biodiversity and amenity. This is especially the case in a densely built country such as the Netherlands, where available space in an urban area is limited.

1.1 Research Questions

The aim of this research is to develop an assessment framework for SUDS-based storm water management solutions in an urban area. This framework is intended to be used to assess the performance of SUDS over a wide range of criteria and help with the selection of the suitable option(s) for a specific area. To evaluate the performance of SUDS, assessment frameworks include Key Performance Indicators (KPIs). KPIs are measurable indicators demonstrating how effectively SUDS are achieving the urban design objectives. Applying this framework can also support the argument for the implementation of SUDS, as it can transparently show that they can help tackle multiple urban challenges.

Based on the objective of this research, the corresponding research question is formulated:

How can an assessment framework for SUDS-based storm water management implementation in the urban landscape be developed to help Dutch municipalities improve their decision making to improve the live-ability of the urban environment?

To accomplish this research' objective, four sub questions are formulated based on the activities performed for the development of the framework. The questions addressed in this thesis are:

1. *What are the Key Performance Indicators of Sustainable Urban Drainage Solutions in urban areas?*

2. *What is the best way to evaluate the selected Key Performance Indicators of Sustainable Urban Drainage Solutions in urban areas?*

3. *What is the performance of the highlighted Sustainable Urban Drainage Solutions in the case study on the selected Key Performance Indicators?*

4. *How does the framework developed in this research compare to the method currently used in engineering practice?*

1.2 Scientific relevance

Urban development is shifting from the traditional 'to pipe' concept to the application of nature-based solutions. Thereby SUDS implementation is experiencing growing momentum, as climate adaptation is becoming increasingly important in sustainable urban development. As stated by Cotterill and Bracken [8], it is crucial that the informative evidence base on the effectiveness of implementation of SUDS grows. This research contributes to this goal, by providing evidence on the performance of SUDS to tackle stress caused by climate change and urbanisation. The development of the framework, i.e. the methodology for evaluation, can function as a helpful tool for further investigations into obtaining evidence into the effectiveness of implementation of SUDS, providing useful insights in the concept of SUDS implementation and thus helping decision making processes in urban planning.

1.3 Thesis structure

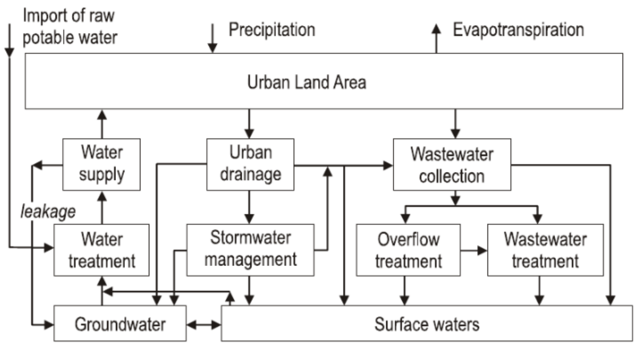
Firstly, a theoretical background is presented in Chapter 2 where the knowledge needed for this research is laid out. Secondly, Chapter 3 includes the literature review conducted for the general assessment of SUDS. The new framework developed for this research is introduced in Chapter 4. Additionally, this research presents the framework currently used in engineering practice. To be able to show the effect of the new framework compared to the conventional framework on the decision making process, both frameworks need to be applied to a case study to obtain the necessary input for the simulation of the decision making process. In Chapter 5 this case study assessment is laid out, including an introduction to the research area and an elaboration of the modelling approach taken and results obtained. Subsequently, the simulation of the decision making process for urban design is presented in Chapter 6. Interventions are selected using both frameworks with a Multi Criteria Decision Analysis (MCDA). Based on the knowledge obtained in this research, the contribution of this research towards its objective is discussed in Chapter 7. This chapter also elaborates on the limitations and relevance of this research. Lastly, the conclusions drawn from this research and recommendations for further work are laid out in Chapter 8.

2 Theoretical Background

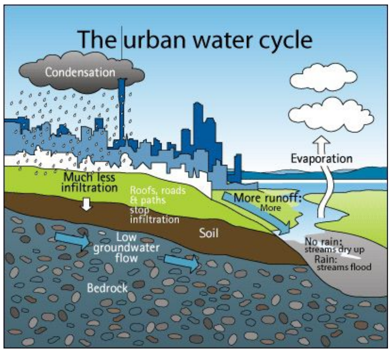
In this section the theoretical background is given, wherein the knowledge needed for this research is elaborated.

2.1 Urban Water Cycle

The water cycle, also known as hydrological cycle, describes how water changes forms and moves above and below the surface of the Earth. Within the Earth's water cycle, a smaller cycle can be recognised; the urban water cycle. The urban water cycle differs from the natural hydrological cycle, as this cycle is almost completely artificial in modern society. Instead of the cycle starting with energy from the sun, as it does in the hydrological cycle, the energy is generated by pumps. The urban water cycle is 'man made' to provide drinking water to homes and businesses, to clean, transport and remove waste water and to redirect storm water to prevent nuisance. The main components and its pathways of the urban water cycle are depicted in Figure 1a. The cycle includes storm water, wastewater and groundwater streams. The interactions between these form the cycle. Accordingly, urban water management includes the plan, design and operation of infrastructure to secure drinking water and sanitation, the control of infiltration and storm water runoff, recreational parks and the maintenance of urban ecosystems [7]. Relevant for this research is that the urban water cycle takes into consideration storm water moving across impervious landscapes where it cannot soak into the ground, decreasing the soil moisture. Figure 1b depicts this storm water stream in an urban area.



(a) Main components and pathways [3]



(b) Storm water streams [9]

Figure 1: Urban Water Cycle

2.2 Storm Water Management

Storm water is water resulting from any form of precipitation that has fallen on a built-up area. If storm water is not drained properly it can cause an inconvenience to the area, but there is also the risk of flooding and resulting damages. Subsequently, storm water contains pollutants which originate from rain, air en the catchment surface and forms a risk for citizen's health.

Conventionally the drainage of storm water is mainly single-objectively oriented design with its focus on water quantity control [1]. Excessive storm water is traditionally seen as a nuisance that must be removed [10]. However, nowadays it is highlighted that a more broad view needs to be embraced. Storm water can also be seen as a utilizable resource. With this shift in perspective, there is a rising demand in the adaption of nature-based solutions.

2.2.1 Traditional versus Nature-Based Solutions

Traditionally urban drainage solutions are based on the 'to pipe' concept. These solutions are centralised, hard and artificial structures focused on rapid drainage by piping networks [1][2][4][10]. This type of drainage is referred to as 'grey infrastructure'. Such systems have two types, a combined or a separate sewer network. In a combined system, wastewater and storm water are transported via the same pipe network. In a separate network, waste streams are separately transported from storm water. Due to its limited capacity for multi-functional water management and limited flexibility for adapting to future climatic and hydrological variations, this type of storm water drainage has been increasingly criticized [4].

Nature-Based Solutions (NBS) are based on the opposite concept, it avoids piping. This type of drainage is often referred to as Green Infrastructure (GI). A definition given by La Rosa and Pappalardo [11] for GI is that GI is a network of both natural, semi-natural and artificial ecological elements, that can be planned, designed and implemented at different spatial scales and is able to provide a wide set of services, contributing to the human well-being [11]. Other examples of NBSs are Sustainable Urban Drainage Solution (SUDS), Low Impact Developments (LID), best management practices and Water Sensitive Urban Design (WSUD). Subsequently, in China they have launched the Sponge Program. Discharging storm water with nature based solutions is focused on the detention, attenuation and utilization of storm water. The solutions are green and more natural. The focus is to decentralise the storm water management. With this trend towards a more holistic view of urban water management, water supply, wastewater disposal and storm water drainage are to be considered as interacting components within a single system [12].

2.3 Sustainable Urban Drainage Systems (SUDS)

A Sustainable Urban Drainage System (SUDS) is a promising solution for the increasing challenges in urban areas [4]. As it is a nature-based solution, it is not a single-objective designed drainage system. The design of SUDS is done with a range of technologies and practices to attenuate storm water runoff, reduce piping network pressure, and mitigate the impact of non source pollution [4]. As SUDS are a form of GI, they do not have one objective. Their design focuses on multi functionality. This multi functionality focuses on four pillars: water quantity, water quality, amenity, and biodiversity [5]. In Figure 2, these pillars are depicted including their goal for SUDS design.

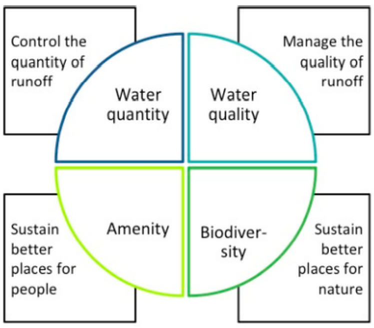


Figure 2: Multi functionality of SUDS [5]

The mentioned key drivers of change in urban water management, climate change and urbanization, need to be incorporated into the design in order for SUDS to adapt to future changing condition [1]. In Europe, SUDS' main focus is on maintaining good public health, protecting valuable water resources from pollution and preserving biological diversity and natural resources for future needs [1]. SUDS thus have the potential to improve the landscape, enhance water quality, promote ecosystems connectivity, and reduce vulnerability to flooding. SUDS can thus be used as a tool in the transition of urbanised areas to water sensitive or sponge cities [13].

There are multiple techniques of sustainable systems, the highlighted ones for this research are:

- Green roof
- Retention pond
- Sustainable road design (e.g., (semi-)permeable pavement etc.)
- Infiltration crates
- Wadi
- Water square

These highlighted types of solutions match the ones that are applied in the conventional method. According to Arcadis, these techniques are subsequently all suitable for polder areas. As this research is done in collaboration with this company, these will be the investigated systems. The development of a framework is necessary to understand the consequences of the application of SUDS. For this, it is essential to understand the benefits of the implementation of sustainable drainage solutions. In the following section, these are laid out.

2.3.1 Co-Benefits

Nature-based solutions, and thereby SUDS, are an essential feature of urban resilience managing storm water. This technique can contribute to urban cooling through evapotranspiration and alleviate the urban heat island effects while supporting urban green with local resources. In their research, Oral et al. [7] have identified categories of challenges in the urban environment, shown in Figure 3. Subsequently, Figure 3 depicts the categories of the benefits provided by nature-based solutions determined by Oral et al. [7] to tackle these challenges.

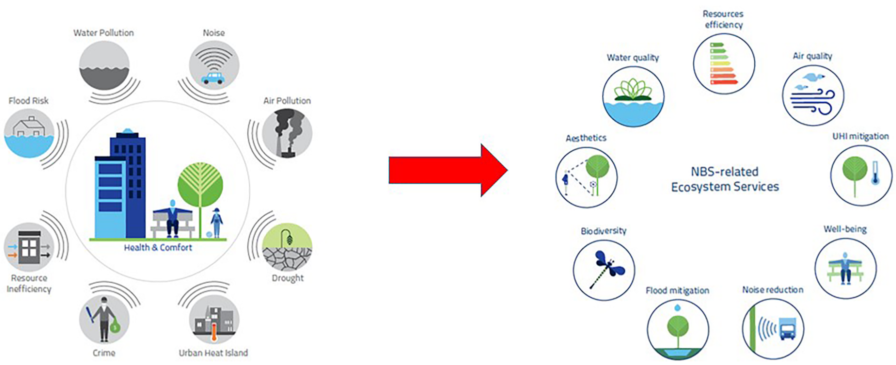


Figure 3: Identified water problems and urban pressures and mitigation options by the application of Nature-Based Solutions [7]

Based on these topics of benefits, the co-benefits for urban areas created by SUDS are investigated. Table 2 shows the information gathered from literature regarding SUDS co-benefit categories, their descriptions and the aspects of the SUDS design that provided the co-benefit.

Table 2: Co-Benefits SUDS

Co-Benefit category	Description	SUDS design element providing co-benefit	Reference
Air quality	Reduced damage to health from improved air quality	Filtration of airborne particulates by vegetation	[7] [14] [15]
Air and building temperature	Reduced urban heat island effect	Green and blue spaces	[6] [7] [15] [16]
	Cooling or insulation, thermal comfort and energy savings	Green and blue spaces	[6] [7] [14]
Biodiversity and ecology	Ecologically significant areas, Ecological support	Creation, enhancement and connecting of habitats	[17] [1] [5] [14] [15] [7] [16]
Carbon reduction and sequestration	Reduced energy needs, water use and planting	Low energy demand (materials, construction, maintenance)	[7] [14] [15]
Climate change adaptation	Ability to modify systems	Designing for exceedance and adaptability	[7] [13] [14]
Community cohesion and crime reduction	Reduced crime against property and people	Green and blue spaces, play features and visual enhancement creating a better living	[14] [16]
Drought protection	Retention of water	Green and blue spaces	[7] [16]
Economic growth and inward investment	Promotion of business jobs, productivity, tourism, and property prices	Created by green and blue spaces	[7] [14] [16] [17]
Education opportunities	Improved access to and availability of educational possibilities	Community engagement (before and after construction), educational programs, information boards, play features	[7] [14] [16]
Flood risk reduction	Reduced damage to property and people	Peak flow attenuation and volume control	[14] [15] [16] [18]
	Control of quantity of runoff	Peak flow attenuation and volume control	[5] [7] [13] [16]
Groundwater and soil moisture recharge	Improved water availability	Interception, infiltration, runoff treatment	[14] [16]
	Improved infiltration to soil	Interception, infiltration	[15]
Health and well-being	Physical, emotional and mental health benefits	Air particulate filtering via vegetation; Green and Blue spaces, and play features; Economic growth following from implementation; Crime reduction; Reduced Flood risk	[7] [14] [16]
Recreation	Participation in specific recreational activities	Green and blue paces and play feature	[7] [14]
Security of water supply	Reduced water flows with less pollution	Rainwater harvesting and groundwater and soil moisture recharge	[1] [14]
Sewerage systems and sewage treatment	Decrease in peak flows and volume to treat in combined systems	Interception and further runoff volume reduction	[14] [18]
Visual character	Creation of aesthetic value	Visual enhancement created by SUDS	[5] [7] [14] [15]
Water quality	Surface water quality improvements	Pollution prevention strategies, interception, runoff treatment	[5] [13] [14] [15] [16] [17] [18]
	Improved receiving river water quality	Pollution prevention strategies, interception, runoff treatment	[6] [16]
Water footprint	Reduced water footprint	Lowered water use	[17]

2.4 Ambition of Future Urban Water Management

In the design of the built environment, there is nowadays the ambition to improve the live-ability in cities [2]. For urban areas this means working towards more sustainable, climate-robust, adaptable, healthy, attractive and pleasant cities keeping in mind the costs and benefits. This transition in urban water management is working towards 'water sensitive cities' [19]. The by Brown et al. [19] defined stages in this transition are shown in Figure 4.

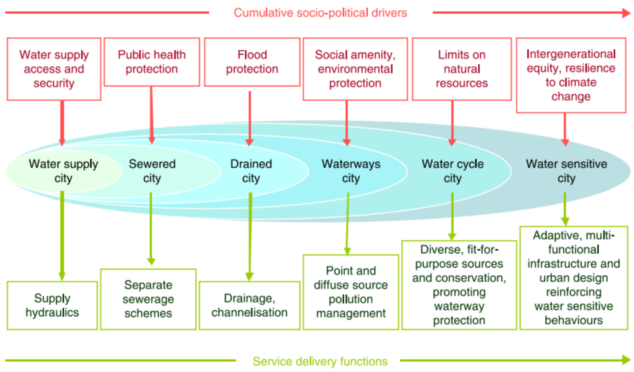


Figure 4: Transition urban water management [19]

To achieve this goal, it is first of all important to acknowledge sustainable urban design is not merely 'an engineering problem', but involves a range of disciplines [20]. Increasing the live-ability of cities leads to questions such as how to best operationalise sustainable urban water management, or what the characteristic features of a live-able city actually are. In urban water management, sustainability at least holds the striving towards minimising the environmental footprint, using water more multi functionally and maximising the use of ecosystem services. Taking these factors into account supports making cities more climate-robust and adaptable, and can be the first steps towards water sensitive cities.

When working towards improvement of the live-ability, the use of GI is being increasingly recognized as a planning and design approach [11]. In such, there is a need to provide sustainable and resilient urban drainage systems to manage storm water. To achieve optimal results in the management of urban storm water, the combined effect of climate change, land use patterns, reuse, treatment, ecology, and societal aspects should be considered [21].

However, as suggested by the key drivers, multiple challenges arise for urban water management. These challenges, including the prevention of flooding, drought, the improvement of water supply-demand resilience and the reduction of heat stress, are becoming increasingly important in the design of urban areas [22]. Furthermore, challenges arising in the integration of GI in the urban landscape include the lack of public open spaces to set as new green areas and economic feasibility [11]. The characteristics of the built-environment, which include ownership, land cover characteristics (density of urban areas), soil contamination and presence of subsurface infrastructure, subsequently contribute to the complexity of this task [22]. The more complex the location, the more difficult it is to retrofit blue-green measures like SUDS.

Next to the challenges, the research of Carmona [20] lists important barriers arising with sustainable, integrated design of the urban landscape. It firstly mentions that established patterns of living that are frequently ingrained and difficult to change, form a complication in the transition towards sustainable cities. Subsequently, public awareness and aspirations form a barrier. This is because this often aspires to unsustainable ways of living, for example low density housing. Economic and governance systems, together with lack of political will, influence development processes. Short-term economic gain is favoured over long-term investment and environmental objectives are overridden by economic and social goals. The lack of will also shows in stakeholders' selfishness. A lot see the environment as 'someone else's problem', neglecting their own potential role. Additional to the lack of will, Carmona [20] also indicated lack of skills and vision and lack of choice. Lastly, the scale of the problem forms a significant barrier. Turning around unsustainable patterns of living and development is a massive long-term process. To achieve this, there must be fundamental changes to attitudes and to the co-operation between these many different stakeholders across spatial scales. In such a context, it is easy to think that individual contributions have little impact and that positive action can be put off for another day.

However, a lot of opportunities are arising. These for example hold using local water as a resource, water for recreation, biodiversity, food production and cooling. Furthermore, water can be used to live and work on, in and above and water can function as collector of solar thermal energy [23].

2.4.1 Stakeholders

For an improved urban design to be successful, a whole series of stakeholders are required to support the design. Urban water management involves a range of disciplines. Stakeholders include at least government agencies, landowners, drinking water companies, consultants, specific interests groups (NGOs) like environmental organisations and cultural heritage groups, and technology developers and manufacturers. Subsequently, with the design of the urban landscape not only water management plays a role. As the Netherlands is a densely built country, available space in urban area's is limited. There are several tasks that lay claim to the urban environment. When answering the question what the city of the future is going to look like, water management needs to be integrated with at least climate mitigation, mobility, and underground infrastructure. As a lot of parties are involved, the design of an urban area becomes complicated. All parties carry out a responsibility and thus need to be satisfied. Subsequently, in the face of current challenges, there is the trend towards sustainable drainage design. This is a multi-disciplinary research field with knowledge from a range of specialist with different backgrounds [1]. These researchers are nowadays important stakeholders to consider.

Stakeholders involved in the sustainable design of urban areas must comprehend its broad scope and consider the urban water cycle as a whole planning unit [1]. The decision-making process for the selection of SUDS involves a variety of stakeholders within public and private sectors holding differing powers and opinions regarding the significance they attribute to differing control factors such as environmental, social, legal and economic criteria [24].

With this increasing number of involved stakeholders, the implementation of urban policies for SUDS becomes more challenging [11]. Next to the previous mentioned stakeholders, public perception is important when considering a successful implementation of SUDS [25]. Research showed that local residential/user stakeholders need to be heard and systemically documented. This can provide critical insight into local expectations and the acceptance or resistance to SUDS projects. Thodesen et al. [25] therefore argues that in such kind of alignment the possibility lies of creating SUDS that would sustainably manage water and be accepted by the public for their perceived social benefits.

2.5 Assessment

The SUDS philosophy of working as a multi functional component in the urban landscape, provides opportunities to manage flood risk, water quality and improve amenity and enhance biodiversity. The multiple benefits provided by SUDS-based storm water management is dependent on having the right design team engaged at the right time to work with the opportunities and constraints of a site. Therefore, based on the technological solutions, local authorities can improve urban development processes by decision support systems, which effectively suggest suitable solutions for the specific area [7]. A helpful tool for adequate decision support systems is an assessment framework, whose final goal is to provide information on systems' behaviour to support their management. The methodology of such assessment involves the following steps [26]:

1. Definition of objectives
2. Definition of criteria
3. Definition of Key Performance Indicators
4. Assessment of performance versus objectives

The overall framework should be simple, well defined and comprehensive (i.e. covering all components) [26]. Additionally, the assessment framework should be applicable to comparable settings of decision making on regional and national level.

2.5.1 Key Performance Indicators

For an assessment of performance of SUDS-based solutions, Key Performance Indicators need to be developed. From the definition it follows that Key Performance Indicators (KPIs) are the critical (key) indicators of progress towards an intended result [27]. As such, KPIs create an analytical basis for decision making and help focus attention on what matters most. They are a fundamental component of the performance assessment system [26]. For a good assessment, quality KPIs [27]:

- Provide objective evidence of progress towards achieving a desired result
- Measure what is intended to be measured to help inform better decision making
- Offer a comparison that gauges the degree of performance over time
- Can track efficiency, effectiveness, quality, timeliness, governance, compliance, behaviors, economics, project performance, personnel performance, or resource utilization
- Are balanced between leading and lagging indicators

In this summation, a lagging indicator indicates past success, while the leading indicator predicts future success.

For the classification of performance in a framework, it is necessary to establish reference values to compare the KPI values to. Santos et al. [26] explains that this can be done by defining performance functions for each KPI. This establishes a relation between the KPI values and a scale of classification. It states that for example limits for good, satisfactory or poor performance can be defined based on legislation requirements, literature references, historical data, or other water utilities' data.

3 General Assessment of SUDS

In this chapter, the literature review conducted for the development of the Key Performance Indicators (KPIs) is presented. The framework developed in this thesis focuses on not only the inclusion of the direct benefits, but also on the co-benefits. The importance of including co-benefits into the decision making framework has been highlighted by recent frameworks [28]. To begin the assessment, the urban challenges that can be addressed by SUDS implementation are presented. This is followed by an outline of sustainable decision making in the water industry, and thereby for the implementation of SUDS. Subsequently, the assessment is carried out. The steps follow the method for assessment described in section 2.5. These hold the definition of the objectives, criteria and indicators. Furthermore, an overview is presented of the assessment of SUDS. Lastly, the knowledge gaps identified in this literature review are laid out.

3.1 Urban Challenges

As stated in section 2.4, urban areas are facing a variety of challenges which can be addressed by SUDS. For the development of the KPIs, this section identifies the needs and challenges in urban areas. This helps to understand the dynamics of the task of the integration of SUDS in the urban environment.

Carbon-neutral urban development is essential for cities. Furthermore, cities need to be climate resilient with less vulnerability for the increasing pollution levels, UHI, decreasing biodiversity, flooding, and extreme events related to climate change. There is the need for climate mitigation and adaptation. Furthermore, climate change increases the need for urban water management, water quality management and flood management (pluvial as well as coastal) [29]. Next to water nuisance, droughts are an increasing threat to the environment.

Regarding the environment, challenges for urban areas are posed by air quality, biodiversity, urban space, and soil management [29][30]. Urban areas are particularly vulnerable for poor air quality. Furthermore, considering the increasing use of green and natural spaces in urban development, there is a trend in re-examination of the way cities are planned. Subsequently, biodiversity in cities is decreasing as there is a lack of green areas. Furthermore, the soil quality is decreasing.

Urban areas are facing challenges regarding resource efficiency [30], focused on the Sustainable Development Goals (SDG's), which target to 'Ensure access to affordable, reliable, sustainable and modern energy for all'(Goal 7), 'Promote inclusive and sustainable economic growth, full and productive employment and decent work for all' (Goal 8), and 'Ensuring sustainable consumption and production patterns' (Goal 12) [30]. In urban areas, this translates to challenges like resource depletion and waste generation and recycling.

Cities are experiencing multiple social challenges in public health and well-being, social justice and cohesion, urban planning and governance, people security and economy [29][30]. Public health and well-being includes the influence of the acoustics of the area on people's health, the quality of life and citizen's health. Social justice and cohesion should be considered in designing SUDS, as they are implemented in a specific local context, and should build on or improve the quality of existing local social networks. With urban planning and governance the focus is on the evaluation of the effectiveness of SUDS when tackling the consequences of intentional and unintended urban transitions. Lastly, the safety of the people in an area poses a challenge. In the context of SUDS implementation, this includes security against man made events like crime.

Regarding the economy, the strive towards a green economy is an important factor for urban development. Furthermore, urban areas aim to have economic growth, for which the implementation of SUDS creates multiple opportunities [29]. For example, the implementation of SUDS enhance property values and introduce job opportunities from low-skill, entry-level positions to high-skill, higher-paid jobs [31].

3.2 Sustainable decision making in the water industry

In light of these urban challenges, it is of significant importance that sustainability is incorporated in urban development. Economic growth and environmental protection should go hand-in-hand. A useful reference for this process is the Sustainable Water industry Asset Resource Decisions (SWARD) project, in which seven standardised phases of decision support processes are established [32]. According to this method, firstly decision objectives need to be defined. Secondly, options of assets need to be generated. Thirdly, criteria and indicators relevant to the decision in question, both qualitative and quantitative, need to be selected. Subsequently, an assessment should be performed to evaluate each specific criterion followed by an analysis of the different options. This can be done by weighting and ranking the results of the assessment. Using a multi-criteria assessment, a suitable selection can then be made by the decision makers. After implementation, post project monitoring should be conducted, and feedback needs to be provided to future decision makers to constantly improve the process.

In the next sections, the objectives, criteria and indicators of SUDS are provided. Subsequently, an overview of the general assessment of SUDS is presented, which helps to bridge the knowledge gap regarding the effectiveness of SUDS. This is an essential factor in working towards sustainable, resilient urban environments. Using the information in the steps for sustainable decision making provided by the SWARD project helps to work towards sustainable, water-sensitive cities.

3.3 Objectives

As indicated above, there are a lot of challenges arising in urban environments which can be addressed by SUDS. Consequently, the objectives of SUDS focus on tackling these challenges, and the extent to which those objectives are achieved present the overall effectiveness of SUDS implementation. The objectives defined in this research follow the multi functionality of SUDS design. With each objective an additional explanation is given to present the extent of influence of the particular objective, ensuring the co-benefits are highlighted by the objectives.

The multi functionality of SUDS design focuses on the representation of the co-benefits categories; water quantity, water quality, amenity, and biodiversity. The four objectives based on these subjects are:

1. *To control the quantity of runoff*
   This is focused on flood protection, indicating coastal as well as pluvial flooding. Moreover, SUDS help against drought protection and thereby also resource depletion, and soil management and quality. Furthermore, by controlling the runoff challenges regarding climate adaptation and mitigation are tackled.

2. *To manage the quality of runoff*
   Managing the quality of runoff leads to less pollution in the area. Next to water quality

control, this supports climate adaptation and mitigation, soil management and quality control, and increases public health and well-being.

3. *To sustain better places for people*
   This aims to improve public health an well-being, including physical, emotional and mental health. Subsequently, better places for people include social justice and cohesion, participatory planning and governance, people security, and a green economy. Regarding climate change, it also supports climate adaptation and mitigation.

4. *To sustain better places for nature*
   Improving places for nature involves striving towards environmental protection and urban sustainability by for example maintaining and restoring habitats and biodiversity, or enhancing green spaces.

3.4 Criteria

To select the suitable types of SUDS for a specific location, the next step is to define the criteria used to assess the previously stated objectives. There are multiple ways to categorise the criteria. There is no one standardised method of evaluation of the sustainability of drainage systems and thereby the criteria that should be considered with the implementation of SUDS. The classification adopted in the SWARD Project uses four sustainability criteria, namely, environmental, economic, social, and technical [32] for assessment. The research of Yang and Zhang [4] uses four categories of criteria, namely technical, socioeconomic, ecological and political criteria. The approach taken by Chow et al. [33] is to focus the decision making process on the evaluation of sustainable drainage design on the criteria quantity, quality, energy and environment. These approaches however do not depict the full picture. For example, Chow et al. [33] exclude the governance systems influencing the choice. As this research's goal is to show the whole extent of effects of SUDS implementation, this research follows the categories used in the research of Revitt et al. [34], Makropoulos et al. [12] and Ellis et al. [24]. These papers do not yet include co-benefits, as the research into this wide range of benefits is more recent. However, their categorisation poses the opportunity for the inclusion of these effects. Contrary to the categorisation of the recently published Nature4Cities [30] research, the KPIs are not categorised following the urban challenges, as KPIs most of the time address multiple challenges, which is also shown in the research of Raymond et al. [29].

The assessment of SUDS therefore uses the categories technical, environmental, operational and maintenance, social and urban community benefits, economic, and legal and urban planning [12][24][34]. This categorisation suits well to the objectives and related urban challenges mentioned in the previous section. The criteria show a full assessment of the factors influencing the choice of implementation in urban development. By dividing the criteria in this manner, the full potential of SUDS can be considered, as it gives the opportunity to highlight the co-benefits. These criteria function as the major established factors on which final judgement, evaluation or decisions can be made. The importance of each criterion differs per location, as the challenges at hand differ in each situation.

An additional important criterion stated by both Ellis et al. [24] and Revitt et al. [34] involves the consideration of the site characteristics. This criterion functions as a prerequisite of implementation. With the decision of implementation the first step should be initial profiling and screening of the location to define the acceptable and unacceptable SUDS alternatives. As this is considered to be a prerequisite, it is not further investigated in this research.

3.5 Key Performance Indicators

The last step in the assessment is the definition of the KPIs. The presented KPIs are categorized into the defined six categories. Overviews of the KPIs per criterion can be found in the Appendix A. The overviews presented provide the KPIs per criterion with their assessment methodologies, scale and references to applications of the KPIs.

3.6 Overview

The general assessment of SUDS includes three steps: the definition of objectives, criteria and of the KPIs. Firstly, the objectives of SUDS implementation are formulated. The objectives of SUDS design focuses on four topics, which include the quantity and quality of runoff and amenity and biodiversity. With the focus on these four categories, the related objectives however tackle a wider range of challenges arising in urban areas. These co-benefits related to SUDS implementation, described in section 2, are an important factor to consider in the assessment. The four pillars of SUDS design thereby have additional effects on multiple other challenges in urban areas. Table 3 presents these formulated objectives based on the four aspect of SUDS design and the direct and indirect challenges they focus on.

Table 3: Urban challenges addressed by objectives SUDS

Objective	**Direct Urban Challenge addressed**	**Indirect Urban Challenge addressed**
Control quantity of runoff	Flood management	Climate adaptation and mitigation Drought protection Public health and well-being Resource depletion Water & Soil management and quality
Manage quality of runoff	Water management and quality	Public health and well-being Climate adaptation and mitigation Waste generation Soil management and quality
Sustain better places for people	Public health and well-being (acoustics, quality of life and citizen's health	Climate adaptation and mitigation Better planning of urban space People security Green economy, inward investment Social justice and cohesion
Sustain better places for nature	Green spaces and biodiversity	Climate adaptation and mitigation Soil management and quality Public health and well-being Resource depletion Carbon reduction and sequestration

For the assessment of SUDS six criteria are established, namely technical, environmental, operational and maintenance, social and urban community benefits, economic, and legal and urban planning criteria. KPIs are defined per criterion, of which descriptions with assessment methodologies can be found in Appendix A. In this section, the KPIs are presented according to which objective they serve and criterion they belong to, which depends on the direct urban challenge each KPI is focused on. The first objective, following the water quantity aspect of SUDS design, namely the control of the quantity of runoff, mainly focuses on runoff mitigation. This quantity objective contains KPIs of each criterion. In Table 4 this first objective of SUDS design and its supporting criteria and KPIs are depicted.

Table 4: Water quantity and corresponding KPIs

Objective	**Criteria**	**KPI**
Control quantity	Technical	Flood control Flood peak reduction/peak flow variation Rainfall/runoff ratio Total rainfall volume Total runoff volume Water detention time
	Environmental (physical)	Evapotranspiration variation
	Operational and maintenance	Water efficiency Water security Water use intensity
	Social and urban community benefits (justice)	Frequency measures of negative effects of extraordinary events
	Economic (monetary)	Life-cycle costs Value of insurance claims
	Legal and urban planning	Urban storm water management regulations

The second focus of SUDS design aims to manage the quality of runoff in an area. In Table 5 the corresponding KPIs categorised per criterion are presented. It is however noteworthy that so little indicators focus on this topic. This lack of indicators is also supported by the recent research of Orta-Ortiz and Geneletti [35]. To accurately determine the effect of SUDS on water quality, assessment methodologies need to include field measurements. Such in situ measurements require a considerable amount of time and investment and are therefore challenging widespread research on the effect of SUDS on water quality [35]. More precise information regarding the effect of SUDS water quality control should be assessed. This to for example shed more light on how SUDS contribute to storm water treatment.

Table 5: Water quality and corresponding KPIs

Objective	**Criteria**	**KPI**
Manage quality of runoff	Technical	Pollution control
	Environmental (chemical/biological)	Annual amount of pollutants captured by vegetation Storm water quality Surface water quality
	Economic (monetary)	Life-cycle costs
	Legal and urban planning	Urban storm water management regulations

The third objective, which aim is to sustain better places for people, contains a lot of indicators to assess SUDS on. This extensive list of KPIs measures the co-benefits generated by SUDS beneficial to the people living in the area. Table 6 provides an overview of this amenity objective with corresponding criteria and KPI's.

Table 6: Amenity and corresponding KPIs

Objective	Criteria	KPI
Sustain better places for people	Technical	System adaptability
	Environmental (chemical/ biological)	Avoided GHG emissions Carbon storage and sequestration Common Air Quality Index Exceedance of air quality limit value
	Environmental (physical)	Air temperature BAF Bowen ratio Urban green space proportion
	Operational and maintenance	Building energy demand Cumulative energy demand Maintenance and requirements Specific waste generation Sustainable practices indicator
	Social and urban community benefits (justice)	Attachment to neighborhood Frequency indicators (of crime categories) Perceived crime measures Security against violence Segregation index
	Social and urban community benefits (process)	Absolute water consumption Accessibility to green space Recreation Urban food production Water scarcity Adaptive Indoor Comfort Day-evening-night noise level Effects of night noise on health Heat induced mortality Long term health effects (air quality) Mean radiant temperature Night noise level
	Social and urban community benefits (public health and well-being)	Outdoor Thermal Comfort Perceived health Perceived temperature Physiological equivalent temperature Population Annoyance indicator Predicted mean vote Premature deaths and hospital admissions averted Quality of life Reduced percentage of obese people Reduction in chronic stress and stress-related diseases Short term health effects (air quality) Thermal load of out-streaming body Universal thermal climate index
	Economic (monetary)	Energy savings Financial risk/exposure Long term affordability Property prices/House price index Tax revenue
	Economic (productivity)	Number of jobs created Tourism
	Legal and urban planning	Accessibility Adoption status Local building and development issues Responsibility Social values for urban ecosystems and biodiversity

Lastly, the biodiversity aspect of SUDS design is addressed. The corresponding objective with criteria and KPIs is shown in Table 7. The objective aims to sustain better places for nature. Indicators regarding biodiversity, soil management and quality, and resources are mostly obtained for this objective.

Table 7: Biodiversity and corresponding KPIs

Objective	**Criteria**	**KPI**
Sustain better places for nature	Environmental (chemical/ biological)	Chemical fertility soil Ecotoxicology factor Ground water quality Soil biological activity Soil contamination Soil organic matter Soil respiration Soil water reservoir for plants
	Environmental (physical)	Connectivity of green spaces Ecological impact Land use and associated impacts on biodiversity Land use related to soil organic matter NDVI Number of invasive alien species Potential of areas likely to host biodiversity Ratio of native plant species Shannon diversity index of habitats Soil classification Soil crusting Soil macro porosity Soil water infiltration Soil water storage Species richness increase
	Operational and maintenance	Raw material efficiency
	Economic (monetary)	Annual budget for natural asset management
	Legal and urban planning	Responsibility

The list of KPIs provided in this research displays a broad range of indicators to assess SUDS on. For each co-benefit category listed in Table 2 presented in section 2.3.1, a KPI is provided in this chapter. Co-benefits can thus be properly assessed with the use of this research. It should be noted that the assessment is however not limited to this list and with the rising popularity of SUDS implementation this list is continuously growing.

3.7 Knowledge Gaps

With this literature review, the KPIs of SUDS and their assessment methodologies are identified. While this led to an extensive list of KPIs and this list is continuously growing due to rising interest, this research highlights the following knowledge gaps:

- *Water quality assessment*: As stated earlier, there is a lack of KPIs assessing the effect of SUDS on the water quality in the design stage of an urban area [35] . Although many studies mention water quality improvements as an important co-benefit, the availability of methodologies to assess the effect of SUDS is lacking. For the decision making process of urban design, it is not possible to apply extensive water quality monitoring programs which assess the performance of SUDS based on in situ measurements. Furthermore, most research assessed the water quality effect of single SUDS types. In the design stage of an urban area it is also important to consider the effect of SUDS trains, for which not much suitable assessment methods are found in this literature review.

- *Assessment methodologies*: While the literature review resulted in an extensive list of KPIs, not many universally (or even country) standard assessment methodologies are found. For example, the Nature4Cities [30] project of the European Union provides long lists of methods and tools to assess NBS but lacks to filter the different indicators on their usefulness. As the list of assessment methods on the effect of SUDS is so long, the assessment of these solutions is missing a direct general assessment that can be used and understood by all. Due to this non-standardized approach, the assessment of the full effect of SUDS on the environment remains vague for practitioners.

- *Translation to engineering practice*: The literature review showed little examples of translation of the assessment of SUDS to engineering practice. Most research is conducted from a scientific point of view while in this thesis the important knowledge gap to bridge occurs in the decision makers of urban design. For practitioners in urban design, it is important that the assessment methods are suitable for their way of working. In the UK CIRIA bridges the gap between research and UK's engineering practice. Such an in-depth translation is not available for the Dutch environment.

Therefore in this research KPIs chosen and the developed methodologies to best evaluate these KPIs are based on data availability in literature and suitability to the case study. The developed framework is presented in the subsequent chapter.

4 Frameworks

In this chapter, the two frameworks applied in this research are laid out. Firstly, the framework currently used in engineering practice is introduced. Secondly, a new framework for the assessment of SUDS is proposed. Lastly, the assessment methodologies of the associated KPIs are explained.

4.1 Conventional framework

Different aspects of urban design are considered by the two frameworks. The framework currently used in engineering practice, called the ”conventional framework”, considers the costs and water quantity aspects of urban design. In engineering practice an assessment tool, called the KA tool, is available. With this tool the conventional framework is easy to apply to different case studies. Furthermore, because only two features of urban design are included and the KA tool is available, this framework provides a fast assessment of an urban design.

Costs are taken into consideration by assessing the investment cost of a design. With the calculation of the water storage capacity of a design, the water quantity benefits of SUDS are investigated. Subsequently, in engineering practice the maintenance score is introduced to consider the management implications of a design. However, this KPI is excluded from the conventional framework as it is currently not used to base a decision on. It is occasionally presented to stakeholders as extra information.

By only assessing the effect of SUDS on water quantity and costs this framework excludes the assessment of co-benefits. Section 2.3.1 presented a lot more benefits from SUDS implementation. While SUDS are seen as a tool to improve the quality of life in an urban area, this framework does not test how the implementation of SUDS contributes to this goal.

4.2 Extended framework

In this study a new framework that builds on the conventional framework is introduced. In this new framework, known as the ”extended framework”, a wider range of considerations of urban design is assessed. In this extended framework, it is ensured that all four objectives of SUDS stated in section 3.3 are addressed in addition to the considered aspects of SUDS in current engineering practice. This framework takes into account the management of a design and adds three extra considerations to the framework: water quality, amenity, and biodiversity. With this addition, all four SUDS design pillars are assessed to ensure the entire effect of SUDS implementation is examined. In this framework, water quantity is assessed with Expected Annual Damages (EAD) instead of the water storage capacity. This because the EAD is a direct measure of flood risk, as opposed to water storage capacity which is an indirect measure. Furthermore, there are two KPIs presented for water quality in this method, namely the Site Pollution Index (SPI) and Pollutant Removal Capacity (PRC). However, as these indicators are not mutually exclusive, the choice should be made between using either the SPI or the PRC. This to ensure no double weight is given to water quality in the decision-making process that follows from the performance assessment applied with this framework. In this research, both are applied to the case study but used separately in the decision making process to investigate the difference in outcome resulting from using either one or the other. The amenity objective is tested on two different KPIs. These indicators are mutually exclusive as the Thermal Comfort Score (TCS) focuses on amenity from a public health and well-being perspective and impervious area is a surrogate measure for the aesthetic appreciation of an urban area.

4.3 Methodology

In this section, each KPI used in the conventional framework and the extended framework is explained and their corresponding assessment methodologies are laid out.

4.3.1 Investment cost

In engineering practice, the cost of implementation of SUDS types is taken into account when designing an urban areas response system to storm water. Based on the design of the urban area the minimum and maximum cost of implementation of SUDS are calculated using the costs per square meter shown in Table 8. Given this range in which the actual cost of a design lays, the average is determined as the indicator used to assess the expenses of the implementation of SUDS on. In real-life projects, investment costs are assessed in more detail, but for the purpose of this research the average is taken.

Table 8: Cost per SUDS type [36]

SUDS type	**Costs (€/m²)**	
	Minimal	*Maximum*
Green roof	€ 50	€ 300
Wadi	€ 50	€ 100
Retention pond	€ 20	€ 50
Water square	€ 25	€ 125
Sustainable road design	€ 20	€ 60
Infiltration crates	€ 150	€ 250

4.3.2 Maintenance score

To assess the impact of SUDS on the management of urban area, a maintenance score is assigned to different combinations of SUDS in a design proposal. This indicator represents the needed time to upkeep the urban design to ensure it performs on its full capacity. A score between 1 and 10 is assigned to each SUDS type in engineering practice. This overall maintenance score is based on scores of individual SUDS types, which are shown in Table 9. The following formula is applied to calculate the overall maintenance score [36]:

$$Maintenance\ score\ = \frac{\sum maintenance\ scores\ of\ SUDS\ in\ intervention\ strategy}{10 * number\ of\ SUDS\ in\ intervention\ strategy} \tag{1}$$

Table 9: Maintenance score per SUDS type [36]

SUDS type	**Maintenance score**
Green roof	6
Retention pond	10
Sustainable road design	8
Infiltration crates	3
Wadi	7
Water square	7

4.3.3 Water quantity

The third consideration of SUDS implementation in the urban environment is water quantity. The water quantity design objective of SUDS design aims to control the quantity of runoff. This is to support the management of flood risk, and to maintain and protect the natural water cycle. In order to do so, and prevent detrimental impact on people, property and environment, the peak runoff rate and runoff volume in an area must be controlled. If this is managed, the likelihood of flooding decreases. In the conventional framework water quantity, and thereby flood risk, is analysed by determining the water storage capacity. In the extended framework, the EAD is used to assess water quantity.

4.3.4 Water storage capacity

In engineering practice, the water storage capacity of intervention strategies is applied to assess the flood risk in an area. The ability of SUDS to retain storm water is shown with this KPI. Subsequently, this KPI shows the change in runoff volume as a result from SUDS implementation.

To asses an intervention strategy on its water storage capacity, the implementation of different kinds of SUDS is considered. In this KPI, the sewer storage capacity in the area is excluded from the water storage capacity calculated with this indicator. To establish the water storage capacity of a design, the initial storage on the surface and storage in SUDS is determined. In engineering practice, it is assumed all surface types have an initial storage capacity of 0.1 m/m^2. Based on the lay out designed for an urban area, the water storage capacities of SUDS combinations are calculated by using the input storage capacities presented in Table 10. The total water storage capacity reported is the sum of these water storage capacities of the SUDS combinations and initial surface storage.

Table 10: Water storage capacity per SUDS type [36]

SUDS type	**Water storage capacity (l/m^2)**
Green roof	20
Wadi	400
Retention pond	300
Water square	300
Sustainable road design	100
Infiltration crates	270

4.3.5 Expected Annual Damages (EAD)

The KPI EAD measures flood risk by determining the average of flood damages calculated across multiple events. The consequences of flood events are calculated to evaluate the performance of combinations of SUDS in an urban area. As flood risk increases due to more intense rainfall events and regional increases in precipitation linked to climate change, this indicator is tested on resilience to climate change. This to show the vulnerability of an area to climate change.

To obtain the EAD, the following formula is applied:

$$Expected\ Annual\ Damage\ (EAD)\ = \sum Likelihood * damages \tag{2}$$

This formula contains 2 variables, the likelihood and the associated damages. The following steps are taken to obtain the EAD:

1. Choice of return periods with associated storm events
2. Modelling of rainfall events in both neighborhoods
3. Reporting of maximum water level on streets for each event

4. Determination of the resulting damages

5. Calculation of the EAD

Step 1: Choice of return periods with associated storm events
With the assessment of the EAD, a range of storm events need to be modelled. It is important to test on a large range because modelling more storm events improves the representation of damages. To obtain storm events, return periods need to be combined with the hydrological response time of an area. Urban areas contain a lot of impervious surface and most urban areas in the Netherlands are considered to be flat. This leads to shorter hydrological response times, for example 10 minutes.

Step 2: Modelling of rainfall events in both neighborhoods
This KPI is assessed by using the modelling tool Tygron. Tygron offers digital infrastructure to support issues related to spatial planning. It enables users to simulate the movement of (liquid) water and its impact on a project area. The used Water Module is primarily created for the analysis of spatial water problems in urban and rural areas. The Water Module is an implementation of a 2D grid based shallow water model, based on the 2D Saint Venant equations. This model requires rainfall data as input, and simulates the water level on the streets by combining this input data with (geo)data, models and applications. In this research, the maximum water level on the streets is simulated for each of the chosen storm events.

Step 3: Reporting of maximum water level on streets for each event
For each chosen storm event, an areas' response system to precipitation is modelled in Tygron. As not all water on the streets causes damage to property, only maximum water depths that exceed a threshold of 20 cm are considered. This threshold is an approximation based on the height difference of the street and the entrance of buildings. Per street that has a water depth higher than this threshold, the maximum water level is reported.

Step 4: Determination of the resulting damages
Damages are assigned to each water depth according to water level and property type. The property types used in this research are educational, residential and industrial, as these types are affected by the storm events modelled. To obtain the damages resulting from the water on the streets, depth-damage curves are used. The graph depicted in Figure 32 in Appendix G shows the used curves on which the damages are based. This graphs originate from engineering practice and apply to the Dutch environment.

For each return period, the total damages are calculated for all the alternatives of urban design. This total amount is the input for the formula of the EAD.

Step 5: Calculation of the EAD
The last step in the assessment of this indicator is to calculate the EAD. First, the likelihood of any storm event is calculated using the return periods of such events. To obtain the likelihood for each modelled storm event, the following equation is used:

$$Likelihood\ = \frac{1}{T} \tag{3}$$

In which T is the return period.

By implementing the acquired likelihoods and associated damages in equation 2, an overall EAD is determined.

4.3.6 Water quality

Subsequently, the extended framework assesses the water quality design objective of SUDS. Diffuse urban pollution plays a significant role in jeopardizing the quality of groundwater and receiving surface water standards mandated by the EU Water Framework Directive (WFD) [5]. The following factors influence the impact of the site on the receiving water's quality [5]:

- Pollutant types on the site, as these have varying effects on the receiving water body
- Peak pollutant concentrations in site runoff, which can cause acute (short-term) toxicity in receiving waters. A detailed elaboration on how this works can be found in Appendix H.
- The total pollutant load that is likely to be conveyed in runoff to the receiving environment, as this can result in chronic (long-term) pollution and gradual deterioration due to accumulated pollutants

Increased use of SUDS is an important way to reduce urban runoff and improve the quality of that runoff's water. This water quality design criterion aims to support the management of water quality of the receiving surface waters and ground waters, as well as contribute to the design of a resilient urban design which is able to cope with future change due to urbanization and climate change. To evaluate SUDS' effect on the water quality in an area, the KPIs listed in Table 5 in section 3.6 can be applied. The best way to assess the water quality is by performing before and after SUDS implementation water quality assessments using in situ water samples as input. However, such assessments are costly to perform and very time consuming. As it is not possible to perform such tests in this study, a different approach is chosen. This research uses two surrogate KPIs that assess the expected improved quality of urban runoff, including the SPI and the pollutant removal capacities of SUDS.

4.3.7 Site Pollution Index (SPI)

The SPI is obtained by applying the simple index approach [5]. This approach is a theoretically based procedure that offers a methodology developed by Ellis et al. [37] to perform an impact assessment on urban surface runoff quality. To evaluate the level of risk mitigation achievable by SUDS drainage infrastructure, this procedure employs an integrated geographical information system (GIS)-based pollution index approach based on surface area impermeability, runoff concentrations, and individual SUDS treatment performance potential. Combining this pollution index data with pollutant mitigation characteristics of SUDS, a SPI can be assigned to an area.

Using this simple index approach, it is important to note that this method is not suitable to use in designing treatment systems for discharges to ground waters.

Using the simple index approach of Woods Ballard et al. [5], based on the method developed by Ellis et al. [37], the following steps are applied to assess the water quality impact of SUDS:

1. Pollution Index (PI) assessment
2. SUDS Pollution Mitigation Index (PMI) assessment
3. Overall Site Pollution Index (SPI) assessment

An additional step can be taken, namely the assessment against an environmental baseline. In the research of Ellis et al. [37], the comparison is made against UK regulations, whereby the method behind the conversion is not explained. Currently there is not yet an Dutch environmental baseline to compare the outcome to. This step is therefore not taken in this research. The objective in this research is to shed light on water quality improvements by showing a reduction in SPI.

This section presents the step-by-step methodology used for the assessment of this KPI. Four different kinds of pollutants are addressed in this method, namely the Total Suspended Solids (TSS), Organic Pollution (Org), Polyaromatic Hydrocarbons (PAH) and Heavy Metals (HM). A SPI is generated for each of these pollutant categories. Pollution from human pathogens in storm water runoff is excluded, as no sufficient data is available to determine the SPI for this type of contamination.

Step 1: PI assessment:
An PI assessment of both neighborhoods is conducted assigning areas according to Land Use Surface Type (LUST). This follows the LUST categories, impermeability, and pollution indices shown in Table 11.

Table 11: Pollution indices per pollutant category [37]

Land use surface type (LUST)	**Impermeability (IMP_{RF})**	**Total suspended solids pollution index (PI_{TSS})**	**Organic pollution index (PI_{Org})**	**Hydrocarbon pollution index (PI_{PAH})**	**Metals pollution index (PI_{HM})**
Roofs					
Industrial/commercial	1	0.3	0.3-0.4	0.2	0.4-0.8
Residential	0.9	0.4-0.5	0.6-0.7	0.1	0.2-0.5
Highways					
Motorways	0.8-0.9	0.9	0.7	0.9	0.8
Major arterial highways	0.7-0.8	0.8	0.7	0.8	0.8
Urban distributer roads	0.6-0.7	0.7-0.8	0.5	0.8	0.7
Residential streets	0.4-0.6	0.4	0.6	0.6	0.6
Pavements	0.5-0.6	0.4	0.6	0.3	0.3
Carparks/hardstanding					
Industrial/commercial	0.6-0.8	0.6-0.7	0.6-0.7	0.7	0.4-0.5
Driveways (residential)	0.5	0.5	0.6	0.4	0.3
Open areas					
Gardens (all types)	0.1	0.3	0.2-0.3	0	0.01
Parks/golf courses	0.2	0.2-0.3	0.2	0	0.02
Grassed areas (including verges; all types)	0.1	0.2-0.3	0.2-0.3	0.05	0.05

Step 2: SUDS PMI assessment
After assigning areas to the different LUSTs, regions of both neighborhoods affected by SUDS are defined. These affected areas get an PMI assigned, depending on the SUDS type and pollutant. For not all SUDS types used in this research PMI's are available. The PMI's used are shown in Table 12. The PMI's of a longer list of SUDS types can be found in the research of Ellis et al. [37].

Table 12: Pollution mitigation indices per SUDS type [37]

SUDS type	**Total suspended solids pollution mitigation index (PMI_{TSS})**	**Hydrocarbon pollution mitigation index (PMI_{PA})**	**Organic pollution mitigation index (PMI_{Org})**	**Heavy metal pollution mitigation index (PMI_{HM})**
Sustainable road design	0.2	0.3	0.2	0.3
Green roof	0.85	0.9	0.5	0.8
Wadis	0.7	0.6	0.4	0.4
Retention pond	0.6	0.5	0.6	0.5

Step 3: Overall SPI assessment
The last step is to calculate the SPI's of both neighborhoods. The overall SPI is the sum of the area weighted Land Use Pollution Index (LUPI) divided by the total site area. Taking the

total PI of a contaminant, the individual LUPI of each LUST is defined as:

$$Area\ LUPIi \ = \ Area\ LUST \ * PI_{\text{pollutant}} * [PMI_{\text{pollutantSUDS1}} * PMI_{\text{pollutantSUDS2}} * ...n] \quad (4)$$

The SPI ranges from zero to one, with zero meaning there is no pollution. The quality of the storm water runoff increases by lowering the SPI.

4.3.8 Pollutant Removal Capacity (PRC)

The quality of storm water runoff plays an important role in considerations about the drainage, discharge and use of this water. In the Netherlands, there are no specific regulations regarding storm water runoff and storm water overflows from the storm water sewage system. The same applies to most surface water in cities, insofar they are not part of a surface water body. The Netherlands does have norms regarding surface water bodies, namely the three environmental quality norms of the Kaderrichtlijn Water (KRW): JG-MKN, the yearly average environmental quality norm for long lasting exposure, MAC-MKN, the maximum allowed concentration with short-term exposure, and MKN-biota, the maximum allowed concentration of a substance in prey. A surface water body is defined as a distinct surface water of significant size, such as a lake, basin, stream, river, canal, transitional water or stretch of coastal water in the Netherlands [38]. Most surface water in a city does not meet this description. In principle, the KRW therefore does not apply to city water, nor does it apply to storm water runoff that is discharged into city water. However, the environmental quality standards of the KRW do provide a practical tool for assessing the chemical quality of rainwater runoff as a source of urban surface water. The quality of storm water runoff in the Netherlands compared to the regulated norms of the KRW is shown in Figure 34 in Appendix I. To assess the quality of urban runoff a distinction is made between two different types of areas, namely urban areas and business parks. Because there are no test values available for storm water runoff, the KRW standard values for fresh surface water are used as a indication by the STOWA and Stichting RIONED [38] to compare Dutch urban runoff to. Groundwater standards according to the KRW usually contain comparable or higher concentration. For the metals cadmium, copper, lead, mercury, nickel and zinc the measured average (total) concentrations in storm water runoff are higher than the KRW standard, and these pollutant therefore raise concern.

SUDS have the ability to reduce these levels of concerning contaminants in storm water runoff. By assessing the pollutant removal capacities of SUDS regarding contaminants with high presence in Dutch storm water, this indicator assesses the effect of SUDS on water quality.

This KPI is calculated by subtracting the amount of contaminant reduced via the pollutant removal capacities of SUDS combinations from the amount of contaminant present in Dutch storm water runoff. The metals assessed include cadmium, copper, zinc and nickel. Additionally, TSS is assessed. This choice resulted from available data on removal performance of SUDS types. The metals assessed all raise concern by their high presence in Dutch storm water, as stated earlier.

This indicator is calculated with a mass balance. The steps taken in the methodology of this indicator consist of:

1. Determination of pollutant removal capacity per SUDS type

2. Calculation of pollutant load in inflow

3. Determination of PRC

Step 1: Determination of pollutant removal capacity per SUDS type

In the research of Woods Ballard et al. [5] the performance of SUDS regarding contamination removal in urban runoff is determined. The presence of contaminants, including Total Suspended Solids (TSS), cadmium, copper, zinc, and nickel, in the inflow and outflow in urban runoff in the UK of SUDS types are presented in Figure 35 in Appendix J. The removal capacities of different SUDS are obtained by using these inflow and outflow data. As there is not sufficient data present for the Dutch environment on these removal capacities, UK data are used in this research. The amount of the pollutant able to be removed per different SUDS type is shown in Table 13. An elaboration on the calculation of these removal capacities per SUDS type is given in Appendix L.6 step 1. The available data on pollutant removal capacities is not limited to the SUDS types presented in this table. This study only uses the SUDS types presented in section 2.3. On not all SUDS types used pollutant removal data is available. Table 13 depict the SUDS types of this list that are used to calculate this indicator. It is important to note that infiltration crates, green roofs, and water squares are not taken into account as there is a lack of sufficient data available regarding these SUDS.

Table 13: Pollutant removal capacities per SUDS type

	TSS (mg/L)		**Cadmium** (µg/L)		**Copper** (µg/L)		**Zinc** (µg/L)		**Nickel** (µg/L)	
SUDS type	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*
Wadis	10	71	0	0.3	2	7	11	57	1	3
Retention ponds	16	86	0.1	0.2	3	15	18	73	1	2
Sustainable road design	6	70	-0.1	0.1	2	11	27	83	2	5

Step 2: Calculation of pollutant load in inflow

In this research the inflow concentrations used for the assessment calculations of storm water in the case study are based on the research of STOWA and Stichting RIONED [38]. Present pollutant concentration data of storm water runoff of two different areas, residential and business, are used as inflow concentrations in this research. Following the quality data presented in Figure 34, the average presence of the investigated pollutants per liter are presented in Table 14. Based on these inflow concentrations per liter, a chosen design storm and the surface area, the total amount pollutant flowing into the area is calculated. The chosen design storm in this research follows engineering practice, meaning a storm event of 20 mm/hrs.

Table 14: Quality Dutch storm water runoff [38]

Pollutant	**Average Residential area (roofs & roads)**	**Average Business area (roofs & roads)**	**Unit**
Cadmium	0.18	1.4	µg/L
Copper	21	20	µg/L
Nickel	4.1	12	µg/L
Zinc	144	594	µg/L
TSS	38	48	mg/L

Step 3: Determination of PRC

This determination can be done for different numbers and combination of SUDS types, leading to a different amount of pollutant removed for each urban design. Assuming no losses of pollutant concentration, a mass balance is applied to a study area. First, the amount of pollutant in the total inflow into the area as calculated in step 2 is used as the total inflow of the mass balance. The outflow of the mass balance consists of the amount of pollutant present removed by SUDS and the total amount of pollutant present in the storm water in the area after treatment. The share of the pollutants removed by SUDS is calculated based on the removal capacities elaborated in step 1. For each SUDS type applied and the area they are applied on, the removal of pollutants from the total pollutants present in the area is obtained. Based on this total amount of pollutants entering the study area and the amount removed by SUDS, the pollutant presence in the storm water flowing out of the study area are calculated. Based on this mass balance, the percentages PRC for a combination of SUDS applied to a study area for each contaminant can be calculated by:

$$PRC_{contaminant\ i} = \left| \frac{Pollutant\ concentration\ in\ total\ outflow}{Pollutant\ concentration\ in\ inflow\ of\ total\ storm\ water} \right| \tag{5}$$

4.3.9 Amenity

Furthermore, the amenity design objective of SUDS aims to provide attractive, pleasant, useful, and, above all, live-able urban environments that support and enhance local communities. This includes the tangible, something measurable in terms of use, as well as less tangible, for example pleasure or aesthetic appreciation, aspects of creating and sustaining better places for people. Amenity includes live-ability, which refers to factors that improve the quality of life for residents. Live-ability encompasses a community's and individuals' well-being, as well as the many characteristics that make a location a desirable place to live and work.

In this research, it is chosen to investigate the effect of SUDS on public health and well-being by determining the thermal comfort of the residents of both neighborhoods. Amenity is subsequently assessed by looking at the percentage green and blue surface versus grey surface, with which the attractiveness of an area is investigated.

4.3.10 Thermal Comfort Score (TCS)

Thermal comfort is one of the influencing factors of public health and well-being. SUDS have the potential to reduce the UHI-effect and decrease the perceived temperature in a neighborhood. When the perceived temperature in an area is lowered, the experienced thermal comfort increases. A higher thermal comfort makes a location a more desirable place to live and work in.

The outdoor thermal comfort is assessed by determining the TCS. The TCS represents the amount of heat stress that is experienced in an area. This comfort level can be obtained for different climate scenarios. To obtain this comfort score, the GREENPASS methodology is applied to the case study in which the following steps are carried out [39]:

1. PET analysis of chosen heat day
2. Assignment of thermal sensation classes
3. Calculation of area ratio
4. Expression of physiological stress
5. Assignment of weighting factors
6. Determination of TCS

Step 1: PET analysis of chosen heat day
To obtain the outdoor thermal comfort the perceived temperature, or PET, has to be known. This temperature is the temperature experienced by people in an area. This temperature is obtained via the use of the modelling tool Tygron, that performs the analysis and presents the results in the form of a heat map, serving the base for the TCS calculation. This heat map shows the perceived temperature outside, and not inside buildings. This tool calculates the perceived temperature for two possible options based on the state an area is in: a cell in shade or at night and a cell in the sun during daytime. The method is based on the Deltaplan Ruimtelijke Adaptatie (DPRA) heat stress report of the Dutch national institute for public health and the environment, the RIVM, providing a standard for heat stress tests in the Netherlands [40].

Step 2: Assignment of thermal sensation classes
Based on the resulting heat map from the PET analysis in Tygron, thermal sensation classes are assigned. These classes represent thermal perception and sensitivity of human beings towards the respective climate zones and cultural behavior. As shown in Table 15 the sensation classes for for Western/Middle Europe are applied in this research. In this research it is chosen to do this based on the average temperature between 12:00 and 18:00.

Step 3: Calculation of area ratio
Following the determination of thermal sensation classes per area, the relative ratio of the specific human sensation classes occurring in the project area's heat map result is split and shows the appearance of areas with thermo-physiological stress within the project area at the observation time.

Step 4: Expression of the physiological stress
Based on the heat map obtained in step 1, physiological stress levels are assigned to the temperatures measured in the case study. These represents the stress human endure due to experiencing the perceived temperature.

Step 5: Assignment of weighting factors
The weighting factors are determined by the severity of thermo-physiological stress. As explained in the research of Scharf et al. [39], the weighting factors have been defined using the Predicted Mean Vote grading system and the Index Indicators principle, counting 'comfortable' with no thermal stress as the upper index base (1) and 'very hot' (and above) and 'very cold' with extreme heat and cold stress as the lower index base (0). In accordance with the Predicted Percentage of Dissatisfied model methodology, a gradation linked to the grade of physiological stress and sojourn quality has been defined (0.5 — 0.75 — 0.9) for the thermal sensation classes in between. In this step, these weighting factors are assigned to the PET categories present in the case study, with Table 15 depicting the used weighting factors per PET category.

Step 6: Determination of TCS
The TCS is expressed in points, which are calculated by multiplying the occurring area ratio of thermal sensation classes in the project area by the respective weighting factor for the classes and then adding up in points at the time of observation. In this research it is chosen to consider the average perceived temperature for the time of observation, as only small differences occurred over the investigated time span. The higher this score, the better the thermal comfort in an area is, having an minimal value of zero and maximum of 100.

Table 15: Input variables TCS methodology [39]

Perceived temperature (PET) (Celcius)	Thermal sensation classes for Western/Middle Europe	Grade of phyiological stress	Weighting factor
<4	Very cold	Extreme cold stress	0
4 - 8	Cold	Strong cold stress	0.5
8 - 13	Cool	Moderate cold stress	0.75
13 - 18	Slightly cool	Slight cold stress	0.9
18 - 23	Comfortable	No thermal stress	1
23 - 29	Slightly warm	Slight heat stress	0.9
29 - 35	Warm	Moderate heat stress	0.75
35 - 41	Hot	Strong heat stress	0.5
41 - 47	Very hot	Extreme heat stress	0
47 - 53	Super hot	Extreme heat stress	0
53 - 59	Extremely hot	Extreme heat stress	0
>59	Hottest	Extreme heat stress	0

4.3.11 Impervious area

This indicator represents the level of aesthetic appreciation an area potentially receives. The research of Wang et al. [41] showed that urban green and blue spaces contribute to the aesthetic appreciation of a neighborhood. Such surfaces are pervious. Therefore, the less sealed, or impervious, an area is, the more the aesthetic appreciation of an area increases. The attractiveness of the urban environment is in this indicator expressed as the proportion of grey surface, which is higher when this proportion decreases. This then improves the quality of life in an area.

To assess this indicator the following equation is used:

$$Impervious\ area\ (\%) \ = \ \frac{\sum Sealed\ surface}{Total\ area} \tag{6}$$

In this equation, not all SUDS types contribute to an pervious surface. This indicator is calculated looking from the perspective of aesthetic appreciation of the neighborhood. Therefore, infiltration crates will keep on contributing to sealed surface while it does have the ability to store and discharge excess storm water. However, this type does not contribute to the attractiveness of the area. Sustainable road design is considered to contribute to an increased visual presentation of an area, as this type is above ground and does change the perception of an area. Green roofs, retention ponds, wadis and water squares also contribute to an increased aesthetic appreciation and contribute to pervious surface when performing this assessment.

4.3.12 Biodiversity

Next, the assessment of the biodiversity objective of SUDS is explained. Biodiversity refers to the number, abundance, and distribution of all living things on Earth. It includes species diversity, genetic diversity within species, and the range of habitats that support them [5]. Considering biodiversity as a design criterion means that natural local habitat and species should be supported and protected. It entails that the design should contribute to habitat connectivity and the achievement of local biodiversity goals. SUDS implementation should create ecosystems that are diverse, self-sustaining, and resilient.

Assessing the impact of SUDS on biodiversity is a time consuming process. Indicators sufficiently showing the effect of different SUDS types on biodiversity use field measurements before and after implementation. KPIs such as the ratio of native plant species, number of invasive alien species, and species richness increase directly measure the potential change in biodiversity. As in this research it is not possible to perform before and after field measurements, applying these KPIs falls outside the scope of this thesis. It is chosen to use a different indicator to assess SUDS performance on biodiversity, namely the Biotope Area Factor (BAF), which shows the ecological value of urban settlements. This indicator represents the functional green in an area, providing an insight into the potential for biodiversity in an area.

4.3.13 Biotope Area Factor (BAF)

With this KPI the absorbent properties of a surface are assessed [42]. It determines the part of an area that is ecologically useful. This indicator represents the potential to create and sustain biodiversity. Additionally, given the issue of heat islands, which have a negative impact on the health of the most vulnerable, this indicator provides a way to improve air quality and increase access to cooler city spaces. In terms of the built environment, it also aids in the resolution of urban flooding by lowering the degree of soil sealing.

The BAF represents the ratio of ecologically effective surface area to total site area and is calculated using the following equation [43]:

$$BAF = \frac{\sum Ecologically\ effective\ surface\ area * \ Ecological\ value\ factor\ per\ m^2}{Total\ surface\ area\ of\ lot} \tag{7}$$

To apply this formula, the following steps are taken:

1. Classification of subject area according to surface types
2. Assignment of ecological value factors
3. Calculation of BAF

Step 1: Classification of subject area according to surface type
Individual parts of a plot of land are weighted according to their ecological value. These individual parts are classified according to the surface types presented in Table 16. To conduct this classification, land cover data are required. These can be obtained via the conventional method of using topographic databases combined with visual interpretation, or via remote sensing data [42]. Because land-use maps describe the geographic distribution of natural resources and can be used to support decisions, their accuracy is critical in planning processes. The spatial heterogeneity in urban areas due to uneven distributed land uses and land cover types creates a difficult problem in the creation and interpretation of satellite images. In this research the conventional method is applied to retrieve the land cover map of both neighborhoods. Based on this input, the classification of the case study's surface types is conducted.

Step 2: Assignment of ecological value factors
The ecological value factors, presented in Table 16 are assigned according to the specific characteristics of a surface area. The main criteria used to assign ecological weights are high evapotranspiration efficiency, the ability to capture and store water in soil, the ability of powder fixation with a reduction in suspended dusts, the conservation and long-term development of soil functions (filtering, buffering, and transformation of pollutants and hazardous substances), and the availability of suitable habitats for plants and animals [44]. The ecological value factors are assigned according to the classified surface types obtained in the previous step.

Step 3: Calculation of BAF
The last step is to apply equation 7. This in done for each intervention strategy in the case study.

Table 16: Classification BAF [45]

Surface type	**Description**	**Weighting factor per m²**
Sealed	Impermeable surface to air and water, no plant growth e.g., concrete, asphalt, slabs with a solid subbase	0
Partially sealed	Permeable surface to air and water, no plant growth e.g., clinker brick, mosaic paving, slabs with a sand or gravel subbase	0.1
Semi-open	Permeable surface to air and water, water infiltration, but no plant growth, e.g., sand, gravel, clinker brick with high water infiltration	0.2
Greened	Permeable surface to air and water, water infiltration, plant growth e.g., gravel with grass, wooden cobbles, grass paving blocks	0.4
Surfaces with vegetation, unconnected to the soil below, small substrate thickness	Surfaces covered in vegetation and 20 to 40 cm of soil with no connection to the ground	0.5
Surfaces with vegetation, unconnected to the soil below, medium substrate thickness	Surfaces covered in vegetation and 41 to 80 cm of soil with no connection to the ground	0.6
Surfaces with vegetation, unconnected to the soil below, large substrate thickness	Surfaces covered in vegetation and 81 to 150 cm of soil with no connection to the ground	0.7
Surfaces with vegetation, unconnected to the soil below, very large substrate thickness	Surfaces covered in vegetation and more than 150 cm of soil with no connection to the ground	0.9
Surfaces with vegetation, connected to the soil below	Vegetation connected to the soil below, available for flora and fauna development	1
Rainwater infiltration per m2 of roof area	Rainwater infiltration for groundwater replenishment; infiltration over surfaces with existing vegetation	0.2
Water surface	Rainwater fed water surface, The weighting factor can be increased to 0.6 by establishing vegetation	0.5
Vertical greenery with connection to the ground	Direct connection of vertical greenery to soil, supply of nutrients and water directly over soil roots	0.5
Vertical greenery without connection to the ground	No direct connection of vertical or horizontal greenery on a wall to soil, permanent planters supplying the vegetation with artificial irrigation	0.7
Extensive roof greening	Naturalistic roof surface design with a substrate thickness of less than 20 cm and no artificial irrigation, weighting factor increases to 0.6 with through water retention systems	0.5
Semi-intensive roof greening	A combination of extensive and intensive roof greening with a substrate thickness ranging from 15 to 50 cm (depending on the plantings chosen), usually in conjunction with artificial irrigation	0.7
Intensive roof greening	Roof design resembling ground-based green areas with a substrate thickness greater than 50 cm, usually in conjunction with artificial irrigation	0.8

With the modelling approach and the methodologies of the applied KPIs in both the conventional framework and extended framework presented in this chapter, the assessment of the case study is carried out. A new assessment framework for SUDS-based storm water management solutions in an urban area is developed, namely the extended framework. The application of both frameworks is conducted of which the results are presented in the following chapter.

5 Case study

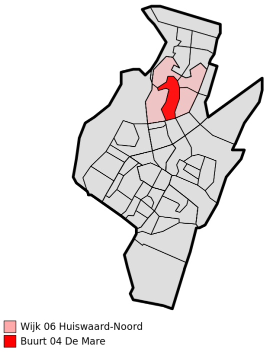
In this chapter, the case study on which the frameworks are applied is laid out. The aim of the application on a case study is to generate the results of both frameworks which are used as the necessary input data in the decision model of urban design. Firstly, an introduction into the research area is presented. This is followed by the modelling approach used in the assessment of this case study. Subsequently, the results of this case study assessment are presented. Lastly, this case study analysis is evaluated.

5.1 Research area

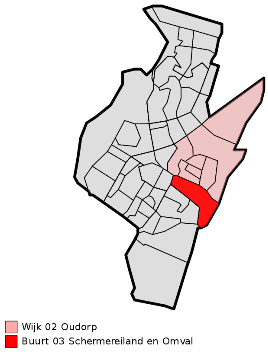
In this section an overview is given about the research area. This area is chosen to properly show the potential of SUDS-based storm water management solutions. This research is focused on the municipality of Alkmaar, the Netherlands. Alkmaar is located in the province North-Holland. The municipality is situated on soil composed of sand, peat and clay and is part of the polder areas in the Netherlands. Furthermore, Alkmaar contains a separate sewer system. The sewer system is designed to withstand a critical rainfall intensity of 20 mm/hrs. Such design storm has a return period of once every two years [46]. Furthermore, in the city of Alkmaar the groundwater level is maximum 70 cm below ground level in public areas.

In Alkmaar's urban water policy plan for 2017-2026, the municipality's strategy regarding water and sewerage is laid out. It addresses four prominent issues, namely flood risk, the ability of public space to withstand heavy precipitation, heat stress, and persistent droughts [47]. The environment is set as the central focus in this strategy, moving away from the conventional urban water handling approach of drainage via sewerage. The municipality aims to respond to new climate developments in a sustainable and future-proof way and act proactively. The focus is thereby mainly on the following spearheads: climate resilience, water awareness by implementing green infrastructures to tackle extreme precipitation events, improving live-ability of the urban area, and sustainable management and implementation of solutions. Additionally, for the municipality of Alkmaar, a strategy for climate-adaptive urban planning has been written. This is a supported strategy to organize the municipality in such a way it can be protected against the effects of climate change [48]. This strategy also expresses the effort made by the municipality towards integrated solutions to tackle urban climate-related challenges. It is thus concluded that there is the desire to implement nature-based solutions in Alkmaar.

For this research, two neighborhoods in the city of Alkmaar are chosen for the thesis' work to focus on. The area's are chosen based on the conducted climate stress-test by Arcadis, which results are shown in Figure 16 in Appendix B. As a pre-requisite, the neighborhoods chosen are both subject to stormwater nuisance. The neigborhoods chosen are 'De Mare' and 'Schermereiland en Omval', shown in Figure 5. More detailed maps of the neighborhoods are depicted in Figures 17 and 18 in Appendix C. An analysis of the conditions of both neighborhoods is conducted and is laid out in Appendix D.



(a) De Mare - Alkmaar [49]



(b) Schermereiland en Omval - Alkmaar [49]

Figure 5: Investigated neighborhoods in Alkmaar

5.2 Modelling approach

Both the conventional framework and extended framework are modelled in this research. In this assessment it is chosen to model four intervention strategies per neighborhood and to test the intervention strategies in two scenarios. The following sections lay out the approach taken in this research.

5.2.1 Intervention strategies

With the assessment of Alkmaar the four modelled intervention strategies regarding the combination and number of SUDS to be implemented are:

A. No change in design urban environment, i.e., no implementation of SUDS

B. SUDS implementation in 20-30% of the public space

C. Half of available public area is used for SUDS implementation

D. In almost all, 75%-100%, of public space SUDS are implemented

This research does not take into account SUDS implementation on private property. This study is conducted for the municipality of Alkmaar and private property falls outside the area in which the municipality is authorised to design the urban environment.

The locations at which SUDS are implemented in de Mare and Schermereiland en de Omval are depicted in Figure 6 and 7. The four intervention strategies per neighborhood contain an increasing number of SUDS following the previously noted approach. Not depicted in these maps is the increased use of sustainable road design. The public roads are developed sustainably for respectively 0, 20-30, 50, and a 100% of available public streets. Moreover, as only public space is used for the incorporation of SUDS, green roofs are implemented only on flat roofs of buildings owned by the municipality. Implementation of other SUDS types are subject to the site characteristics and available area in both neighborhoods.

The areas used for the implementation of the individual SUDS applied in the intervention strategies is given in Appendix K. In this section of the Appendix, Tables 56 and 58 show which streets are used for the implementation of sustainable road design per intervention strategy.

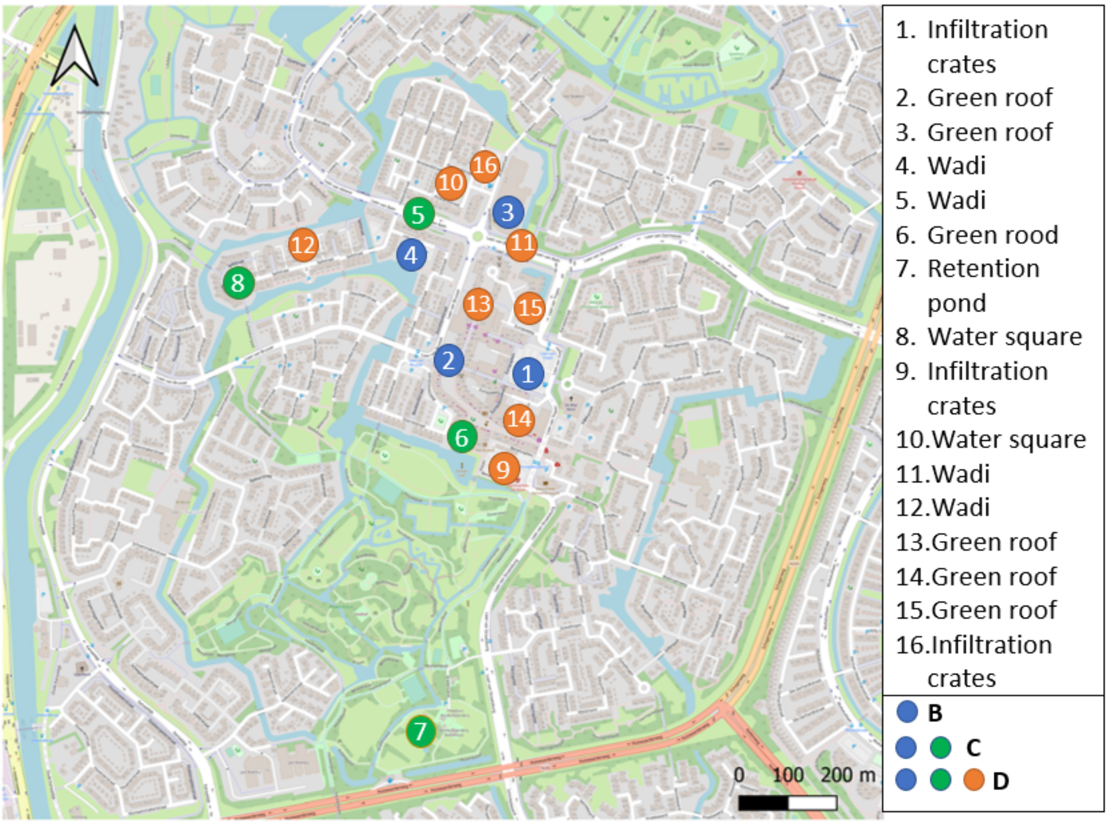


Figure 6: Intervention strategies de Mare. The numbered coloured dots show the locations for SUDS

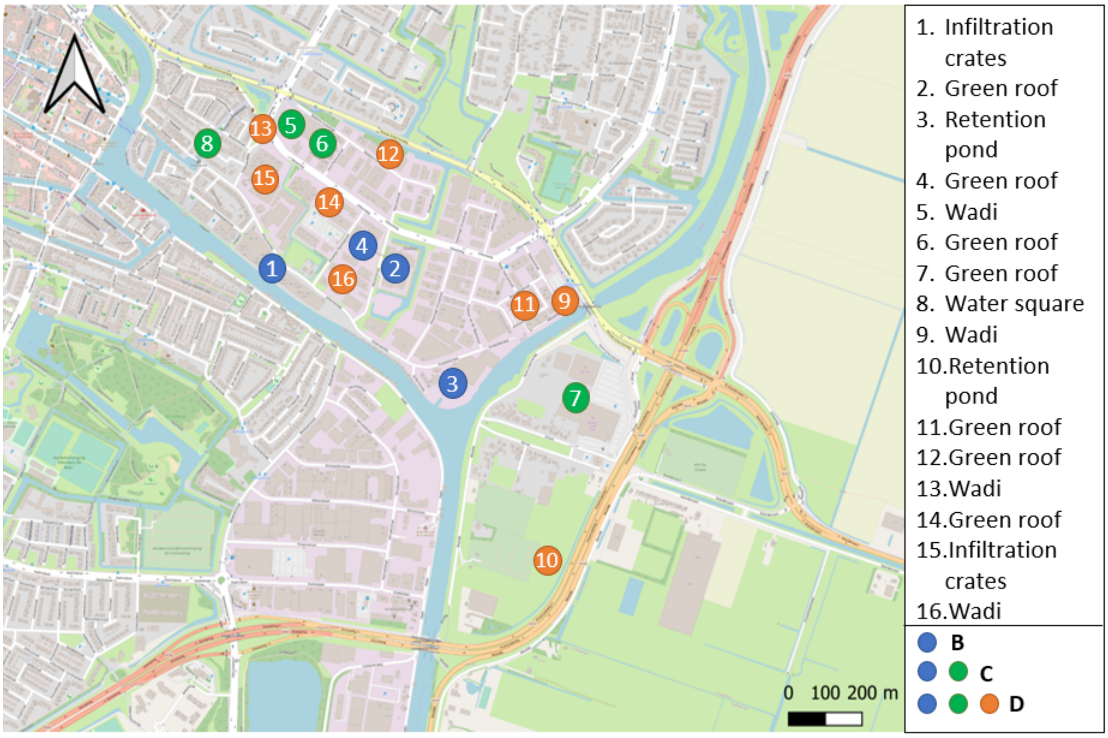


Figure 7: Intervention strategies Schermereiland en de Omval. The numbered coloured dots show the locations for SUDS

5.2.2 Scenarios

This research models two scenarios: the current climate assessment and a future climate for resilience assessment.

With increasing influence of climate change and urbanization on urban development, these factors should be taken into account when designing sufficient urban response systems in urban areas. However, this research is applied to neighborhood scale, in which both neighborhoods are not likely to change due to urbanization. Urbanization scenarios need to be included when considering a larger scale, for example on city scale, as at that level multiple variables are prone to change because of population growth and the increasing density and area of cities associated with urbanization. Variables affected by urbanization on larger scales include the amount of impervious area, the number of inhabitants, water consumption, and the need for proper infrastructure amongst others.

To find out how climate change affects urban design, this assessment uses the KNMI'14 climate scenarios for 2050. The KNMI's climate scenarios are based on the scientific insights from the IPCC report of 2013. The IPCC is the United Nations climate panel. With the KNMI scenarios, KNMI translates the global climate projections of the IPCC into a description of possible climate change in the Netherlands. Considering a strong, +2°C, and moderate, +1°C, temperature increase for 2050, a distinction is made in the scenarios between the influence of changing air currents being low (L) and high (H). The four KNMI'14 scenarios together describe the boundaries within which climate change in the Netherlands is likely to take place:

- WH: strong temperature rise (warm), high value change air currents
- WL: strong temperature rise (warm), low value change air currents
- GH: moderate temperature rise, high value change air currents
- GL: moderate temperature rise, low value change air currents

This research, following the recommendation of the STOWA, Rioned and the KNMI, models the future climate for resilience assessment by applying the WH scenario of the KNMI climate scenarios. Not all indicators used in this study are however subject to a changing climate. The indicators originating from engineerings practice, which include the average investment cost, water storage capacity, and maintenance score, are calculated based on site characteristics and/or characteristics of the design of an intervention strategy. These input variables are independent of the areas climate. KPIs chosen that assess land use in the urban environment are not subject to change as the input variables do not differ with changing climate, namely the indicators BAF, SPI, PRC and impervious area of the extended framework. The vulnerability of climate change is thus tested solely via the indicators EAD and TCS. By modelling EAD and TCS for 2050, the effect of climate change on flood risk and heat stress is investigated.

EAD

While applying the assessment methodology for this indicator laid out in section 4.3.5, the following case specific steps are taken with the application of the scenarios:

- Return periods chosen include 2, 25, 50, 100, 250 and 1000 years. For the choice of storm events based on these return periods a hydrological response time of 1 hour is chosen. While short hydrological response times are recommended for flat urban areas, this research follows engineering practice of using a response time of an hour.

- Following engineering practice, the upper bandwidth of the WH scenario for 2050 is applied to the prediction of increase of storm events. This leads to an increase of 21.3% of the current intensity of precipitation for each return period in 2050.

The storm events that used for both scenarios are shown in Table 17.

Table 17: Storm events applied in modelling EAD

Return period (years)	**Current intensity mm/hour**	**2050_WH mm/hour**
2	20	24.3
25	39.5	47.9
50	47.7	57.9
100	57.7	70.0
250	74.5	90.4
1000	110.6	134.2

TCS

With the application of the methodology to obtain the TCS laid out in section 4.3.5, the following case specific steps are taken in the modelling approach of this case study:

- To model the PET in Tygron, the weather conditions of July 1st in 2015 are chosen as heat day. The perceived temperature in degrees Celsius for the period 12:00-18:00 local time on this hot summer day is modelled. This is a hot day that occurs approximately once every 5.5 years in the current climate. It is hereby chosen to follow the method of the Klimaateffectatlas [50], which is commissioned by the Ministry of Infrastructure and Water Management of the Netherlands.

- With the application of the resilience check, the WH-scenario of the KNMI results in a perceived temperature rise of 3 °C in 2050 in the Netherlands [50]. This rise of the perceived temperature is used for the PET analysis in this scenario.

5.3 Results case study

In this case study assessment results are obtained for the conventional framework as well as the extended framework. In this section, an overview of the results is shown. Firstly, the results are presented of the application of the conventional framework. Secondly, the results for the application of the extended framework are shown. The results for both these frameworks are elaborated per KPI in Appendix L. Lastly, the case study results are analysed and their influence on this research is laid out.

The results of the case study assessment using the conventional framework are laid out in Tables 18 and 19. In the conventional framework there is no difference between the results of the two scenarios analyzed. This as the KPIs used cannot model the effect of climate change. Firstly, Table 18 shows the results obtained for de Mare.

Table 18: Results conventional framework, de Mare

Intervention strategy	**Water storage capacity (mm)**	**Average investment cost (*10^6 €)**
A	13	0
B	21	8.5
C	27	12
D	42	21

The results obtained from the assessment of the intervention strategies in Schermereiland en de Omval are shown in Table 19.

Table 19: Results conventional framework, Schermereiland en de Omval

Intervention strategy	**Water storage capacity (mm)**	**Average investment cost (*10^6 €)**
A	15	0
B	19	8
C	25	13
D	41	22

Subsequently, the results for the extended framework are presented. Firstly, the results obtained for current climate scenario applied to the neighborhood de Mare are shown in Table 20.

Table 20: Results extended framework current climate scenario for de Mare

Intervention strategy	**EAD**	**SPI (TSS)**	**SPI (ORG)**	**SPI (PAH)**	**SPI (HM)**	**PRC (Cd)**	**PRC (Cu)**	**PRC (Ni)**	**PRC (Zn)**	**PRC (TSS)**	**TCS**	**Impervious area**	**BAF**	**Average investment cost**	**Maintenance score**
	*10^6 €	-	-	-	-	%	%	%	%	%	-	-	-	*10^6 €	-
A	0.38	0.35	0.37	0.18	0.23	0	0	0	0	0	57.44	0.47	0.479	0	1.00
B	0.29	0.34	0.35	0.17	0.22	0.3	0.6	1.5	0	1.2	58.33	0.41	0.512	8	0.60
C	0.22	0.33	0.34	0.16	0.21	1.6	1.7	3.7	1.8	3.4	58.36	0.37	0.528	12	0.68
D	0.18	0.32	0.31	0.14	0.18	1.3	2.5	6.1	2.9	4.9	58.41	0.30	0.567	21	0.64

Only the results of the EAD and TCS change in the future scenario. In Table 21 the performances of the intervention strategies on these KPIs for the resilience assessment are presented.

Table 21: Results of KPIs EAD and TCS for future climate in 2050 in de Mare

Intervention strategy	**EAD *10^6 €**	**TCS -**
A	0.71	44.15
B	0.54	44.74
C	0.43	44.77
D	0.35	44.82

Furthermore, in Table 22 an overview is shown of the results obtained during the assessment of the current climate in Schermereiland en de Omval.

Table 22: Results extended framework current climate scenario for Schermereiland en de Omval

Intervention strategy	**EAD**	**SPI (TSS)**	**SPI (ORG)**	**SPI (PAH)**	**SPI (HM)**	**PRC (Cd)**	**PRC (Cu)**	**PRC (Ni)**	**PRC (Zn)**	**PRC (TSS)**	**TCS**	**Impervious area**	**BAF**	**Average investment cost**	**Maintenance score**
	*10^6 €	-	-	-	-	%	%	%	%	%	-	-	-	*10^6 €	-
A	1.9	0.42	0.46	0.32	0.37	0	0	0	0	0	7.23	0.67	0.266	0	1
B	1.5	0.42	0.45	0.31	0.36	0.1	0.7	0.7	0.3	1.2	7.97	0.64	0.281	8	0.66
C	1.4	0.41	0.43	0.30	0.35	0.9	1.7	2.0	1.1	3.2	8.68	0.61	0.297	13	0.67
D	1.3	0.40	0.41	0.29	0.33	1.3	2.2	3.6	1.7	6.3	8.82	0.57	0.318	22	0.73

Lastly, the results obtained during the resilience check of Schermereiland en de Omval are depicted in Table 23.

Table 23: Results of KPIs EAD and TCS for future climate in 2050 in Schermereiland en de Omval

Intervention strategy	EAD $*10^6$ €	TCS -
A	2.3	4.82
B	2.2	5.31
C	2.1	5.79
D	2.0	5.88

The results show that when more SUDS are implemented, the performance on the KPIs assessing water quantity, water quality, amenity and biodiversity improves. The results obtained for intervention strategies B, C and D improve compared to the results of intervention strategy A, which includes no SUDS implementation. Only on cost the performance worsens. This is however a logical result, as with an increasing number of SUDS implementation, the investment needed to implement these SUDS increases. The performance improvements are laid out in Figures 40 and 41 in Appendix M.

In the following sections, first the effect of the modelling approach on the results is presented. Subsequently, the influence of the assessment methodologies developed for the KPIs on the results from the case study assessment is laid out.

5.3.1 Modelling approach

With the set up of the intervention strategies, soil contamination influencing infiltration possibilities is not taken into account. Locations where soil remediation is needed, for example the soil between Schermerweg and Jaagpad, are used as locations for SUDS implementation regardless of present contamination. Secondly, with the implementation of green roofs, the foundation of buildings to account for the extra force resulting from the implementation is not considered. It is assumed that all public flat roofs are suitable for the application of green roofs. This is however not the case in real-life.

However, as this research's objective is to show the effect on the decision making process of applying a more complete set of KPIs of SUDS, these factors are neglected. The case study acts as an example to apply the KPIs, and these limitations do not affect the objective of this study.

5.3.2 Expected Annual Damages (EAD)

With the calculation of the EAD, a threshold of 20 cm water depth is used before storm water causes any damage to buildings. This is an estimate of the real situation. It is based on the difference in depth between the middle of the streets and the entrance to the buildings. In real-life, this difference is not the same for all locations. The EAD presented in this research is thus an estimation, and the real EAD may differ from the results reported in this research.

Additionally, the depth-damage curves used originate from the end of 2019. The damages might currently be higher, as prices have increased rapidly over the last years.

It is important to be aware of these aspects while using the results of the EAD. However, because this threshold and the depth-damage curves have little influence on the differences in results between the intervention strategies, the impact on the decision making process is small.

5.3.3 Site Pollution Index (SPI)

It is important to note that with the application of the SPI, a limited range of SUDS types is used. Not all used SUDS types have data available for this assessment. The influence of infiltration crates and water squares is not considered. While these SUDS types do not treat water quality in their design, infiltration crates and water squares positively influence the water quality in an area when maintained properly according to Amsterdam Rainproof [51][52]. This because these SUDS types have the ability to store and/or infiltrate water into the ground, reducing the amount of storm water needed to be drained by the sewer system. Reducing the peak flow to the sewers lowers the risk of sewer overflows to the surface water bodies. Combined sewer overflows decrease the quality of the receiving water as sewer waste is released to surface water bodies without treatment.

Furthermore, pathogen pollution is not considered with the determination of the SPI. No index data is currently available for this type of pollution. However, research has shown that SUDS influence pathogen pollution in an area. For example, Sales-Ortells and Medema [53] showed that the exposure to human pathogens increased in water squares with recreational value, meaning an increased risk to human health.

Due to insufficient input data for all considered SUDS types and pathogen pollution, these are excluded from the assessment whilst they do influence the pollution present in the area in real-life. This is important to note for the decision making process, as the results obtained in the case study might be an under- or overestimation of the true SPI.

5.3.4 Pollutant Removal Capacity (PRC)

In this research, the PRC from the total storm water inflow into the neighborhoods is calculated per intervention strategy. The results obtained showed small removal capacities. However, if the SUDS types are considered at an object scale these removal capacities are much larger. In Appendix N these results can be found. This indicator is therefore sensitive to the scale it is applied to and manner which it is applied in.

Important to note is that this indicator uses the ability of SUDS types to remove pollutant concentrations per liter of storm water inflow. This indicator is therefore independent of the amount of storm water inflow. This capacity of removal of the SUDS types is considered to be infinite meaning that the SUDS types work at their optimum level, even when the SUDS types might not be able to treat the storm water inflow at their optimal capacity. In real-life, the SUDS types might for example contain blockages whereby it will not be possible to capture the pollutants within the SUDS types anymore. Therefore, the results presented in this research might be an overestimation of the true removal capacity.

Moreover, this indicator does not take into account all SUDS types used in the intervention strategies. It is important to note that infiltration crates, green roofs, and water squares are left out from the calculation as there is a lack of sufficient data available for these SUDS types. The total PRC of the intervention strategies might therefore turn out to be higher in real-life.

Considering both water quality indicators, it is important to note that storm water quality can vary greatly over time per location and even at one location. This is partly due to the influence of hydraulic processes, including flow velocity and shear stresses, on the amount of undissolved components that run off to which contaminants such as metals are bound.

5.3.5 Thermal Comfort Score (TCS)

In this research, the outdoor thermal comfort is assessed by determining the TCS on July 1st of 2015. However, other results are obtained when another heat day is chosen. Additionally, in this research the TCS is based on the average perceived temperature between 12 and 6 in the afternoon, following the Klimaateffectatlas [50]. However, a different time slot can also be chosen, leading to a different TCS. Changing both these approaches influence the results of this KPI, but the effect of these most likely does not influence the decision of the best intervention strategy in a later state. This because in this research SUDS are only applied in public area and the not all types of SUDS used influence the perceived temperature in an area. However, this should be investigated in further research as the influence of this choice of heat day and time frame can have a larger influence in other applications.

5.3.6 Impervious area

In the assessment of amenity with the application of the indicator impervious area no differentiation is made between the influence of different types of SUDS on the aesthetics of an area. In real-life, the different SUDS types could have different contributions to aesthetic appreciation. In this research, this nuance is assumed to be negligible but it is recommended to investigate this in further research.

5.3.7 Biotope Area Factor (BAF)

With the determination of the BAF, the implementation of sustainable road design did not change the outcome. Most residential streets in the case study are built with clinker bricks, and the implementation of sustainable road design does not change the assigned surface type. If the surface type does not change, the same ecological value factor is used and therefore results in no change of BAF.

In this research, the implementation of green roofs is considered to be the extensive roof greening surface type. This is the most simple form of green roofing available in the classification of surface types of this indicator. This type is chosen as this option is assumed to be the most likely green roof type to be implemented on the available public flat roofs, as it leads to the lowest effect on the buildings structure concerning weight and management. However, implementing semi-intensive or intensive roof greening would lead to higher BAF results.

With the application of this indicator to the Mare, the results for the neighborhood excluding the park Rekerhout show a much larger increase of the BAF score. This is shown in Table 24. As stated in section D.1 this neighborhood contains only a small amount of green per household when the park is excluded. The BAF score increase relating to the SUDS implementation in the intervention strategy in this built-up part of the neighborhood causes a larger increase of BAF when only that part of the neighborhood is considered. When the entire neighborhood is considered, the BAF scores increases with 7%, 10%, and 18% with intervention strategy B, C, and D compared to doing nothing. When excluding Rekerhout in the analysis, the BAF scores increase with 53%, 94% and 158% respectively. This is interesting to note, as it is in the municipality's interest to increase the available green space per household in the part of the neighborhood that is not the Rekerhout.

Table 24: Nuance in BAF results de Mare

Intervention strategy	**Biotope Area Factor (BAF)** *Total area*	*Area excl. Rekerhout*
A	0.479	0.106
B	0.512	0.162
C	0.528	0.205
D	0.567	0.273

When evaluating the results of the BAF for the second neighborhood, a distinction is made between the results looking at Schermereiland and de Omval seperately and together. The neighborhood consists of both these parts. However, the land use is very different in both parts. Just looking at de Omval itself, it contains a lot of green space, having a high BAF score. Schermereiland is the densely built industrial area which the municipality of Alkmaar wants to change. Considering only the area of Schermereiland, the intervention strategies show a larger increase in BAF score than when looking at the whole neighborhood, which is important to consider when using this indicator.

Table 25: Nuance in BAF results Schermereiland en de Omval

Intervention strategy	**Biotope Area Factor (BAF)**		
	Total area	*Schermereiland*	*de Omval*
A	0.266	0.102	0.608
B	0.281	0.129	0.608
C	0.297	0.144	0.629
D	0.318	0.185	0.619

As shown in both de Mare and Schermereiland en de Omval, applying this indicator is affected by the scale it is applied to. The scale used can be determined based on the desire of the client for which the framework and this indicator are applied.

Lastly, regarding all indicators used in the framework, the performance of SUDS is inherently variable and depends on a wide range of variables. These include, amongst others, the concentration of inflow, climate and time of year, the condition of the component, the design characteristics of particular components, and the rainfall intensity and duration of any particular event [5]. The results obtained with the assessment could turn out differently in real-life as a result of these variables. This should be taken into consideration when using this framework for the performance assessment of SUDS.

The results of the case study analysis obtained in this chapter form the input needed to carry out the comparison between both framework, which is elaborated in the subsequent chapter. Taking into account this evaluation while using the results, the effect of both frameworks on a municipalities decision-making process is discussed.

6 Interventions Selection using Existing and Extended KPIs with MCDA

In this chapter, the decision model has been simulated for urban design. The preferred intervention strategies are identified for multiple different stakeholders for both frameworks. The goal of this simulation of the selection process is to investigate what the influence is of using either of the two frameworks on the choice of optimum intervention strategy.

To identify the best intervention strategy multiple steps are taken. Figure 8 gives an overview of these steps. The first two steps, the design and evaluation of the alternatives, which are the intervention strategies, are laid out in chapter 5. Based on the obtained results of this case study assessment, a MCDA is applied to find the best alternative, using the Compromise Programming (CP) method. To apply this decision-making tool decision matrices are built for both frameworks, the conventional and extended framework, in which the choices of the normalization factors are included. This is followed by the development of the user preferences according to decision drivers of stakeholders. Based on the application of the user preferences to the matrices, the CP method is applied leading to the identification of the best intervention strategy for the stakeholder assessed.

Firstly, the CP method is explained in section 6.1. This is followed by an elaboration of the decision matrices formulated for the case study, laid out in section 6.2. Subsequently, the two approaches taken for the distribution of user preferences are presented in section 6.3. Lastly, based on the decision matrices and user preferences, the CP method is applied and the best intervention strategies are identified, which is laid out in section 6.4.

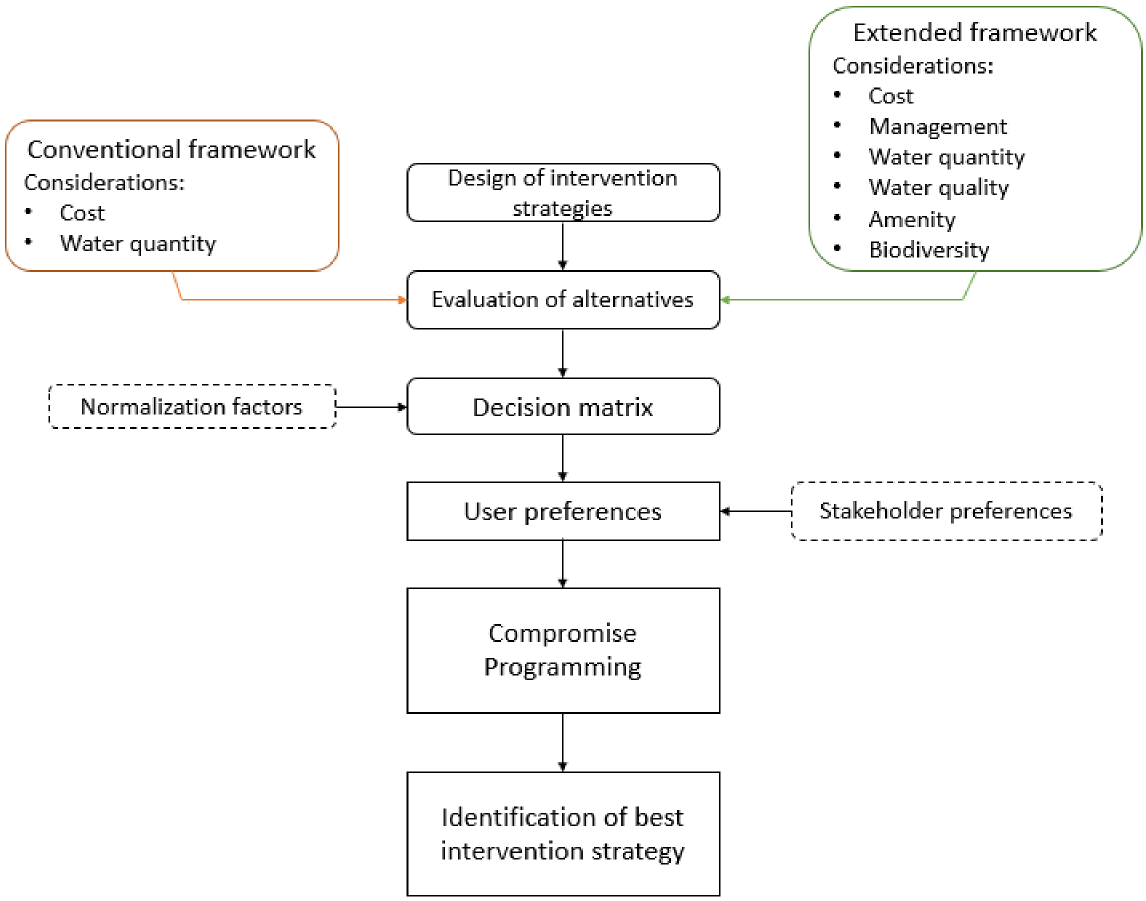


Figure 8: Flowchart of steps in decision making process of urban design

6.1 Compromise Programming (CP) method

A MCDA is a method used to help people make complex decisions by taking into account multiple different criteria or factors that are relevant to the decision. In a MCDA process, the different criteria are defined and weighted according to their importance, and then the possible options are evaluated against those criteria to determine the best option. This can be a useful tool for helping people make decisions in situations where there are many different factors to consider, and where it is difficult to compare the options using a single metric. There are a lot of different types of MCDAs. In this research, the CP method is applied to the results of the case study analysis of both frameworks.

The CP method calculates a distance function for each strategy based on a subset of efficient solutions, called the compromise set, that are nearest to an ideal point for which all criteria are optimized. These distances are then used to rank the strategies. In the CP method the user preferences are expressed as criteria weights, making this method more suitable for less experienced users. The distance function of this method is calculated with the following equation [54]:

$$minimise\ L_{\mathrm{p}} \ = \ \left[\sum_{i=1}^{n\ criteria} \left(\frac{w_{\mathrm{i}}(f_i^* - f_{\mathrm{i}})}{f_i^* - f_{\mathrm{i}^*}} \right)^{\mathrm{p}} \right]^{1/\mathrm{p}} \quad , w_{\mathrm{i}} > 0,\ 1 \leq p \leq \infty \tag{8}$$

In this equation f_{i} is the evaluation function. The variable w_{i} represents the weight or relative importance of each criterion. The minimum and maximum absolute values of the evaluation function are symbolozed by f_{i^*} and f_i^* respectively. Lastly, p indicates the topological metric. In this research p is taken as 2, meaning the Euclidean plate is used. Using a larger value for p leads to more weight to the maximum, which is undesirable in this research.

6.2 Decision matrices

A decision matrix is an useful tool to facilitate decision making because these matrices help to systematically evaluate and compare different options based on specific criteria. A decision matrix is created by identifying the available options, here intervention strategies, and criteria, here the KPI's that assess the performance of the intervention strategies regarding considered objectives, used to evaluate these options on. For each option, the result obtained in the case study analysis is added to the matrix indicating how well that option performs on each KPI.

As the decision matrices built in this research are used as input for the CP method, it is noted if the distance function should be minimized for each KPI in Tables 26 27, 29, 30, 31, and 32. Furthermore, the normalization factors are included in these decision matrices. The normalization factors are taken as the minimum and maximum absolute value able to be obtained for each indicator. Only the normalization maximum for the KPI average investment cost is different, as for this KPI the normalization maximum is taken as the maximum investment cost possible when the total amount is considered instead of the average.

For both neighborhoods, the decision matrices are built based on the results of the performance analysis of the intervention strategies presented in Appendix L. The conventional framework consists of one decision matrix for each neighborhood. With the analysis of the extended framework, both the current climate and a resilience check are carried out, leading to two decision matrices per neighborhood.

6.2.1 Conventional framework

In the conventional framework, the water quantity and cost aspects of an intervention strategy are considered when designing an urban area. Water quantity is assessed by calculating the water storage capacity of each strategy. This indicator is not minimised, as a strategy's performance improves on this KPI when a higher capacity is obtained. The costs are taken into account by considering the average investment costs of each option. It is desired to keep investment costs as low as possible, therefore this indicator is minimised in the CP method.

Table 26 shows the decision matrix for de Mare. The results for the four intervention strategies per indicator and the corresponding normalization factors are laid out in this matrix.

Table 26: Decision matrix conventional framework, de Mare

Considerations **Indicator**	**Water quantity** *Water storage capacity*	**Cost** *Average investment cost*
Units	mm	*10^6 €
Minimisation?	FALSE	TRUE
Normalization minimum	0	0
Normalization maximum	42	34
A	13	0
B	21	8.5
C	27	12
D	42	21

The decision matrix including normalization factors for the conventional framework for Schermereiland en de Omval is depicted in Table 27.

Table 27: Decision matrix conventional framework, Schermereiland en de Omval

Considerations **Criteria**	**Water quantity** *Water storage capacity*	**Cost** *Average investment cost*
Units	mm	10^6 €
Minimisation?	FALSE	TRUE
Normalisation minimum	0	0
Normalisation maximum	42	29
A	15	0
B	19	8
C	25	13
D	41	22

6.2.2 Extended framework

In the extended framework, in addition to considering water quantity and cost, the performance of the intervention strategies regarding water quality, amenity, biodiversity and management is assessed. In this framework, water quantity is assessed by the EAD which is a direct measure of flood risk. This monetary indicator is minimised as the cost associated with flooding is desired to be as low as possible. Water quality is measured via either using the SPI or PRC. The SPI is minimised, as the closer to zero, the better this index. The PRC is maximised, as the higher this percentage the less the polluted the discharge of storm water. The TCS and impervious area results represent the amenity performance of an option. As alternatives perform better when the TCS is higher, minimisation is not applied. With a decreasing impervious area, amenity increases meaning minimisation of the distance function is applied for this KPI. In the extended framework, the maintenance score introduced in engineering practice is used. The closer to the maximum value of 1 the result is, the better an intervention strategy scores on this KPI. It is therefore not minimised in the distance function of the CP method.

First, the two decision matrices retrieved for de Mare are shown in Tables 29 and 30. The matrices obtained for Schermereiland en de Omval are depicted in Tables 31 and 32. There only appear differences between the matrices of the current climate and resilience check in the column of the indicators EAD and TCS, as in this framework solely these indicators are affected in their input data by climate change.

6.3 User preferences

In the CP method, user preferences are used to reflect the relative importance of different considerations in a decision-making process. These preferences are typically assigned by the decision-maker or by a group of stakeholders, and they serve as a way to prioritize the considerations and guide the decision-making process. It is important to note that user preferences are subjective and are influenced by personal biases and preferences of stakeholders involved in the decision-making process. Therefore, it is crucial to carefully select the considerations involved in the decision and their relative importance when assigning user preferences in a MCDA.

Two main approaches are taken while assigning these preferences. Firstly, equal weighting of all considerations taken into account is applied. Subsequently, a simulation of a real-life urban design team using the extended framework is conducted.

6.3.1 Equal weighting

With the application of equal weights to the conventional framework, the user preferences assigned to both water quantity and costs are 0.5. They are both assessed by a single indicator, namely the water storage capacity and average investment cost.

With the application of the CP method to the extended framework, equal weighting is applied twice. This to ensure water quality is not weighted twice in the decision making process as the SPI and PRC are not mutually exclusive. The total weight distributed over the considered aspects of urban design is 1.

Table 28: Equal weight distribution extended framework

	User preferences															
	Water quantity	**Costs**	**Management**	**Water quality**										**Amenity**		**Biodiversity**
	Expected annual damage	*Average investment cost*	*Maintenance Score*	*Site Pollution Index*				*Pollutant removal capacity*						*Thermal Comfort Score*	*Impervious area*	*BAF*
				TSS	ORG	PAH	HM	Cd	Cu	Ni	Zn	TSS				
1	0.2	0.2	0.2	0.05	0.05	0.05	0.05	-	-	-	-	-		0.1	0.1	0.2
2	0.2	0.2	0.2	-	-	-	-	0.04	0.04	0.04	0.04	0.04		0.1	0.1	0.2

Table 29: Decision matrix extended framework for current climate de Mare

Considerations	**Water quantity**				**Water quality**							**Amenity**	**Biodiversity**	**Cost**	**Management**
Indicators	*EAD*	*SPI-TSS*	*SPI-ORG*	*SPI-PAH*	*SPI-HM*	*PRC-Cd*	*PRC-Cu*	*PRC-Ni*	*PRC-Zn*	*PRC-TSS*	*TCS*	*Impervious area*	*BAF*	*Average CAPEX*	*Maintenance*
Units	$*10^6$ €	-	-	-	-	%	%	%	%	%	-	-	-	$*10^6$ €	-
Minimisation?	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE
Normalisation minimum	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
Normalisation maximum	0.38	1.00	1.00	1.00	1.00	100.00	100.00	100.00	100.00	100.00	100.00	1.00	1.00	34	1
A	0.38	0.35	0.37	0.18	0.23	0	0	0	0	0	57.44	0.47	0.479	0	1.00
B	0.29	0.34	0.35	0.17	0.22	0.3	0.6	1.5	0	1.2	58.33	0.41	0.512	8	0.60
C	0.22	0.33	0.34	0.16	0.21	1.6	1.7	3.7	1.8	3.4	58.36	0.37	0.528	12	0.68
D	0.18	0.32	0.31	0.14	0.18	1.3	2.5	6.1	2.9	4.9	58.41	0.30	0.567	21	0.64

Table 30: Decision matrix extended framework of resilience check de Mare. The blue cells indicate the changed results compared to the current climate.

Considerations	**Water quantity**				**Water quality**							**Amenity**	**Biodiversity**	**Cost**	**Management**
Indicators	*EAD*	*SPI-TSS*	*SPI-ORG*	*SPI-PAH*	*SPI-HM*	*PRC-Cd*	*PRC-Cu*	*PRC-Ni*	*PRC-Zn*	*PRC-TSS*	*TCS*	*Impervious area*	*BAF*	*Average CAPEX*	*Maintenance*
Units	$*10^6$ €	-	-	-	-	%	%	%	%	%	-	-	-	$*10^6$ €	-
Minimisation?	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE
Normalisation minimum	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
Normalisation maximum	0.71	1.00	1.00	1.00	1.00	100.00	100.00	100.00	100.00	100.00	100.00	1.00	1.00	34	1
A	0.71	0.35	0.37	0.18	0.23	0	0	0	0	0	44.15	0.47	0.479	0	1.00
B	0.54	0.34	0.35	0.17	0.22	0.3	0.6	1.5	0	1.2	44.74	0.41	0.512	8	0.60
C	0.43	0.33	0.34	0.16	0.21	1.6	1.7	3.7	1.8	3.4	44.77	0.37	0.528	12	0.68
D	0.35	0.32	0.31	0.14	0.18	1.3	2.5	6.1	2.9	4.9	44.82	0.30	0.567	21	0.64

Table 31: Decision matrix extended framework for current climate Schermereiland en de Omval

Considerations	**Water quantity**				**Water quality**						**Amenity**		**Biodiversity**	**Cost**	**Management**
Indicators	*EAD*	*SPI-TSS*	*SPI-ORG*	*SPI-PAH*	*SPI-HM*	*PRC-Cd*	*PRC-Cu*	*PRC-Ni*	*PRC-Zn*	*PRC-TSS*	*TCS*	*Impervious area*	*BAF*	*Average CAPEX*	*Maintenance*
Units	$*10^6$ €	-	-	-	-	%	%	%	%	%	-	-	-	$*10^6$ €	-
Minimisation?	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE
Normalisation minimum	1.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
Normalisation maximum	1.85	1.00	1.00	1.00	1.00	100.00	100.00	100.00	100.00	100.00	100.00	1.00	1.00	29	1
A	1.85	0.421	0.457	0.318	0.370	0	0	0	0	0	7.23	0.67	0.266	0.00	1.00
B	1.50	0.415	0.445	0.311	0.359	0.1	0.7	0.7	0.3	1.2	7.97	0.64	0.281	8	0.66
C	1.41	0.409	0.432	0.304	0.349	0.9	1.7	2.0	1.1	3.2	8.68	0.61	0.297	13	0.67
D	1.29	0.395	0.410	0.289	0.329	1.3	2.2	3.6	1.7	6.3	8.82	0.57	0.318	22	0.73

Table 32: Decision matrix extended framework of resilience check Schermereiland en de Omval. The blue cells indicate the changed results compared to the current climate.

Considerations	**Water quantity**				**Water quality**							**Amenity**	**Biodiversity**	**Cost**	**Management**
Indicators	*EAD*	*SPI-TSS*	*SPI-ORG*	*SPI-PAH*	*SPI-HM*	*PRC-Cd*	*PRC-Cu*	*PRC-Ni*	*PRC-Zn*	*PRC-TSS*	*TCS*	*Impervious area*	*BAF*	*Average CAPEX*	*Maintenance*
Units	$*10^6$ €	-	-	-	-	%	%	%	%	%	-	-	-	$*10^6$ €	-
Minimisation?	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE
Normalisation minimum	1.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
Normalisation maximum	2.28	1.00	1.00	1.00	1.00	100.00	100.00	100.00	100.00	100.00	100.00	1.00	1.00	29	1
A	2.28	0.421	0.457	0.318	0.370	0	0	0	0	0	4.82	0.67	0.266	0.00	1.00
B	2.16	0.415	0.445	0.311	0.359	0.1	0.7	0.7	0.3	1.2	5.31	0.64	0.281	8	0.66
C	2.06	0.409	0.432	0.304	0.349	0.9	1.7	2.0	1.1	3.2	5.79	0.61	0.297	13	0.67
D	1.98	0.395	0.410	0.289	0.329	1.3	2.2	3.6	1.7	6.3	5.88	0.57	0.318	22	0.73

6.3.2 Real-life simulation

As mentioned in section 2.4.1 there are multiple stakeholders involved in urban design. To mimic a real-life decision-making process of urban design in a municipality, a team is simulated with different roles representing different perspectives of urban design. Four team members influencing the choice of urban design are considered: a project manager, an urban designer, a technical manager, and a water manager. The assigned weights are shown in Table 33.

Table 33: User preferences per stakeholder, extended framework

	User weights														
	Water quantity	**Costs**	**Management**	**Water quality**									**Amenity**		**Biodiversity**
	Expected annual damage	*Average investment cost*	*Maintenance Score*	*Site Pollution Index*				*Pollutant removal capacity*					*Thermal Comfort Score*	*Impervious area*	*BAF*
				TSS	ORG	PAH	HM	Cd	Cu	Ni	Zn	TSS			
PM 1	0.2	0.4	0.1	0.025	0.025	0.025	0.025	-	-	-	-	-	0.05	0.05	0.1
PM 2	0.2	0.4	0.1	-	-	-	-	0.02	0.02	0.02	0.02	0.02	0.05	0.05	0.1
UD	0.1	-	-	-	-	-	-	-	-	-	-	-	0.3	0.3	0.3
TM	0.3	0.2	0.3	-	-	-	-	-	-	-	-	-	0.1	0.1	-
WM 1	0.4	-	-	0.1	0.1	0.1	0.1	-	-	-	-	-	0.1	0.1	-
WM 2	0.4	-	-	-	-	-	-	0.08	0.08	0.08	0.08	0.08	0.1	0.1	-

The project manager is responsible for the team. His/her focus lies on making sure that the team does not overshoot the budget while balancing the preferences of other team members. However, this role's primary interest is the associated costs of a design. This role's decision drivers therefore focus on balancing all stakes, but putting most weight towards cost.

Secondly, the urban designer is interested in the attractiveness of an urban area, focusing on creating better places for people and nature. Decision making depends on the criteria amenity and biodiversity. This role also represents an inhabitant of an urban area, as its interests regarding urban design are similar.

Furthermore, the technical manager is responsible for the management of an urban design after construction. This person maintains the design to ensure it does not deteriorate. However, this team-member also influences the choice of design. The main decision driver of this role is the maintenance of a design. Additionally, the technical manager is interested in both the capital and operational costs.

Lastly, the water manager focuses on ensuring that storm water in an area is drained away without causing nuisance. This role considers both the quantity and the quality of water in its decision-making and the factors that (in-)directly influence these factors.

6.4 Identification of best alternative

In this section, the final step of the decision making process shown in Figure 8 is taken. With the application of the CP method, using the defined decision matrices and user weights, the optimum intervention strategies are identified. Firstly, the results of the CP method applied with equal weights are presented. Subsequently, the findings of the real-life simulation of an urban design team are laid out.

6.4.1 Equal weighting

When the conventional framework is used to base the choice of design on, the CP method identifies intervention strategy C as optimum design for both de Mare and Schermereiland en de Omval, which is shown in Figure 9. However, in Schermereiland en de Omval the difference between strategies B and C (0.001) is negligible, and option B is also identified as the best choice.

The conventional framework includes two KPIs that are calculated based on the characteristics of the design of the intervention strategies. Because the design of the intervention strategies for both neighborhoods follows the same pattern of increasing number of SUDS implementation, the results obtained in the assessment of the individual neighborhoods are similar. This leads to similar decision matrices in the CP method, which results in almost the same rankings of intervention strategies identified for the two neighborhoods of the case study.

In Schermereiland en de Omval intervention strategy B ranks best together with option C because of the choice of normalization maximum. The maximum investment costs used as normalization maximum is much closer to the maximum result obtained than in de Mare, leading to much smaller range by which the results are normalized in the CP method. The maximum investment costs possible is lower for Schermereiland en de Omval as the combination of SUDS types applied in intervention strategy D showed a lower maximum in its range of costs. The differences in the results obtained in Schermereiland en de Omval between option B and C are relatively negligible. When equal weights are applied these intervention strategies have the same preference.

Intervention strategy C ranks best for this framework because relative to the normalization factors the performances of the subsequent intervention strategies on the KPI water storage capacity improve more than the investment cost increase. Comparing the results of the case study assessment while considering the normalization factors, the improved performance of intervention strategy C compared to B is larger in de Mare.

The influence of the choice of normalization factors is highlighted by this result. In this research the normalization maximum of the investment costs is chosen to be the maximum investment costs possible and not the maximum result reported in the case study results. When this normalization maximum is changed to the maximum result reported in the decision matrix, the CP method reports intervention strategy B as the best option in both neighborhoods. In Schermereiland en de Omval, intervention strategy B is clearly the best option in this case. However, in de Mare intervention strategy C is still a close second with only a 0.01 difference. This difference is much larger when the maximum possible investment cost is used as normalization maximum, in which strategy C has a 0.03 smaller distance than B in de Mare. Furthermore, intervention strategies A and D score as either the best or worst performing strategy on the two KPIs for both neighborhoods. Changing the normalization factor of the investment costs results in the exactly the same CP distances for these options instead of identifying strategy D as the third best choice. This follows from the the application of equation 8, in which the results of intervention strategy A and D are then the exact same as the normalization factors.

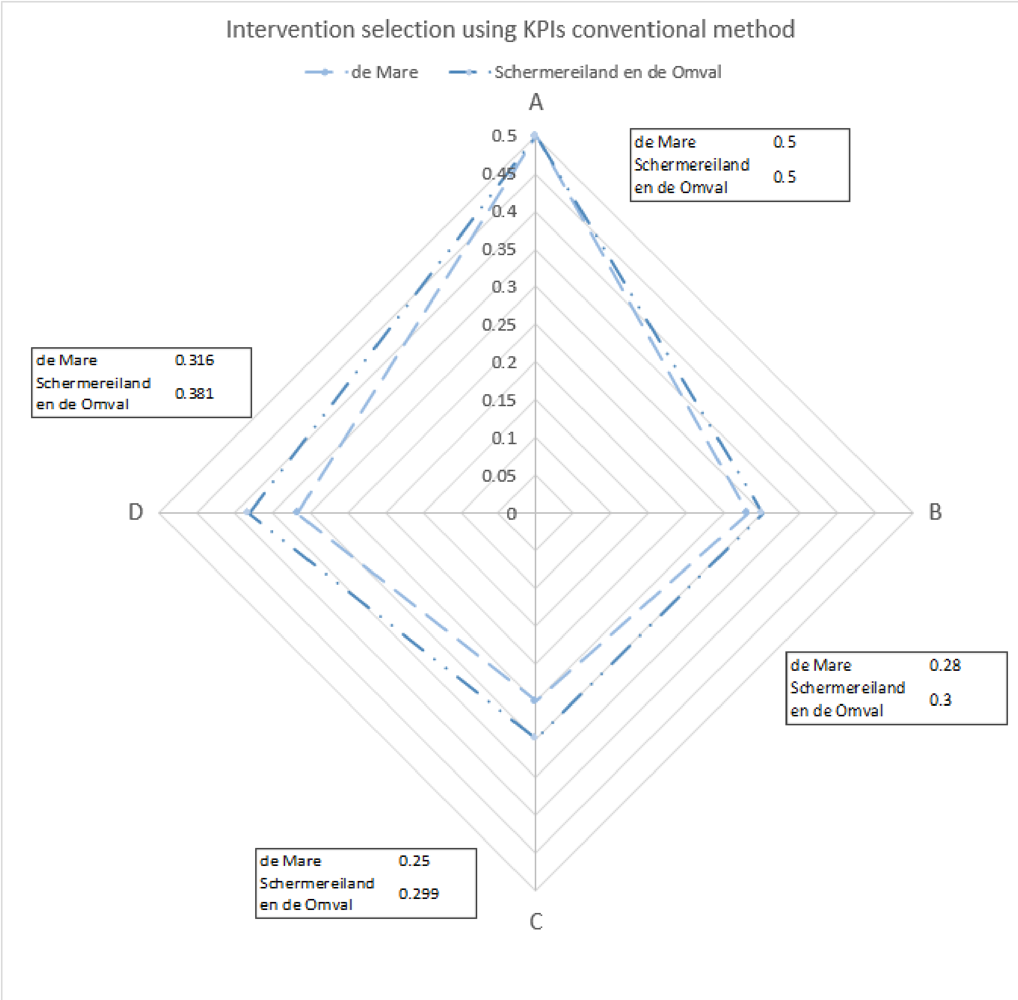


Figure 9: Results CP method using equal weighting applied to KPIs of conventional framework

The application of the extended framework does not change the optimum intervention strategy in de Mare regardless of use of water quality indicator (SPI or PRC) and climate scenario analysed (current and future). Using the extended framework, the CP method also selects intervention strategy C as the best choice in Figure 10a. This corresponds to the ranking for the conventional framework showed in Figure 9. However, the extended framework does increase the attractiveness of intervention strategy D in de Mare. Applying the CP method to the results of this framework changes the order of preference from C-B-D-A to C-D-B-A. With intervention strategies C and D including the most implemented SUDS, this extended framework supports the choice for strategies including more SUDS implementation in de Mare even though they are more costly.

In Figure 10b, the results of the CP method for Schermereiland en de Omval are shown. When this MCDA is applied to the results of the current climate of the extended framework applied, this tool selects two best intervention strategies, B and C, with a negligible difference in CP distance of 0.001. This is the same as the ranking obtained for the conventional framework shown in Figure 9. However, the extended framework does identify one best option for the future scenario for resilience assessment. The resilience analysis identifies intervention strategy C as the single best choice, as is depicted in Figure 10b. The two KPIs in the extended framework of which the results show the largest differences between the performance results of the case study are EAD and investment cost. These KPIs have the largest influence on the choice of design in this case study. Additionally, changing the normalization factors to the minimum and maximum obtained results of the case study assessment for the other KPIs did not influence the rankings obtained, indicating EAD and investment costs are the most influencing KPIs. Compared to the results of the analysis of the current climate in Schermereiland en de Omval, the KPI EAD resulted in a larger decrease in damages from intervention strategy B to D in the 2050 climate scenario. With more intense rainfall associated with climate change, the EAD decreases more with SUDS implementation in this neighborhood. This causes a larger influence on the CP method, resulting in intervention strategy C becoming the optimum design.

While in de Mare the use of the extended framework to base the selection on results in an increasing desirability of intervention strategy D, this intervention strategy still ranks third in Schermereiland en de Omval regardless of the choice of water quality indicator and climate scenario analysed. This is because the result for intervention strategy D has a percentage-wise higher decrease in EAD compared to no SUDS implementation (strategy A) in de Mare than in Schermereiland en de Omval. While the the total reduction of EAD between intervention strategy A and intervention strategy D (SUDS in circa 100% of public space) is around 0.5 million Euro, this is lower than the percentage-wise change seen in de Mare. However, in de Mare this is only 0.2 million Euro. When normalization is applied to the decision matrix, the results with a larger percentage-wise difference have more influence on the CP method. However, as the results of the investment costs are similar in both neighborhoods, this difference in reduced damages might be interesting to the municipality of Alkmaar when they are considering their options for design. This because more damages are prevented in Schermereiland en de Omval when more SUDS are implemented. It is therefore important to analyse individual results from the extended framework when they are used to base a decision on.

Moreover, by distributing the weights equally over the considerations addressed in the extended framework leads to smaller differences in ranking of the intervention strategies compared to the outcome of the conventional framework. For example, the difference between the CP distance of the best and worst choice of intervention strategy is much smaller. In the conventional framework, this difference is 0.25 for de Mare and 0.2 for Schermereiland en de Omval, as shown in Figure 9. Using the KPIs from the extended framework in the decision making process shows differences between the optimum and the worst choice between 0.04 and 0.07 in the neighborhoods in the tested scenarios. This is a logical result as more effects of SUDS are taken into account. The results from the assessment of the case study with the extended framework showed results with little differences between the intervention strategies' performances on 5 out of 8 KPIs. This is a consequence of the modelling approach taken in this research. Only public space is used and a limited range of different SUDS types resulting in these small differences in performances on neighborhood scale.

Subsequently, the optimum intervention strategy obtained from the CP method are almost similar for both neighborhoods in the case study. This is due to the modelling approach taken in this research. With the same increase of public space used for SUDS implementation per intervention strategy, the performances of the KPIs changes with almost the same amount per subsequent intervention strategy in both neighborhoods.

Furthermore, the following takeaways from this approach using the extended framework are important to highlight:

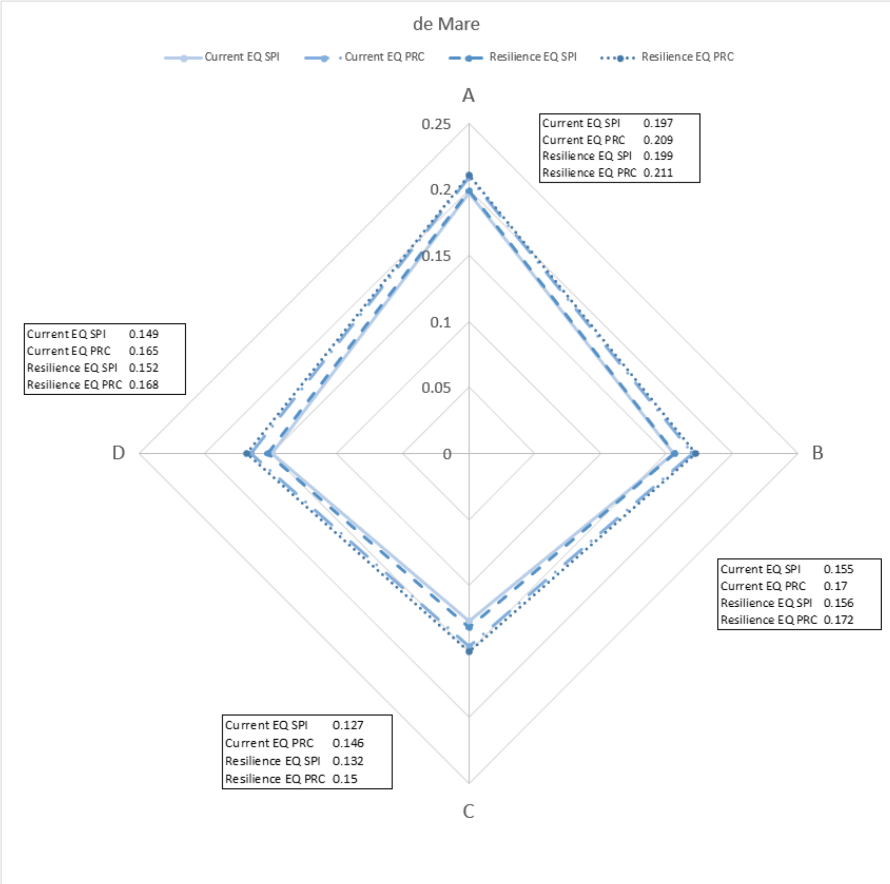
- *Climate change*: Climate change needs to be taken into account in the decision making for this specific case study when applying equal weights. While de Mare shows no difference in preferred intervention strategy, Schermereiland en de Omval does show a clearer optimum intervention strategy in Figure 10b, namely intervention strategy C.

- *Influence of SPI*: The SPI has little effect on the outcome of the MCDA in this case study when equal weights are applied. For example, considering the current climate scenario, Figures 11a and 11c depict little difference between the normalized indicators values of the available intervention strategies for the SPI. This is a result of the small difference between the results retrieved from the case study assessment. This is the consequence of the modelling approach used in this research, as stated previously. The modelling approach uses an increasing amount of public space for each subsequent intervention strategy. However, because public space is only a small portion of the whole area and only three of the SUDS types used in this research affect the SPI, only small differences occur between the performance results.

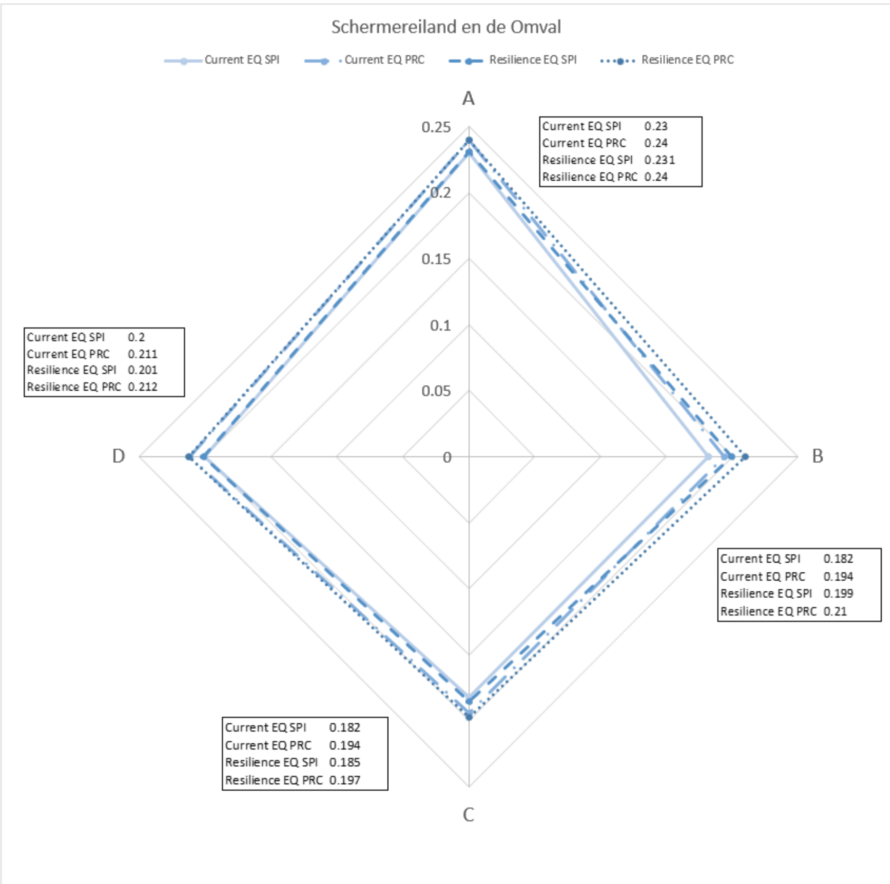
- *Influence of PRC*: In this case study, the PRC contributes little to the outcome of the CP method when equal weights are assigned. This is shown in Figures 11b and 11d, as there are no differences depicted between the normalized values of each intervention strategy for this KPI. The modelling approach of SUDS taken in this study has as a consequence that the results of the PRC for the intervention strategies are very similar. Taken on this scale, the total amount of pollutant removed compared to the total inflow over the whole area is small as only little space in both neighborhoods is considered public space which is used for implementing SUDS in. Furthermore, the normalization factors used are the minimum and maximum outcome possible for this indicator, which has a much larger range in between then the results of the case study assessment.

- *Choice of water quality indicator*: In this case study using equal weighting, the same order of preference of intervention strategies is obtained using either of the two water quality indicators in the extended framework. For both scenarios in both neighborhoods, the rankings are similar when either SPI or PRC is used. In de Mare the order of preference ranging from best to worst choice is C-D-B-A, as is shown in Figure 10a. In Schermereiland en de Omval this is C-B-D-A. This is however subject to the characteristics of this case study, as these rankings are based on the results obtained in the assessment of the case study. In the methodologies developed in the extended framework for these KPIs, only limited space is used leading to little effect of SUDS on the storm water quality. Moreover, for both KPIs there is no data available for all the SUDS types used in the intervention strategies, possibly leading to an underestimation of the effect and less differences between the results obtained.

- *TCS*: The TCS contributes little to the ratings obtained for this case study. The results for this indicator obtained in the assessment of the case study show little differences between the intervention strategies. This results in close normalized indicator values for the intervention strategies for this KPI, for example depicted in Figure 11 for the current climate. This also holds for the future resilience scenario. The types of SUDS used in this research have little effect on the temperature in an area as they do not provide any shade and/or limited SUDS types used in the assessment increase the amount of green in an area which lowers the temperature.

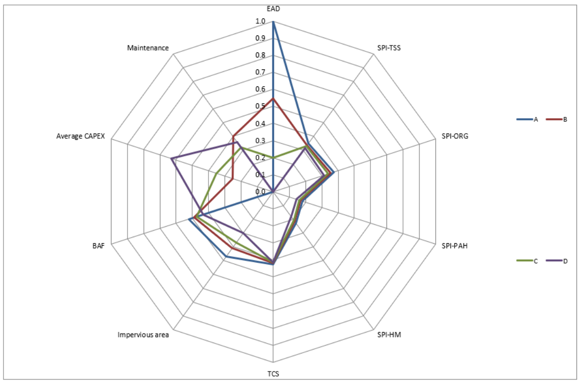


(a) de Mare

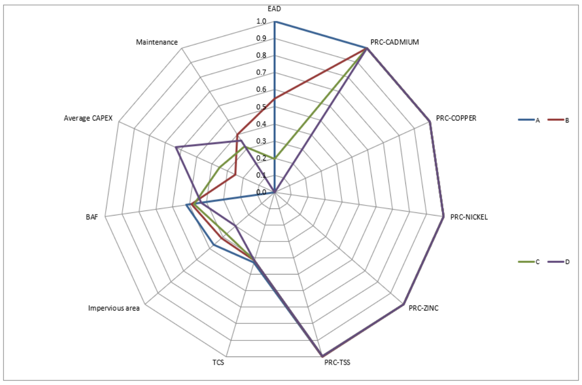


(b) Schermereiland en de Omval

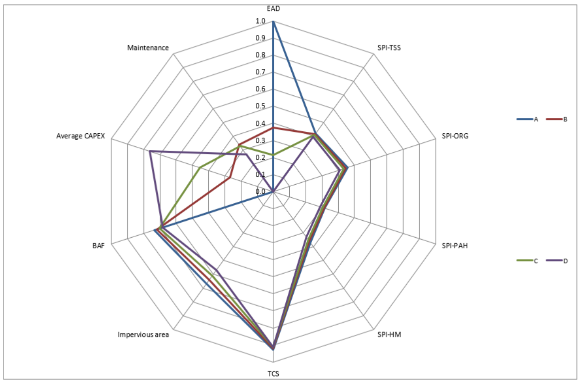
Figure 10: Simulation decision making process using the extended framework. The results of the CP method are shown. In this analysis, the user weights are distributed equally and the different scenarios are depicted.



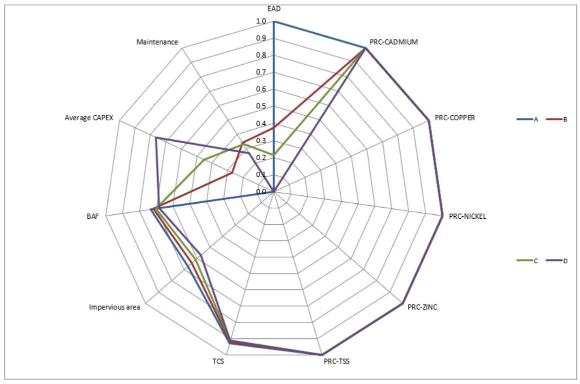
(a) Using SPI, de Mare



(b) Using PRC, de Mare



(c) Using SPI, Schermereiland en de Omval



(d) Using PRC, Schermereiland en de Omval

Figure 11: Normalized indicator values in CP method. Equal weights are applied to the considerations of urban design for the current climate scenario.

6.4.2 Simulation urban design stakeholders

Figures 12 and 13 show that the selection of optimum intervention strategy differs per stakeholder. The rankings obtained for the CP method differ per stakeholder. Each stakeholder is modelled with its own user preferences, influencing the KPIs that are used in the CP method.

When investment costs are not considered, which is not done by the urban designer and water manager, the ranking obtained from the CP method is D-C-B-A (best to worst option) in all cases. In the assessment of the case study, the performances on the KPIs EAD, TCS, impervious area and BAF improve when more SUDS are implemented. The subsequent intervention strategies from A to D are designed to include an increasing number of SUDS. When only considering these KPIs for the selection of design, it automatically translates to an increased appeal of choosing intervention strategies including more SUDS.

Noteworthy are the CP distances obtained for the urban designer. The difference in CP distance between the best and worst choice of intervention strategy is small compared to other stakeholders. The urban designer considers the KPIs EAD, TCS, impervious area and BAF in its decision, with EAD only having little weight. The small difference in CP distances follows from the results obtained from the performance assessment with this extended framework. With the application of the different SUDS types used in this research and only implementing SUDS in public space, the difference between the performances of the intervention strategies on the TCS is negligible. This additionally results in only small differences in results obtained in the case study for the KPIs impervious area and BAF. The CP method calculates similar CP distances when such close results are used as input in equation 8.

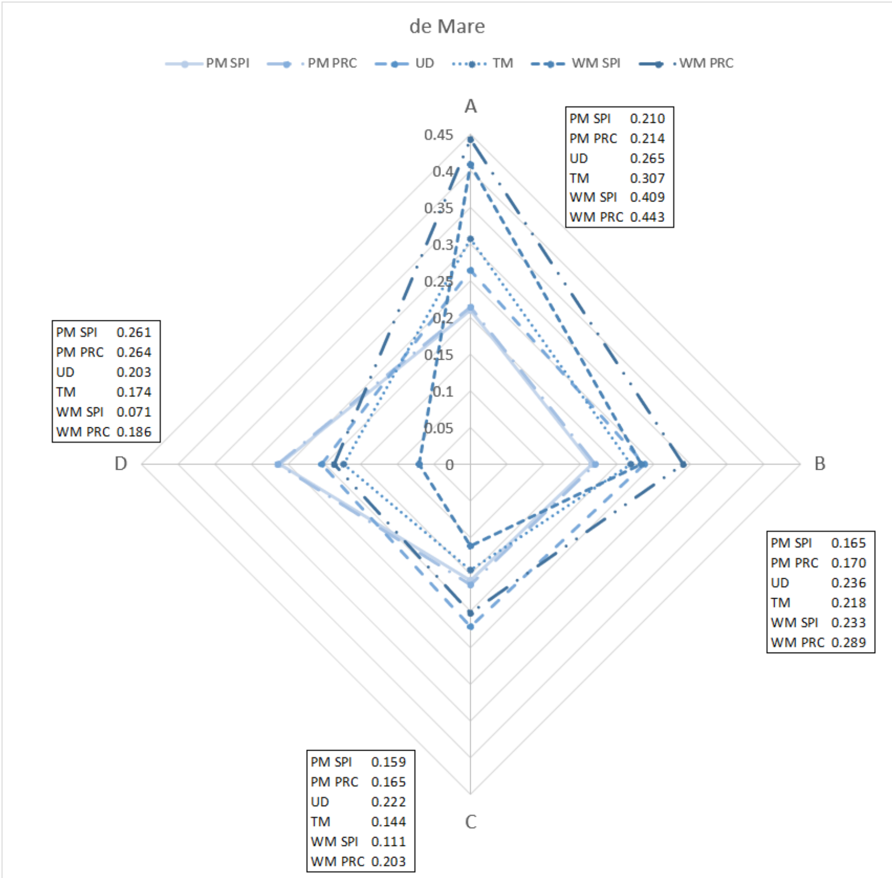
Subsequently, a difference is shown between results of the urban designer in de Mare in Figure 12 and Schermereiland en de Omval in Figure 13. In de Mare the CP distances are much smaller than in Schermereiland en de Omval. This is a consequence of the TCS results obtained in both neighborhoods. In de Mare the comfort level is much more pleasant (between 40-60) than in Schermereiland en de Omval (between 4 and 9). De Mare includes a large park, while Schermereiland en de Omval is mostly industrial area. De Mare is therefore a much more thermally pleasant area to be in. Considering these results relative to the normalization factors of this KPI, the CP distances obtained for de Mare are much lower than those of Schermereiland en de Omval as they are much closer to the normalization maximum which is the best result possible.

The CP method identified intervention strategy C as the best option to implement for the technical manager in both neighborhoods. Interestingly, when considering the results of Schermereiland en de Omval for the technical manager, the resilience assessment changes the ranking of the intervention strategies. In the current climate intervention strategy B shows as second best option, while the desirability of this choice reduces significantly in the resilience assessment. Figure 13b depicts intervention strategy B with a CP distance of 0.242 for the resilience assessment compared to a CP distance of 0.196 in the current climate shown in Figure 13a. This follows from the results obtained in this neighborhood for the EAD in the future climate scenario in combination with the normalization factors applied. While the total possible decrease of damages associated with SUDS implementation is more significant in the current climate (0.5 million Euro), the smaller difference seen in the future scenario (0.3 million Euro) results in normalized values in the CP method that increase the preference level of strategy D.

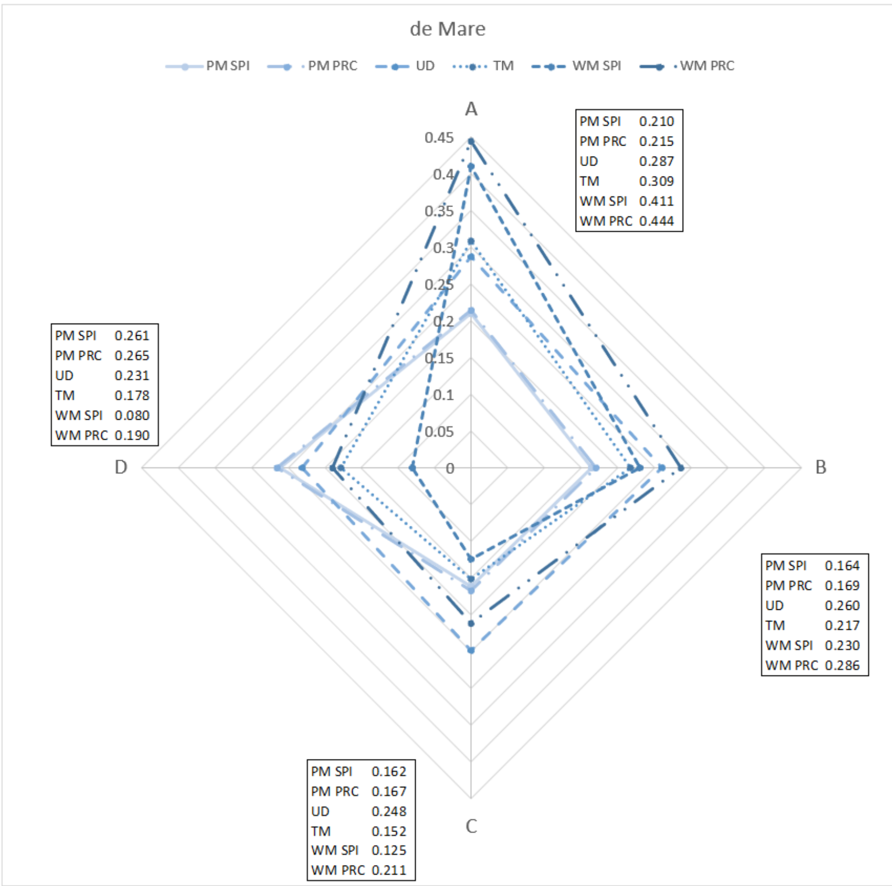
This reduction in difference between the maximum and minimum EAD for the future climate scenario follows from the application of the depth damage curve (Figure 32). In the future climate scenario, the maximum water levels are reported higher than in the current climate. At higher water levels, the depth-damage curve is less steep. This indicates that the associated damages decrease at a lower rate with these higher water levels.

While the CP method resulted in the same ranking for the water manager when either of the water quality indicators was used, there is still a significant difference between the results of both indicators seen in both neighborhoods. When looking at the CP distances using SPI (WM SPI) in Figures 12 and 13, these are a much smaller than those obtained with the PRC. This is a result of the influences of these KPIs as explained in the previous section. The SPI results are relatively a much closer to their best performance than the results of the PRC. The CP distances calculated with equation 8 are therefore larger.

In this simulation of stakeholders, it is shown that the extended framework is able to be used to better express the interests of different individual stakeholders in the decision making process compared to the conventional framework. This because a wider range of effect of SUDS implementation is assessed in the extended framework. The results obtained in this framework give a more holistic view of the influence of SUDS. Stakeholders can choose their indicators of interest from a larger set of KPIs to base their decision on. This simulation also showed that no single intervention strategy is the best for all considered stakeholders. In real-life a group of stakeholders affects the decision making process and a compromise is made between stakeholders. In this research for both neighborhoods, intervention strategy C is the best option when a compromise is made. Considering all four stakeholders and both scenarios, this intervention strategy ranks either first or second in most applications of the CP method.

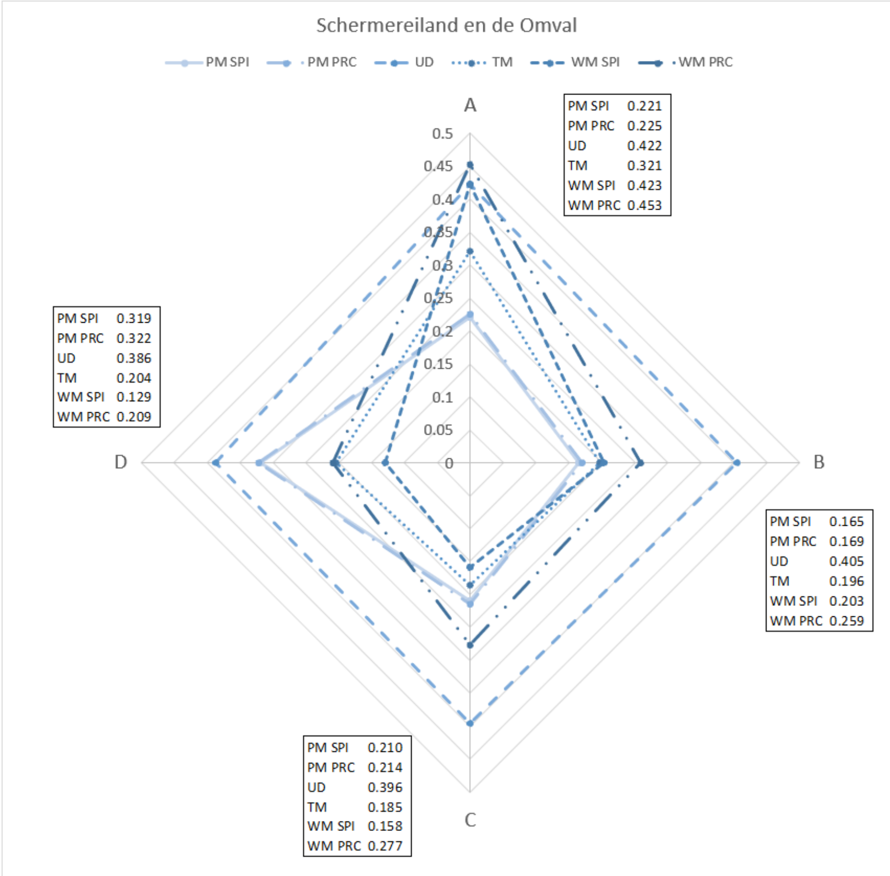


(a) Current climate

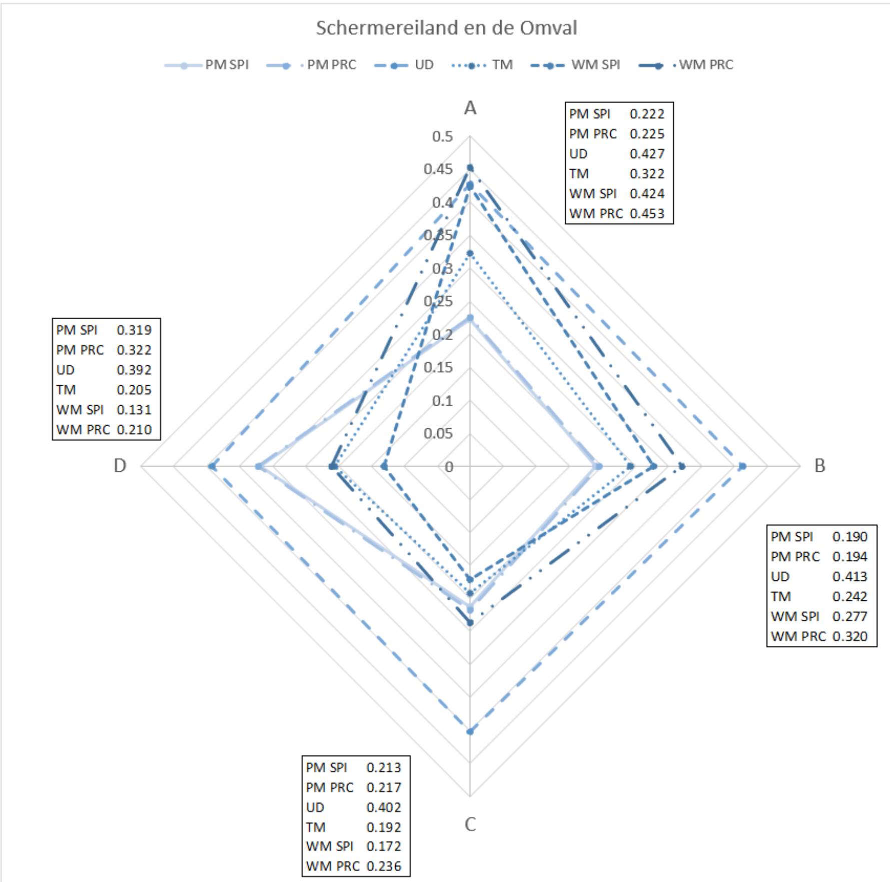


(b) Future resilience assessment for 2050

Figure 12: Simulation decision making process of urban design stakeholders for de Mare using the extended framework. The results of the CP method for both scenarios are shown.



(a) Current climate



(b) Future resilience assessment for 2050

Figure 13: Simulation decision making process of urban design stakeholders for Schermereiland using the extended framework. The results of the CP method for both scenarios are shown.

7 Discussion

In this chapter the contribution of this research towards its objective is discussed in section 7.1. Secondly, the limitations of this research are presented in section 7.2. Furthermore, the scientific relevance of this research is discussed in section 7.3. Lastly, the significance of this research for engineering practice is reviewed in section 7.4.

7.1 Research contribution

The objective of this research is to build an assessment framework for SUDS-based storm water management implementation in an urban area to help Dutch municipalities improve their decision making to improve the live-ability of the urban environment. This objective is split into three parts for which the contribution of this research is discussed, namely:

1. The development of an assessment framework for SUDS-based storm water management implementation in an urban area
2. Improvement of decision making process
3. Improvement of live-ability of the urban environment

7.1.1 The development of an assessment framework for SUDS-based storm water management implementation in an urban area

To address the first part of the objective of this thesis, the following two sub questions were formulated:

1. *What are the Key Performance Indicators of Sustainable Urban Drainage Solutions in urban areas?*
2. *What is the best way to evaluate the selected Key Performance Indicators of Sustainable Urban Drainage Solutions in urban areas?*

To built an assessment framework, the steps described in section 2.5 are carried out, which include the definition of objectives, criteria and KPIs. The multi functionality of SUDS is taken into account with the formulation of the objectives and criteria. The objectives are based on the four design pillars of SUDS. To categorize KPIs for each objective, criteria are defined. The assessment of the performance of SUDS include technical, environmental, operation and maintenance, social and urban community benefits, economic, and legal and urban planning criteria [34]. For each objective the indicators belong to one of these criteria. A literature review is conducted to find out what the available KPIs for assessment of SUDS are. This resulted in a list of 112 KPIs to assess SUDS on, which are laid out in chapter 3.5. With this knowledge obtained, sub question one is answered.

The total number of KPIs that can assess SUDS is not limited to the ones mentioned in this research. With the rising interest in this subject this number in increasing rapidly. In this study, suitable KPI's are selected to use in the proposed framework. With this selection, the suitability to engineering practice and the Dutch environment is taken into account. Furthermore, data availability influenced the choice of KPIs and other indicators might be preferred in other case studies. For example, while it is known in the case study that soil contamination is present, the effect of SUDS on soil quality is not assessed. Data availability limited the choice of KPIs that could be included in the extended framework. With the choice of KPIs, the second sub question is addressed with the formulation of the assessment methodologies. To formulate the best way to assess the selected KPIs, methodologies are researched in literature and the applicability to the case study is considered. This to ensure the developed methodologies are suitable for the Dutch environment. With this last step, the new framework, called the extended framework, is established. An overview of the development of this framework is presented in Figure 14.

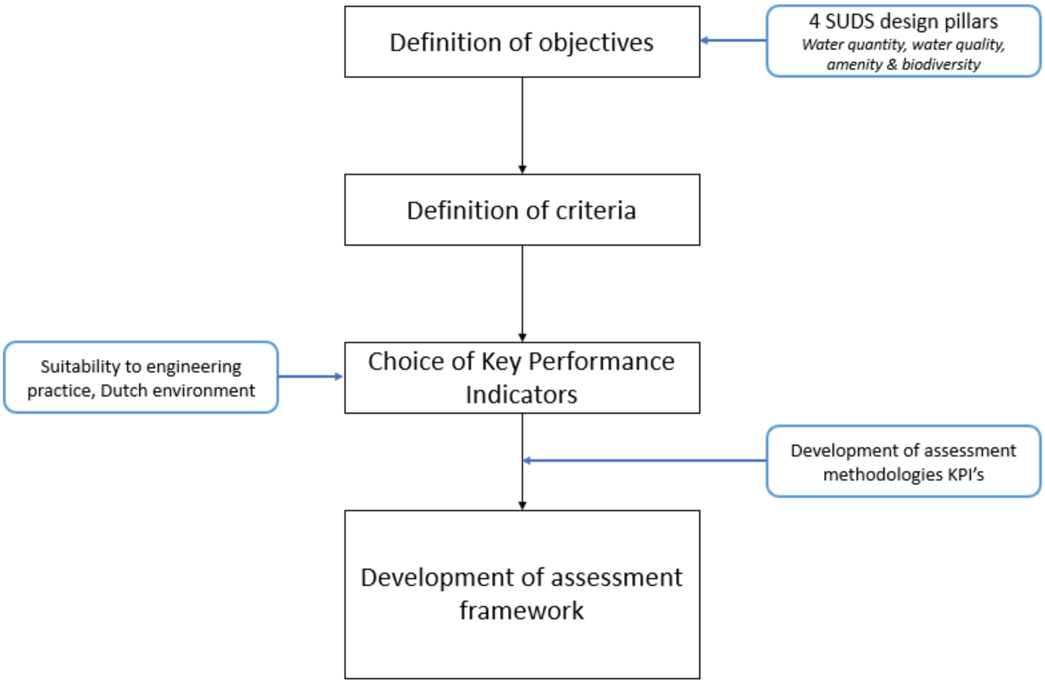


Figure 14: Set up of assessment framework SUDS-based storm water management implementation

7.1.2 Improvement of decision making process

To be able to show the effect of the developed assessment framework on the decision making process, this study proposed two sub questions:

3 *What is the performance of the highlighted Sustainable Urban Drainage Solutions in the case study on the selected Key Performance Indicators?*

4 *How does the framework developed in this research compare to the method currently used in engineering practice?*

To address the third sub question, both frameworks are applied to a case study, presented in chapter 5, and the performances of the SUDS combinations of the intervention strategies are determined. Based on the results obtained in this case study assessment, the decision making process for this case study is simulated with the use of the CP method, which is laid out in chapter 6. Based on the outcomes of this CP method, the most defining differences between the influence of the two frameworks on the decision making process are discussed in this section, thereby addressing the fourth sub question.

Firstly, the identification of the best intervention strategies for both frameworks showed that the extended framework has the ability to change the order of preference of the intervention strategies in the decision making process. Considering an equal weight distribution, the best intervention strategy identified in this case study is the same for either framework. However, the difference between attractiveness of the intervention strategies decreases when using the

KPIs of the extended framework. Also, the second and third best intervention strategies were observed to change or become clearer in the case study when the results of the KPIs of the extended framework are used in the CP method. This shows the potential of this new framework to lead to different conclusions in other applications.

Secondly, the outcomes of the simulation of real life stakeholders of the decision process showed that the optimum intervention strategy changed when different preferences were applied to the decision. The conventional framework includes only two KPIs to assess SUDS on. The extended framework adds six KPIs which all assess different effects of SUDS implementation. Using the extended framework to base the decision making process on makes it more easy to express different stakeholders due to the addition of these KPIs. Furthermore, the extended framework can show the effect of climate change with its KPIs due to the inclusion of the KPIs EAD and TCS. It is shown in the analysis of the decision making process that resilience to climate change should be taken into account in the decision as it showed that the future scenario led to a clearer optimum intervention strategy in Schermereiland en de Omval when equal weights were applied. In the conventional framework, the effect of climate change cannot be directly measured. This as the KPI water storage capacity is based on the characteristics of the SUDS types implemented and surface types. It is therefore not subject to change due to the effect of climate change, for example changing rainfall patterns will not influence the outcome of this KPI. However, climate change can indirectly be taken into account in the decision making process that follows when thresholds are set on this KPI that need to be met in the urban area. Furthermore, the simulation of the decision making process showed that the intervention strategies including more SUDS in addition to the grey infrastructure in their design can be the better options for climate change adaptation, which is compatible with other recent studies [55].

Additionally, the difference between both frameworks is investigated, highlighting the strengths and weaknesses of the conventional and extended framework. The frameworks are evaluated on five criteria, namely accuracy, applicability, time consumption, usability and strategic fit. By assessing the accuracy, the methodology by which the results of the indicators are obtained is discussed. Applicability refers to the extend to which a framework can be applied. Considering time consumption, the time needed to apply each framework is analysed. Furthermore, the usability looks at the ease of use of both methods. Lastly, by evaluating the strategic fit, the balance between easy integration in the way of working of engineering practice and best results is investigated. This evaluation is presented in Table 34. In the following, the explanation of the results of this evaluation is laid out.

Table 34: Evaluation of frameworks

	Conventional method	**Extended method**
Accuracy	-	+/-
Applicability	+	++
Time consumption	++	-
Usability	+	+
Strategic fit	+	++

Accuracy

The accuracy of the conventional framework is considered to be poor. In the calculation of the water storage capacity it is assumed that all initially present surface types have the same storage capacity of 0.1 m/m^2, independent of the area being impervious or not. This assumption is considered to be incorrect, because in real life there is a difference of water storage capacity between green areas and impervious surface. This led to an underestimation of the water storage capacity of the baseline in which no SUDS are implemented in the urban area. The subsequent storage capacities build further on this baseline, and are therefore also underestimations of the true value. The accuracy of the extended framework is better, however this method is still rated as neutral. Each indicator of the extended framework includes its own assumptions, but these are scientifically verified by reliable sources, for example Nature4Cities [30] and Woods Ballard et al. [5]. Therefore, the assumptions taken are assumed to be accurate enough for an initial performance analysis to base urban design, on which the substantiation is laid out in the evaluation of the assessment method in section 5.3. Additionally, the modelling tool Tygron used in the extended framework is a verified reliable tool to use for urban climate modelling by the STOWA [56].

Applicability

Both frameworks can be used for multiple applications. The frameworks are not limited to a specific scale, but can be applied to several scales. For example object, neighborhood and city scale suit both the conventional framework as well as the extended framework. However, considering applicability from a wider perspective, the extended framework performs better on this criterion. In the extended framework a holistic point of view is taken as all four design objectives of SUDS are addressed. The extended framework can therefore be applied to a wider range of interests due to the larger number of aspects of urban design that are considered in this framework. Lastly, in the extended framework the effect of climate change on the considerations of SUDS implementation is able to be tested.

Time consumption

The conventional framework is a fast assessment tool. Only two indicators are tested which are both easy to apply. As the proposed framework in this research is an extension of this conventional framework and additionally includes four times as many indicators, this framework consumes more time. When applied in engineering practice, more time needs to be available to be able to apply the extended framework.

Usability

The conventional framework as well as the extended framework are easy to apply. For the conventional framework a calculation tool is available in engineering practice which ensures this method can be easily integrated to the assessed case study. The methodologies of the indicators for the extended framework are suitable to be easily integrated in engineering practice. In this study a step by step calculation method for each of the indicators of the extended framework is provided making it easy to reapply the indicators to other case studies.

Strategic fit

The indicators of the extended framework can be easily integrated in the method used in engineering practice. The framework it is compared to is not hard to expand and adding automated calculations for the indicators of the extended framework is simple. By integrating the extended framework in engineering practice, the choice of applicable indicators can be made for each project. The incorporation of the extended set of indicators consumes more time in earlier stages but leads to more accurate conclusions on the effects of SUDS implementation. Furthermore, with the addition of the assessment of the co-benefits of SUDS in the extended framework, more stakeholders are able to take part in the decision making process as more preferences can be included. This leads to more robust urban designs.

Considering this comparison, the effect on the decision making process is discussed. Considering the evaluation presented in Table 34, it is concluded that both methods have their own strengths and weaknesses. The extended framework improves the decision making process as it makes it possible for more stakeholders to be included in the decision making process and this framework assesses more effects of SUDS on the urban environment ensuring that a more informed decision can be made by the decision makers. However, it slows the decision making process down as more time is needed for the assessment of the area. Additionally, with small improvements in the KPI water storage capacity of the conventional framework, the accuracy of this framework can be improved significantly. If such small improvements are made, this method would score higher on accuracy than the extended framework. This because in the extended framework a lot of assumptions are taken that, while supported by literature, can lead to a lower accuracy. The PRC and BAF indicators for example use UK and German data, which might differ when they would be retrieved from the Dutch environment. The most important strengths obtained in this analysis of both frameworks are shown in Figure 15.

Conventional Framework	Extended Framework
Easy Assessment	Better express effect of SUDS on quality of life
Fast Assessment	Holistic approach
Focuses on cost and resilience to water nuisance	Wider range applicable

Figure 15: Strengths of both frameworks applied in this research

7.1.3 Improvement live-ability of urban environment

The last part of the objective of this research states that the proposed framework should help to make better decisions to improve an urban areas live-ability. With the consideration of all four design pillars of SUDS it is made sure that co-benefits of SUDS are addressed in the extended framework. With this more holistic view on urban design taken in the extended framework compared to the conventional framework, this extended framework helps decision makers to base their urban design decisions not only on cost and water quantity but on this wider range of considerations. Basing the decision making process on the KPIs of the extended framework thus has the ability to better inform stakeholders. Furthermore, this framework shows a wider impact of SUDS on the areas live-ability, thereby being able to act as a useful tool to improve the live-ability of the urban environment.

7.2 Limitations of research

This section discusses the limitations of this research. The limitations of the developed framework and the decision making process are presented. The effect of these limitations on the goal of this study is discussed.

Firstly, the limitations of the developed framework are laid out:

- *Co-benefits*: The inclusion of co-benefits in the extended framework is limited due to the consideration of only those co-benefits able to be represented by KPIs that are suitable to the case study and engineering practice. Additionally, the KPIs were chosen based on data availability, limiting the number of KPIs that could be used in this research.

For example, the research of Bouzouidja et al. [57] highlights the contribution of SUDS to sustainable soil management and proposes KPIs to measure the benefits. While it is known that the case study experiences soil contamination, the assessment of this co-benefit is not included in the framework due to data availability. The assessment of other benefits, such as an improved water-food-energy nexus [30] or increased property values [55], and so on, can further increase the evidence base of the full effect of SUDS on an urban area. The developed framework, the extended framework, therefore provides a holistic approach to urban design, but the full effect of SUDS on the urban environment is not limited to the co-benefits considered in this research.

- *KPI's*: Firstly, this research showed there is a lack of KPIs that assess the effect of SUDS on water quality, which is also concluded in the research of Orta-Ortiz and Geneletti [35]. The KPIs used in the extended framework assess the effect of the intervention strategies on the water quality, but there accuracy is lacking due to insufficient data availability. Furthermore, the assessment methodologies of the KPIs BAF, SPI and PRC are based on data outside the Dutch environment. This reduces the accuracy of the application of these indicators to urban areas in the Netherlands. Moreover, the water quality, amenity and biodiversity KPIs are indirect measures of these features of SUDS design. As these are chosen based on data availability, characteristics of the case study and preferences of engineering practice, there might be more suitable KPIs present that more directly assess these considerations in other case studies. Lastly, for not all SUDS types used in this research performance data was available for each KPI, possibly leading to underestimations of the performance of intervention strategies on these KPIs, undervaluing the co-benefits related to SUDS implementation.

- *Scale*: In this research the case study analysis is conducted on neighborhood scale. Additionally, only public space is used to implement SUDS in, which is only a small portion of both neighborhoods in the case study. As a result of these factors together with the assessment methodologies developed, the results of the performance assessment of the extended framework shows little difference between the results for the indicators BAF, SPI and PRC. Applying the framework to a smaller scale and/or also using private property most likely results in more profound performance improvements of intervention strategies on these KPIs. For example, when applying the BAF on a plot scale and implementing SUDS, Centre d'écologie urbaine de Montreál [43] showed a more convincing difference between the BAF results of different designs.

- *Performance assessment*: In real life, the performance of SUDS is inherently variable and relies on how well these solutions are implemented and maintained. The results obtained in the case study assessment are an approximation of the true performance. This research does not attempt to provide precise performance data. Rather, the main goal of this research was to show how a holistic approach helps the decision making process. Furthermore, the analysis presents uncertainties and constraints based on data availability and local data and issues.

- *Pollutant removal capacity cadmium*: Uncertainty lies in the results obtained for the PRC of cadmium. The cadmium concentration in urban runoff is very low, as is shown in Table 14. Due to this low concentration the presence of cadmium in runoff is more difficult to be accurately detected with measurement equipment [58]. This limits the reliability of the data used for the calculations of the PRC of cadmium. For example, in Table 13 a negative removal of cadmium by sustainable road design is determined for the 25^{th} percentile. This is based on in- and outflow data from CIRIA [5]. As this is a respected institute, it is a noteworthy result. The research of Liu and Borst [58] for the Environmental

Protection Agency of the US found that there is no statistically measurable difference between inflow and outflow concentrations of cadmium from this SUDS type, concluding it has no effect on the cadmium concentration in urban runoff. However, more recent research of Leisenring et al. [59] found that when cadmium influent concentrations were detectable, most SUDS types, including sustainable roads, do show statistically significant reductions of the cadmium concentration. The influence of SUDS on cadmium should be further investigated as the analysis in this research presents uncertainties in the measured concentrations used to calculate the PRC.

Secondly, the limitations of this extended framework to function as a decision support system are discussed:

- *Decision support*: In this research, the extended framework assessed SUDS trains on their joined performance on neighborhoods scale. Based on the results obtained in the case study assessment, the decision making process for the selection of design is simulated. However, a stage occurs previous to this. Ferrans et al. [60] classify five components of SUDS implementation for which decision support systems are needed; "Where", "How Many", "Which", "Design" and "Trains". The extended framework developed in this research addresses the SUDS trains component, as it is able to assess the performance of such treatment trains. In this research, it is not shown how this framework can support the other four components. The KPIs developed in the extended framework are however applicable on multiple scales, possibly addressing the "Where" and "Design" components. But, in the design of the intervention strategies in this research, the locations where SUDS types are implemented are assumed to be suitable to the case study. No in-depth validation is performed to ensure whether the locations, number, and types of SUDS are locally accepted or are applicable due to particular circumstances. This is an important step to take when such analysis is performed in engineering practice. Furthermore, if a threshold is applied to minimal performances on the tested KPIs, this framework helps to determine how many SUDS are needed. While the framework has the potential to support these other classifications, this cannot be substantiated on the basis of this research.

- *Simulation decision making process*: The decision making process simulated in this research shows three limitations. Firstly, no real interviews were conducted to substantiate the simulation of the decision making process in the municipality, but the stakeholders and user weights were based on knowledge obtained via engineering practice. Important stakeholders might be missing from the simulation and the weights developed might differ in real-life. These weights represent the level of trade-offs accepted and should in real-life be jointly defined with local stakeholders. Secondly, in engineering practice there is usually a threshold of water quantity or heat stress that should be at least met by the intervention strategies. In this research, such threshold is not included in the decision making process. When such threshold would be applied, intervention strategies designed will automatically be excluded as they do not meet the requirements. However, in this research, it was chosen to model the effect of implementing an increasing number of SUDS to base the decision making process on. The extended framework can be used with a threshold, but the effect on the decision making process cannot be concluded from this research. Lastly, as there is a long list of co-benefits associated with SUDS, the framework possibly misses performance data of SUDS that assess considerations whether to implement SUDS types or not in other case studies. Including more co-benefits in the framework influences the outcome of the decision making process because more effects of SUDS are considered.

- *Societal preferences*: While the KPIs from the extended framework can be used to express the preferences of a wide range of stakeholders, it not yet truly reflects societal priorities. The framework designed better informs decision makers on the effect of SUDS, but cannot model and predict the impact of water governance, management and infrastructure swifts. According to Franco-Torres et al. [61], these aspects play a crucial role in the development of innovative urban water management. These new paradigms will undoubtedly have an impact on SUDS decision-making and must be considered in order to provide concrete guidance that truly reflects current societal priorities. To accomplish this, Ferrans et al. [60] states that decision support systems for SUDS necessitate an interdisciplinary team of practitioners and scholars who can provide state-of-the-art input in the various SUDS dimensions (i.e., economic, environmental, social). The extended framework promotes working with interdisciplinary teams and support the modelling of water governance, management and infrastructure swifts, but has a limited ability to support the prediction of these components in the decision making process.

- *Validation*: Although the application of the extended framework to base the decision making process on showed to be promising, further discussion and validation of the framework with local stakeholders is required. Such validation can improve the extended framework's functionality and usability.

7.3 Scientific relevance

As stated by Keeler et al. [62], solutions like SUDS have the greatest potential to directly improve the health, safety and well-being of vulnerable populations like those in urban environments. Furthermore, as stated in section 1.2, it is crucial that the informative evidence base on the effectiveness of implementation of SUDS grows [8]. With the application of this framework to the case study, the results of the performance assessment showed that with an increasing number of implemented SUDS the performance regarding the co-benefits of SUDS improved. This research thus provides evidence on the performance of SUDS to increase the livability of an urban area. This research therefore adds to the informative evidence base on effect of SUDS.

Additionally, this research contributes to the transition to 'water sensitive cities' as defined by Brown et al. [19], in which both cumulative socio-political drivers and service delivery functions of urban water management are optimized. The extended framework takes a holistic view on SUDS implementation and assesses a broad range of the effect of SUDS. This research can thus help to work towards this goal.

Furthermore, the importance of understanding sustainable urban design is not merely 'an engineering problem', but involves a range of disciplines as highlighted by Carmona [20] is addressed in this research. The developed framework is able be used to more easily express the preferences of multiple different stakeholders. While the stakeholders and their preferences are not limited to the decision making process simulated in this research, this framework can be used to support sustainable urban planning.

Moreover, this research takes a novel approach relative to other recent studies. While other recent studies also propose assessment methods including indicators that show the co-benefits of SUDS, this research took into account all four design pillars and ensured the assessment methodologies are workable for practitioners. For example in the research of both Raymond et al. [29] and Kabisch et al. [63], KPIs are examined that show the effectiveness of SUDS in the urban environment, but they do not provide substantiation on a case study. Another common used approach is to compare SUDS designs via a cost-benefit analysis as is done by Chow et al. [33]. Such assessments have less focus on improving the quality of life with SUDS.

Furthermore, other studies focus on mainly one co-benefit next to flood risk reductions. For example, Bouzouidja et al. [57] chose one of the challenges defined by the Nature4Cities [30] project and focused on how SUDS affect that urban challenge next to flood risk reduction.

7.4 Relevance for engineering practice

In engineering practice, they aspire to bridge the knowledge gap on the effect of SUDS and aim to improve their communication on this effect to decision makers. The framework developed in this research builds further on the conventional framework used in engineering practice. With the addition of KPIs that assess the co-benefits, it is ensured that the new framework quantifies all four design pillars of SUDS, which include water quantity, water quality, amenity, and biodiversity. This research can therefore contribute to closing this knowledge gap.

Furthermore, it is important to bridge the gap between urban water infrastructure and urban planning. Urban areas are dealing with either too much, too little, or too dirty storm water. Urban water infrastructure and urban planning need to work together to support sustainable, climate-resilient, healthy, and attractive cities. In line with statements made by Wareco [64], when designing public space, attention should be paid to climate-proofing public space, built-up plots and surface water. This has both a technical component (where are problems opportunities located, which measures are effective?) and an organisational one (how to get residents, businesses and colleagues on board?). The framework proposed in this research helps to bridge the gap between these two components. The extended framework can be used to effectively communicate the technical aspect of SUDS to the organisational component of urban design.

8 Conclusion

To bridge the knowledge gap in decision makers in urban design on the full effect of SUDS implementation, the objective of this research was to develop an assessment framework for SUDS-based storm water management in the urban landscape to help Dutch municipalities improve their decision making to improve the live-ability of the urban environment.

In this research, a new framework (called the ”extended framework”) is developed that builds on the framework currently used in engineering practice (called the ”conventional framework”). The conventional framework assesses SUDS implementation on cost and water quantity. The extended framework adds KPIs that assess the other three design pillars of SUDS: water quality, amenity and biodiversity. It is therefore able to assess co-benefits associated with SUDS implementation. The KPIs included in this new framework are chosen based on data availability and the characteristics of the case study from an extensive list of available KPIs that assess SUDS. In this thesis, the corresponding assessment methodologies that best evaluate these extended KPIs are defined.

With the application of both frameworks on a case study, two performance assessments are conducted. The assessment showed that with more SUDS implementation, the performance of the intervention strategies on water quantity, water quality, amenity and biodiversity improved. This therefore contributes to the informative evidence base of the positive influence of SUDS on the urban environment.

Based on the results obtained from the application of the two frameworks, a simulation of the decision making process is conducted through which conclusions are drawn on the impact of using either one of the frameworks on the choice of SUDS implementation. While the use of the results of either the conventional or extended framework not always led to the same choice of design, it is concluded that both methods have their own strengths and weaknesses regarding their use for the decision making process of Dutch municipalities.

The conventional framework is a fast and easy assessment framework. It focuses on cost and resilience to water nuisance. It is not able to represent the co-benefits of SUDS. Using this performance assessment makes it more difficult to consider multiple stakeholders in the subsequent decision making process. It does not help to improve the decision making process to improve an areas live-ability, but might be a more suitable option to use with time constraints and when stakeholders are only interested in cost and water quantity.

The extended framework is applicable on a wider range of aspects of urban design as it assesses more effects of SUDS implementation. Furthermore, as more aspects of an urban area are considered, this framework can more easily be used to consider individual preferences of a variety of stakeholders in the decision making process. Subsequently, the effects of climate change on an urban environment can be measured for flood risk and the UHI effect in this framework. With the holistic approach taken in this framework, more robust urban environments can be designed. Even though this framework is more time-consuming and may lead to more costly solutions, using the extended framework to base the decision making process on is likely to result in a better quality of life for humans with a reduced negative impact on the associated natural environment.

In engineering practice, the choice of framework depends on what the goal of the project is, which stakeholders are present in the municipality addressed, and how much time is available.

However, it is important to note that regarding the goal of this research, the extended framework better equips decision-makers to face emerging storm water challenges and make more informed decisions to improve the live-ability in urban areas.

8.1 Recommendations

In this section, the most important recommendations based on this research are laid out. Firstly, recommendations for future research are discussed. This is followed by the presentation of the recommendations for engineering practice.

8.1.1 Further research

- *Co-benefits*: As stated, one of the limitations of this research is that only case relevant and easily quantifiable co-benefits are considered in the extended framework. It is recommended to further investigate additional co-benefits presented in 2.3.1 in following research. A future framework can be built including such a broader range of co-benefits. Moreover, the KPIs assessing the water quality co-benefits of SUDS need to be improved by for example data collection from the Dutch environment.

- *Climate change*: While this research highlights that climate change should be considered when designing an urban area, the developed framework has limited ability to show the effect of climate change. To improve the mapping of the effect of climate change on the urban environment, additional research should focus on understanding how the considered components of SUDS design can be sufficiently assessed on climate change. In the extended framework, only the EAD and TCS are able to show the effect of climate change, while climate change also impacts water quality and biodiversity.

- *Case study*: To prove the effectiveness of the framework, additional work should be conducted. Multiple different case studies need to be tested to draw more substantiated conclusions on the effect of this framework on the decision making process.

- *Decision support*: This research does not substantiate the use of the developed framework for all five components of SUDS implementation classified by Ferrans et al. [60]. Further research should be conducted and additions to the framework should be made to ensure this framework can support all five components.

- *Modelling approach*: In this research, the co-benefits of SUDS are tested using an increasing number of SUDS types in the intervention strategies. Intervention strategy A, in which no SUDS are implemented, forms the baseline only including grey infrastructure. While with the results of the case study a comparison can be made between using traditional grey infrastructure and adding SUDS, the modelling approach did not consider that in real life the comparison should be made with adding either additional traditional grey infrastructure or technical solutions or adding SUDS. Keeler et al. [62] argue that it is essential to the decision making process that comparative data is generated juxtaposing SUDS, costs and effectiveness of various urban development pathways, including potential co-benefits and disservices in terms of human well-being at various scales. Substitutes that meet the same goals as SUDS, for example indoor air conditioning, water treatment facilities, and so on, are not included in this research. Further research should be conducted addressing this need.

- *Urbanization*: In this research the choice was made to not investigate urbanization scenarios based on characteristics of the case study. However, urbanization is one of the main drivers of the need for sufficient urban response systems. By 2050, two out of every three people will be living in cities, implying that the continued development of cities will increasingly shape human well-being [62]. Additional work should research how the performance of SUDS can tackle the challenges resulting from different future urbanization scenarios.

- *Water quality*: In the water quality assessment the influence of SUDS on the pollution by pathogens is excluded. These microorganisms form a risk to human health, as they cause serious diseases from pathogenic bacteria like Salmonella and Cryptosporidium parvum [65]. The effect of SUDS on pathogen pollution should be further research is future work.

8.1.2 Engineering practice

- *Assessment tool*: The KA Tool should be expanded by including KPIs that assess the co-benefits. This can be done with the incorporation of the KPIs developed in the extended framework. Even though the results obtained from the application of the KPIs on the case study are indicative and uncertainty should be further assessed, it is recommended to use the extended framework. Furthermore, it is recommended to further investigate additional KPIs that fit the need of clients and engineering practice.

- *Co-creation*: Co-creation has the ability to significantly increase the performance of SUDS in an urban area. It can provide the awareness needed to implement and maintain SUDS in the correct manner to ensure SUDS perform on their full potential. Wilk et al. [66] provide a classification of collaborative governance arrangements within the co-creation operating space to provide conceptual clarity and make co-creation operational. In their research they focus on an European context. In the case studies examined, Wilk et al. [66] concluded that non-governmental actors frequently lead and steer co-creation processes, whereas governmental actors initiate, enable, or support these processes in part. New mechanisms for collaboration are required, in which civil society needs to step outside its comfort zone and contribute to efforts made to improve a cities' live-ability. It is therefore recommended to engineering practice to promote this way of working in urban planning. Moreover, to ease the transition into co-creation, engineering practice can create a community of stakeholders that more actively share experiences and monitor historical data regarding SUDS planning, deployment, and performance in accessible databases.

- *Overcoming challenges*: It is recommended to further investigate key barriers to implementation of SUDS and limitations in the market system. The identification of these challenges is helpful to engineering practice. When these are known, engineering practice can target to improve those identified challenges. This leads to a more effective workflow, as the framework can be further improved to perfectly fit customers' needs. Additionally, as recommended by Ashley et al. [32], post project monitoring should be conducted after the implementation of SUDS. The feedback retrieved needs to be provided to future decision makers to constantly improve the decision making process.

References

[1] Q. Zhou, "A review of sustainable urban drainage systems considering the climate change and urbanization impacts," *Water*, vol. 6, no. 4, pp. 976–992, 2014.

[2] Z. Kapelan, "CIE4491: Lecture 1.2 Water Management in Urban Areas - Introduction." TU Delft, 2020.

[3] J. Marsalek, B. Jiménez, P.-A. Malmquist, M. Karamouz, J. Goldenfum, and B. Chocat, *Urban Water Cycle Processes and Interactions*, 01 2007.

[4] W. Yang and J. Zhang, "Assessing the performance of gray and green strategies for sustainable urban drainage system development: A multi-criteria decision-making analysis," *Journal of Cleaner Production*, vol. 293, p. 126191, 2021.

[5] B. Woods Ballard, S. Wilson, H. Udale-Clarke, S. Illman, T. Scott, R. Ashley, and R. Kellagher, "The SuDS Manual," *Ciria C753*, 2015.

[6] D. Johnson, J. Exl, and S. Geisendorf, "The potential of stormwater management in addressing the urban heat island effect: An economic valuation," *Sustainability*, vol. 13, no. 16, p. 8685, 2021.

[7] H. V. Oral, P. Carvalho, M. Gajewska, N. Ursino, F. Masi, E. D. v. Hullebusch, J. K. Kazak, A. Exposito, G. Cipolletta, T. R. Andersen *et al.*, "A review of nature-based solutions for urban water management in european circular cities: A critical assessment based on case studies and literature," *Blue-Green Systems*, vol. 2, no. 1, pp. 112–136, 2020.

[8] S. Cotterill and L. J. Bracken, "Assessing the effectiveness of sustainable drainage systems (SuDS): interventions, impacts and challenges," *Water*, vol. 12, no. 11, p. 3160, 2020.

[9] National Geographic Society, "Urban water cycle," https://www.nationalgeographic.org/photo/urban-water-cycle/, Jul 2018, (Accessed on 05/19/2022).

[10] H. H. Loc, P. M. Duyen, T. J. Ballatore, N. H. M. Lan, and A. Das Gupta, "Applicability of sustainable urban drainage systems: an evaluation by multi-criteria analysis," *Environment Systems and Decisions*, vol. 37, no. 3, pp. 332–343, 2017.

[11] D. La Rosa and V. Pappalardo, "Policies and planning of urban green infrastructure and sustainable urban drainage systems," in *Urban Services to Ecosystems.* Springer, 2021, pp. 297–316.

[12] C. K. Makropoulos, K. Natsis, S. Liu, K. Mittas, and D. Butler, "Decision support for sustainable option selection in integrated urban water management," *Environmental modelling & software*, vol. 23, no. 12, pp. 1448–1460, 2008.

[13] S. L. Jiménez Ariza, J. A. Martínez, A. F. Muñoz, J. P. Quijano, J. P. Rodríguez, L. A. Camacho, and M. Díaz-Granados, "A multicriteria planning framework to locate and select sustainable urban drainage systems (SUDS) in consolidated urban areas," *Sustainability*, vol. 11, no. 8, p. 2312, 2019.

[14] M. Davis and S. Naumann, "Making the case for sustainable urban drainage systems as a nature-based solution to urban flooding," in *Nature-based solutions to climate change adaptation in urban areas.* Springer, Cham, 2017, pp. 123–137.

[15] R. Ashley, B. Gersonius, C. Digman, B. Horton, T. Bacchin, B. Smith, P. Shaffer, and A. Baylis, "Demonstrating and monetizing the multiple benefits from using SuDS," *Journal of Sustainable Water in the Built Environment*, vol. 4, no. 2, p. 05017008, 2018.

[16] Arcadis and &Flux, "Kosten klimaatadaptieve stadsharten," Nov 2021.

[17] L. Liu and M. B. Jensen, "Green infrastructure for sustainable urban water management: Practices of five forerunner cities," *Cities*, vol. 74, pp. 126–133, 2018.

[18] C. Lamera, G. Becciu, M. C. Rulli, and R. Rosso, "Green roofs effects on the urban water cycle components," *Procedia Engineering*, vol. 70, pp. 988–997, 2014.

[19] R. R. Brown, N. Keath, and T. H. Wong, "Urban water management in cities: historical, current and future regimes," *Water science and technology*, vol. 59, no. 5, pp. 847–855, 2009.

[20] M. Carmona, "Sustainable urban design: principles to practice," *International Journal of Sustainable Development*, vol. 12, no. 1, pp. 48–77, 2009.

[21] L. R. N. P. Rentachintala, M. Reddy, and P. K. Mohapatra, "Urban stormwater management for sustainable and resilient measures and practices: a review," *Water Science and Technology*, 2022.

[22] I. M. Voskamp and F. H. Van de Ven, "Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events," *Building and Environment*, vol. 83, pp. 159–167, 2015.

[23] J. Langeveld and M. Rutten, "Cie5510: Lecture 1 - water management in urban areas." TU Delft, 2021.

[24] J. B. Ellis, L. Lundy, and M. Revitt, "An integrated decision support approach to the selection of sustainable urban drainage systems (SUDS)," in *SWITCH Conference: The Future of Urban Water*, 2011.

[25] B. Thodesen, B. Time, and T. Kvande, "Sustainable urban drainage systems: Themes of public perception—a case study," *Land*, vol. 11, no. 4, p. 589, 2022.

[26] L. F. Santos, A. F. Galvão, and M. A. Cardoso, "Performance indicators for urban storm water systems: a review," *Water Policy*, vol. 21, no. 1, pp. 221–244, 2019.

[27] KPI.org, "What is a key performance indicator (kpi)?" https://kpi.org/KPI-Basics, 2022, (Accessed on 18/05/2022).

[28] J. Ommer, E. Bucchignani, L. S. Leo, M. Kalas, S. Vranić, S. Debele, P. Kumar, H. L. Cloke, and S. Di Sabatino, "Quantifying co-benefits and disbenefits of nature-based solutions targeting disaster risk reduction," *International Journal of Disaster Risk Reduction*, p. 102966, 2022.

[29] C. M. Raymond, N. Frantzeskaki, N. Kabisch, P. Berry, M. Breil, M. R. Nita, D. Geneletti, and C. Calfapietra, "A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas," *Environmental Science & Policy*, vol. 77, pp. 15–24, 2017.

[30] Nature4Cities, "D2.1 - system of integrated multi-scale and multi-thematic performance indicators for the assessment of urban challenges and nbs," https://www.nature4cities.eu/_files/ugd/55d29d_3b17947e40034c168796bfc9a9117109.pdf, 2019, (Accessed on 27/06/2022).

[31] C. M. Raymond, M. Breil, M. Nita, N. Kabisch, M. de Bel, V. Enzi, N. Frantzeskaki, G. Geneletti, L. Lovinger, M. Cardinaletti *et al.*, *An impact evaluation framework to support planning and evaluation of nature-based solutions projects. Report prepared by the EKLIPSE Expert Working Group on Nature-Based Solutions to Promote Climate Resilience in Urban Areas.* Centre for Ecology and Hydrology, 2017.

[32] R. M. Ashley, D. Blackwood, and P. Jowitt, *Sustainable water services.* IWA publishing, 2004.

[33] J.-f. Chow, D. Savić, D. Fortune, Z. Kapelan, and N. Mebrate, "Using a systematic, multi-criteria decision support framework to evaluate sustainable drainage designs," *Procedia Engineering*, vol. 70, pp. 343–352, 2014.

[34] D. M. Revitt, L. Scholes, J. B. Ellis, and D. Thevenot, *Assessment criteria for sustainable urban drainage systems.* IWA Publishing, London, UK, 2008.

[35] M. S. Orta-Ortiz and D. Geneletti, "What variables matter when designing nature-based solutions for stormwater management? a review of impacts on ecosystem services," *Environmental Impact Assessment Review*, vol. 95, p. 106802, 2022.

[36] J. Rijsdijk, "Personal communication, October 2022," 2022.

[37] J. B. Ellis, D. M. Revitt, and L. Lundy, "An impact assessment methodology for urban surface runoff quality following best practice treatment," *Science of the Total Environment*, vol. 416, pp. 172–179, 2012.

[38] STOWA and Stichting RIONED, "Kwaliteit afstromend hemelwater Nederland - Database kwaliteit afstromend hemelwater," 2020.

[39] B. Scharf, M. Kogler, F. Kraus, I. Garcia Perez, and L. Gutierrez Garcia, "Nbs impact evaluation with greenpass methodology shown by the case study 'fischbeker höfe'in hamburg/germany," *Sustainability*, vol. 13, no. 16, p. 9167, 2021.

[40] Tygron, "Heat module overview," https://support.tygron.com/wiki/Heat_Module_overview, 2022, (Accessed on 10/11/2022).

[41] R. Wang, J. Zhao, M. J. Meitner, Y. Hu, and X. Xu, "Characteristics of urban green spaces in relation to aesthetic preference and stress recovery," *Urban Forestry & Urban Greening*, vol. 41, pp. 6–13, 2019.

[42] R. De Lotto, M. Sessi, and E. M. Venco, "Semi-automatic method to evaluate ecological value of urban settlements with the biotope area factor index: Sources and logical framework," *Sustainability*, vol. 14, no. 4, p. 1993, 2022.

[43] Centre d'écologie urbaine de Montreál, "Biotope Area Factor," https://participatoryplanning.ca/sites/default/files/upload/document/tool/20191002_biotope_area_factor.pdf, Oct 2019, (Accessed on 26/08/2022).

[44] R. D. Lotto, V. Casella, M. Franzini, V. Gazzola, C. M. d. Popolo, S. Sturla, and E. M. Venco, "Estimating the biotope area factor (baf) by means of existing digital maps and gis technology," in *International Conference on Computational Science and Its Applications.* Springer, 2015, pp. 617–632.

[45] Senate Department for the Environment, Urban Mobility, Consumer Protection and Climate Action, “Calculating the BAF,” https://www.berlin.de/sen/uvk/en/nature-and-green/landscape-planning/baf-biotope-area-factor/calculating-the-baf/, 2022, (Accessed on 14/09/2022).

[46] STOWA, “Neerslagstatistieken voor korte duren,” 2018.

[47] Standwerk072 and Gemeente Alkmaar, “Beleidsplan stedelijk water 2017-2026,” 2017.

[48] Arcadis, “Klimaatadaptatie strategie en uitvoeringsagenda regio Alkmaar,” https://www.samenblauwgroen.nl/assets/files/klimaatadaptatiestrategie-en-uitvoeringsagenda-regio-alkmaar-def.pdf, Mar 2021, (Accessed on 05/27/2022).

[49] CBS, “Geografische data,” https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data, 2008, (Accessed on 27/05/2022).

[50] Klimaateffectatlas, “Hittekaart gevoelstemperatuur,” https://www.klimaateffectatlas.nl/nl/hittekaart-gevoelstemperatuur, 2022, (Accessed on 10/08/2022).

[51] Amsterdam Rainproof, “Infiltratiekratten,” https://www.rainproof.nl/toolbox/maatregelen/infiltratiekratten, 2022, (Accessed on 21/01/2023).

[52] Amsterdam Rainproof, “Waterpleinen,” https://www.rainproof.nl/toolbox/maatregelen/waterpleinen, 2022, (Accessed on 14/11/2022).

[53] H. Sales-Ortells and G. Medema, “Microbial health risks associated with exposure to stormwater in a water plaza,” *Water research*, vol. 74, pp. 34–46, 2015.

[54] K. Behzadian, M. Morley, D. Vitorino, S. Coelho, R. Ugarelli, and Z. Kapelan, “Final report with DSS methodology, software and case study from an idealized pilot city,” 2015.

[55] A. Alves, Z. Vojinovic, Z. Kapelan, A. Sanchez, and B. Gersonius, “Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation,” *Science of the Total Environment*, vol. 703, p. 134980, 2020.

[56] STOWA, “Benchmark inundatiemodellen,” vol. 34, 2017.

[57] R. Bouzouidja, P. Cannavo, P. Bodénan, Á. Gulyás, M. Kiss, A. Kovács, B. Bechet, K. Chancibault, E. Chantoiseau, P.-E. Bournet *et al.*, “How to evaluate nature-based solutions performance for microclimate, water and soil management issues–available tools and methods from nature4cities european project results,” *Ecological Indicators*, vol. 125, p. 107556, 2021.

[58] J. Liu and M. Borst, “Performances of metal concentrations from three permeable pavement infiltrates,” *Water Res.*, vol. 136, pp. 41–53, 2018.

[59] M. Leisenring, J. Clary, P. Hobson, J. Jones, and E. Strecker, “International Stormwater BMP Database: 2020 Summary Statistics,” no. 4968, 2020.

[60] P. Ferrans, M. N. Torres, J. Temprano, and J. P. R. Sánchez, “Sustainable urban drainage system (SUDS) modeling supporting decision-making: a systematic quantitative review,” *Science of the Total Environment*, vol. 806, p. 150447, 2022.

[61] M. Franco-Torres, B. C. Rogers, and R. Harder, "Articulating the new urban water paradigm," *Critical Reviews in Environmental Science and Technology*, vol. 51, no. 23, pp. 2777–2823, 2021.

[62] B. L. Keeler, P. Hamel, T. McPhearson, M. H. Hamann, M. L. Donahue, K. A. Meza Prado, K. K. Arkema, G. N. Bratman, K. A. Brauman, J. C. Finlay *et al.*, "Social-ecological and technological factors moderate the value of urban nature," *Nature Sustainability*, vol. 2, no. 1, pp. 29–38, 2019.

[63] N. Kabisch, N. Frantzeskaki, S. Pauleit, S. Naumann, M. Davis, M. Artmann, D. Haase, S. Knapp, H. Korn, J. Stadler *et al.*, "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*, vol. 21, no. 2, 2016.

[64] Wareco, "Beleidsplan stedelijk water 2017-2026," October 2018.

[65] F. N. Chaudhry and M. Malik, "Factors affecting water pollution: a review," *J. Ecosyst. Ecography*, vol. 7, no. 1, pp. 225–231, 2017.

[66] B. Wilk, I. Säumel, and D. Rizzi, "Collaborative governance arrangements for co-creation of nbs," in *Nature-Based Solutions for More Sustainable Cities–A Framework Approach for Planning and Evaluation.* Emerald Publishing Limited, 2021.

[67] F. Rodriguez, F. Morena, H. Andrieu, and G. Raimbault, "Introduction of innovative stormwater techniques within a distributed hydrological model and the influence on the urban catchment behaviour," *Water Practice and Technology*, vol. 2, no. 2, 2007.

[68] X. Stavropulos-Laffaille, K. Chancibault, H. Andrieu, A. Lemonsu, I. Calmet, P. Keravec, and V. Masson, "Coupling detailed urban energy and water budgets with teb-hydro model: Towards an assessment tool for nature based solution performances," *Urban Climate*, vol. 39, p. 100925, 2021.

[69] S. Rokia, G. Séré, C. Schwartz, M. Deeb, F. Fournier, T. Nehls, O. Damas, and L. Vidal-Beaudet, "Modelling agronomic properties of technosols constructed with urban wastes," *Waste Management*, vol. 34, no. 11, pp. 2155–2162, 2014.

[70] P. Cannavo, R. Guénon, G. Galopin, and L. Vidal-Beaudet, "Technosols made with various urban wastes showed contrasted performance for tree development during a 3-year experiment," *Environmental Earth Sciences*, vol. 77, no. 18, pp. 1–13, 2018.

[71] J. A. Keuskamp, B. J. Dingemans, T. Lehtinen, J. M. Sarneel, and M. M. Hefting, "Tea bag index: a novel approach to collect uniform decomposition data across ecosystems," *Methods in Ecology and Evolution*, vol. 4, no. 11, pp. 1070–1075, 2013.

[72] D. M. Olson, E. Dinerstein, E. D. Wikramanayake, N. D. Burgess, G. V. Powell, E. C. Underwood, J. A. D'amico, I. Itoua, H. E. Strand, J. C. Morrison *et al.*, "Terrestrial ecoregions of the world: A new map of life on eartha new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity," *BioScience*, vol. 51, no. 11, pp. 933–938, 2001.

[73] K. E. Saxton and W. J. Rawls, "Soil water characteristic estimates by texture and organic matter for hydrologic solutions," *Soil science society of America Journal*, vol. 70, no. 5, pp. 1569–1578, 2006.

[74] R. Frischknecht, F. Wyss, S. Büsser Knöpfel, T. Lützkendorf, and M. Balouktsi, "Cumulative energy demand in lca: the energy harvested approach," *The International Journal of Life Cycle Assessment*, vol. 20, no. 7, pp. 957–969, 2015.

[75] M. Patel, "Cumulative energy demand (ced) and cumulative co2 emissions for products of the organic chemical industry," *Energy*, vol. 28, no. 7, pp. 721–740, 2003.

[76] I. Voskamp, J. Voeten, and P. Roebeling, "Nature based solutions for circular urban food systems," 2021.

[77] C. V. Gál and N. Kántor, "Modeling mean radiant temperature in outdoor spaces, a comparative numerical simulation and validation study," *Urban Climate*, vol. 32, p. 100571, 2020.

[78] WHO, "Whoqol - measuring quality of life— the world health organization," https://www.who.int/tools/whoqol, 2012, (Accessed on 20/27/2022).

[79] P. Schrijvers, H. Jonker, S. De Roode, and S. Kenjereš, "The effect of using a high-albedo material on the universal temperature climate index within a street canyon," *Urban Climate*, vol. 17, pp. 284–303, 2016.

[80] Arcadis, "Basisinventarisatie klimaatkwetsbaarheden," https://www.samenblauwgroen.nl/assets/files/20190724-klimaatstresstest-alkmaar.pdf, Jul 2019, (Accessed on 25/05/2022).

[81] Gemeente Alkmaar, "Digitale tweeling," https://digitale-tweeling-alkmaar.azurewebsites.net/digitale_tweeling, 2022, (Accessed on 09/08/2022).

[82] SWECO and Gemeente Alkmaar, "Kansen voor vergroenen," Nov 2019.

[83] SWECO and Gemeente Alkmaar, "Kansen voor biodiversiteit," Nov 2019.

[84] Klimaateffectatlas, "Kaartviewer," https://www.klimaateffectatlas.nl/nl/, 2022, (Accessed on 10/08/2022).

[85] KNMI, "KNMI'14-klimaatscenario's," https://www.knmi.nl/kennis-en-datacentrum/achtergrond/knmi-14-klimaatscenario-s, 2022, (Accessed on 10/08/2022).

[86] A. Pliester, "Personal communication, September 2022," 2022.

[87] STOWA, Koninklijk Nederlands Meteorologisch Instituut, and HKV, "Neerslagstatistiek en -reeksen voor het waterbeheer 2019," 2019.

A List of Key Performance Indicators

In this section the KPI's obtained from the literature review are presented. They are categorized into the criteria presented in section 3.4.

A.1 List Technical KPI's

Table 35: Technical KPIs

KPI	Description	Assessment method	Scale	Reference
Flood control	Overflow frequency based on design storm	Assessment of e.g. overflow frequency, peak runoff and storage volume	City, neighborhood	Revitt et al. [34]
Flood peak reduction/ peak flow variation	Change in runoff pattern due to SUDS implementation	URBS-Mo model TEB-Hydro	City	Rodriguez et al. [67] Stavropulos-Laffaille et al. [68]
Pollution control	Measurement of water quality improvement by e.g. pollutant removal capacity	Captured dissolved or solid pollutants	City, neighborhood, object	Revitt et al. [34]
Runoff/rainfall ratio	Response created by SUDS for rainfall - runoff	Total volume runoff divided by total volume rainfall	City, neighborhood	Nature4Cities [30]
System Adaptability	Indicates the ease of retrofitting required with urban growth	E.g., measurement of changes in runoff coefficient	City, neighborhood	Revitt et al. [34]
Total rainfall volume	Potential for/Need of SUDS to take advantage of the total precipitation	Regression analysis	City, neighborhood, object	Nature4Cities [30]
Total runoff volume	Change in runoff volume through SUDS in catchment	Hydrological model	City, neighborhood, object	Nature4Cities [30]
Water detention time	Analysis for SUDS to estimate protection against flood	Hydrological model	City, neighborhood, object	Nature4Cities [30]

These technical indicators address multiple urban challenges. Next to the direct urban challenge they are focused on, they indirectly relate to several other urban challenges as well. In Table 36 the KPI's and their addressed challenges are shown.

Table 36: Technical KPIs with corresponding urban challenges

KPI	Direct Urban Challenge addressed	Indirect Urban Challenge addressed
Flood control	Flood management	Public health & well-being, people security, social justice & cohesion
Flood peak reduction/ peak flow variation	Flood management	Public health & well-being, people security, green space and biodiversity
Pollution control	Water management and quality	Public health & well-being, waste generation soil management and quality
Runoff/rainfall ratio	Flood management	Public health & well-being, green spaces
System Adaptability	Planning urban space	Green economy and inward investment
Total rainfall volume	Flood management	Water management and quality, climate adaptation and mitigation
Total runoff volume	Flood management	Water management and quality, climate adaptation and mitigation
Water detention time	Flood management	Water management and quality

A.2 List Environmental KPI's

In this section the environmental KPI's are laid out. This criterion is subdivided into chemical/biological KPI's and physical KPI's. This to make the lists more comprehensible and KPI's easier to find.

Chemical/Biological

Table 37: Environmental (Chemical/Biological) KPIs

KPI	Description	Assessment method	Scale	Reference
Annual amount of pollutants captured by vegetation	Measures air quality of street, urban and metropolitan scale	E.g., Forest Inventory Analysis	City, neighborhood	Nature4Cities [30] Raymond et al. [31]
Avoided Green House Gas (GHG) emissions	Total amount of GHG emissions avoided as result of SUDS implementation	Annually measured at either the midpoint level (accounting of equivalent CO_2 emissions) or endpoint level (human and ecosystem health impacts) with e.g., LCA software	City, neighbor-hood, object	Bouzouidja et al. [57] Nature4Cities [30]
Carbon storage and sequestration in vegetation and soil	Avoided carbon emission by	E.g., via Life Cycle Assessment	City, neighbor-hood, object	Nature4Cities [30] Raymond et al. [31]
Chemical fertility of soil	Represents the mineral nutrition of plants	Fertility EM	City, neighbor-hood, object	Bouzouidja et al. [57] Rokia et al. [69] Cannavo et al. [70]
Common Air Quality Index	Measures air quality	CAQI method	City, neighbor-hood	Nature4Cities [30]
Ecotoxicology factor	Shows how chemicals affect ecosystems	Ecotox EM	City, neighbor-hood, parcel	Bouzouidja et al. [57]
Exceedance of air quality limit value	Shows the fraction of urban population that is exposed to air quality lower than EU limit	Measurement of pollutant (µg/m^2) for $PM_{2.5}$, PM_{10}, O_3, NO_2 and SO_2 in air quality measurement stations	City, neighborhood	Nature4Cities [30]
Ground water quality	Increase of ground water quality due to implementation SUDS	Water quality tests either in situ or via laboratory assessments	Regional	Raymond et al. [31]
Soil biological activity	Represents the rate of decomposition of 2 different types of organic matter	SBA EM	Parcel	Bouzouidja et al. [57] Keuskamp et al. [71]
Soil contamination	The diffuse and the point source soil contamination by inorganic contaminants, nutrients and pesticides, persistent organic pollutants, and acidifying soil	Fertility EM	City, neighbor-hood,object	Bouzouidja et al. [57] Nature4Cities [30]
Soil Organic Matter	Crucial parameter of soil biological, chemical and physical quality	Fertility EM	Object	Nature4Cities [30]
Soil respiration	Biological activity representing respiration rates of soil microbes, fauna and roots	Monitoring via infra-red gas analyser	Object	Nature4Cities [30]
Soil water reservoir for plants	Capacity of soil to provide water for plant uptake compared to a reference value	Fertility EM	Object	Nature4Cities [30] Bouzouidja et al. [57] Cannavo et al. [70]
Storm water quality	Possible improvement of storm water quality leaving system	Chemical analysis of storm water samples	City, neighbor-hood,object	Nature4Cities [30]
Surface water quality	Change in water quality of receiving water bodies by SUDS	Simplified European WFD	Parcel	Bouzouidja et al. [57] Ommer et al. [28]

This category of indicators addresses multiple urban challenges. Next to the direct urban challenge they are focused on, they indirectly relate to several other urban challenges as well. In Table 38 the KPI's and their addressed challenges can be found.

Table 38: Environmental (Chemical/Biological) KPIs with corresponding urban challenges

KPI	**Direct Urban Challenge addressed**	**Indirect Urban Challenge addressed**
Annual amount of pollutants captured by vegetation	Climate adaptation	Public health & well-being, green spaces and biodiversity, carbon reduction and sequestration
Avoided Green House Gas (GHG) emissions	Climate adaptation and mitigation	Carbon reduction and sequestration, public health & well-being
Carbon storage and sequestration in vegetation and soil	Carbon reduction and sequestration	Climate adaptation and mitigation, green spaces and biodiversity, soil management
Chemical fertility of soil	Soil management and quality	Green spaces and biodiversity, planning urban space
Common Air Quality Index	Climate adaptation and mitigation	Public health & well-being, green spaces and biodiversity
Ecotoxicology factor	Green spaces and biodiversity	Climate adaptation and mitigation, public health & well-being, soil management and quality
Exceedance of air quality limit value	Climate adaptation and mitigation	Public health & well-being, green spaces and biodiversity
Ground water quality	Water management and quality	Soil management and quality, public health & well-being
Soil biological activity	Soil management and quality	Green spaces and biodiversity, planning urban space
Soil contamination	Soil management and quality	Green spaces and biodiversity, planning urban space
Soil Organic Matter	Soil management and quality	Green spaces and biodiversity, planning urban space
Soil respiration	Soil management and quality	Green spaces and biodiversity, planning urban space, water management and quality
Soil water reservoir for plants	Soil management and quality	Green spaces and biodiversity, planning urban space, water management and quality
Storm water quality	Water management and quality	Public health & well-being, soil management and quality
Surface water quality	Water management and quality	Public health & well-being, green spaces and biodiversity

Physical

Table 39: Environmental (Physical) KPIs

KPI	Description	Assessment method	Scale	Reference
Air temperature	Lowered temperatures as a result of SUDS implementation	FLUENT-ANSYS, ENVI-met, TEB	Neighborhood, parcel	Bouzouidja et al. [57] Nature4Cities [30]
Biotope Area Factor (BAF)	Tool to measure the absorbent properties of a surface	GIS-analysis	Neighborhood, object	Centre d'écologie urbaine de Montreál [43] Nature4Cities [30]
Bowen ratio	Ratio between sensible heat and latent heat	ENVI-met, SURFEX SOLENE	Object	Bouzouidja et al. [57] Nature4Cities [30]
Connectivity of green spaces	Assesses natural habitats best connected to each other	GIS-analysis	City, neighborhood, object	Nature4Cities [30]
Ecological impact	Indicator of biotic diversity	EU WFD	Neighborhood, object	Revitt et al. [34] Raymond et al. [31]
Land use and associated impacts on biodiversity	Potential species loss due to land occupation	LCA tools, EPESUS tool, Excel	City, neighborhood, object	Olson et al. [72] Nature4Cities [30]
Land use related to soil organic matter	Assessment of changes in soil organic matter based on land occupation and transformation	LCA tools, EPESUS tool, Excel	City, neighborhood, object	Nature4Cities [30]
Normalized Difference Vegetation Index (NDVI)	Represents land use mix. Shows access to major green spaces	GIS-analysis	City, neighborhood	Nature4Cities [30]
Number of invasive alien species	Number of animals and plants that are not usually found in that specific area which forms a threat to native species	Field measurements	Neighborhood, object	Nature4Cities [30]
Potential of areas likely to host biodiversity	Highlights natural areas able to accommodate a higher level of biodiversity due to their size and shape	GIS-analysis	City	Nature4Cities [30]
Ratio of native plant species	Ratio between number of native plant species and total plant species richness	Field tests	Neighborhood, object	Nature4Cities [30]
Shannon diversity index of habitats	Indicates the proportion bare, turf grass, rough grassland and herbs, shrubs, trees of built environment	Excel or GIS-analysis	Neighborhood, object	Nature4Cities [30]
Soil classification	Characterization of soil which indicates which soil is used for SUDS use	Textural Function method	City, neighborhood	Saxton and Rawls [73]
Soil crusting	Crust creation as a result of a poor aggregation capacity/ stability of soil	Fertility EM	City, neighborhood, object	Bouzouidja et al. [57]
Soil water infiltration	Represents capacity of soil to let water drain into the soil	Measured parameter (property)	Object	Nature4Cities [30]
Soil water storage	Possible increase of infiltration as a results of SUDS	URBS-MO TEB-Hydro	City, neighborhood, object	Bouzouidja et al. [57] Nature4Cities [30]
Species richness increase	Measurements regarding increase in biodiversity in area	Field measurements	City, neighborhood, object	Raymond et al. [31] Kabisch et al. [63]
Urban Green Space proportion	Ratio natural areas per total area	GIS analysis	City, neighborhood	Nature4Cities [30]

The presented indicators focus on multiple urban challenges. They have a direct and indirect focus regarding the urban challenges. In Table 40 the KPI's and their addressed challenges can be found.

Table 40: Environmental (Physical) KPI's with corresponding urban challenges

KPI	**Direct Urban Challenge addressed**	**Indirect Urban Challenge addressed**
Air temperature	Public health & well-being	Climate adaptation and mitigation, green space and biodiversity
Biotope Area Factor (BAF)	Public health & well-being	Green spaces and biodiversity
Bowen ratio	Climate adaptation and mitigation	Public health and well-being
Connectivity of green spaces	Green spaces and biodiversity	Social justice & cohesion, planning urban spaces
Ecological impact	Green spaces and biodiversity	-
Evapotranspiration variation	Water management and quality	Green spaces and biodiversity, soil management and quality, drought protection
Land use and associated impacts on biodiversity	Green spaces and biodiversity	Soil management and quality, planning urban space
Land use related to soil organic matter	Soil management and quality	Green spaces and biodiversity, planning urban space
Normalized Difference Vegetation Index (NDVI)	Green spaces and biodiversity	Planning urban space, social justice and cohesion
Number of invasive	Green spaces and biodiversity	-
Potential of areas likely to	Green spaces and biodiversity	-
Ratio of native plant species	Green spaces and biodiversity	-
Shannon diversity index	Green spaces and biodiversity	-
Soil classification	Soil management and quality	Planning urban space
Soil crusting	Soil management and quality	Planning urban space
Soil macro porosity	Soil management and quality	Green spaces and biodiversity, planning urban space
Soil water infiltration	Soil management and quality	Water management and quality
Soil water storage	Soil management and quality	Water management and quality
Species richness increase	Soil management and quality	Green spaces and biodiversity
Urban Green Space porportion	Green spaces and biodiversity	Social justice and cohesion, planning urban space

A.3 List of Operational and Maintenance KPI's

Table 41: Operational and Maintenance KPIs

KPI	Description	Assessment method	Scale	Reference
Building energy demand	Thermal impact by SUDS on buildings	ENVI-met, SOLENE, Energy-Plus, EnviBatE with SURFEX	Neighborhood, object	Nature4Cities [30]
Cumulative energy demand	The by SUDS created decrease in total energy consumption	Multiplication of the flows of raw resources and energy with characterisation factor	City, neighborhood, object	Frischknecht et al. [74] Patel [75] Nature4Cities [30]
Energy efficiency	Change in efficiency of energy use per capita due to implementation SUDS	Quantitative evaluation of energy consumption per capita per time	City, neighborhood, object	Nature4Cities [30]
Maintenance and servicing requirements	Need and frequency for operational and maintenance service	Qualitative Life Cycle Assessment	City, neighborhood, object	Revitt et al. [34]
Raw material efficiency	Provides a percentage change in the amount of main raw material consumed per person as a result of stategic SUDS implementation	Quantitative assessment of public administration of raw material consumption using Excel	City	Nature4Cities [30]
Specific waste generation	Represents the yearly municipal solid waste generation per person. This is significantly related to SUDS	Calculated in kilogram per year using the formula: $Municipal\ Solid\ Waste/popultation$	City, neighborhood, object	Nature4Cities [30]
Sustainable practices index	Represents the level of acceptance of sustainable solutions	Questionnaire	City, neighborhood, object	Nature4Cities [30]
System reliability durability	Risk of system failure	E.g., via safety level, hydraulic retention time, clogging etc.	Object	Revitt et al. [34] Ellis et al. [24]
Water efficiency	Measurement of improvemement of reduced water waste	Monitorig via WaterCAD or SewerCAD	City, neighborhood, object	Nature4Cities [30]
Water security	Water supply coverage, waste water treatment, urban flooding	Calculated using urban water supply, wastewater treated drainage and adjustment factors for urban growth rate and river health	City, neighborhood	Nature4Cities [30]
Water use intensity	Ratio between water intake and a defined unit of production, which can change due to SUDS	Water balance in which the ratio between the water intake and the produced water is calculated	City, neighborhood, object	Nature4Cities [30]

The indicator defined in this criterion aim on tackling multiple urban challenges. Which urban challenges are addressed per KPI can be found in Table 42.

Table 42: Operational and Maintenance KPIs with corresponding urban challenges

KPI	Direct Urban Challenge addressed	Indirect Urban Challenge addressed
Building energy demand	Climate adaptation and mitigation	Planning urban space, carbon reduction and sequestration, public health & well-being
Cumulative energy demand	Climate adaptation and mitigation	Planning urban space, carbon reduction and sequestration, public health & well-being
Energy efficiency	Climate adaptation and mitigation	Planning urban space, carbon reduction and sequestration, green economy and inward investment
Maintenance and servicing requirements	Planning urban space	Green economy and inward investment
Raw material efficiency	Resource depletion	Waste generation
Specific waste generation	Waste generation	Water management and quality, soil management and quality
Sustainable practices index	Social justice and cohesion	Planning urban space, public health & well-being
System reliability and durability	Green economy and inward investment	Planning urban space
Water efficiency	Water management and quality	Waste generation, green economy and inward investment
Water security	Water management and quality	Drought protection, public health & well-being, resource depletion
Water use intensity	Water management and quality	Waste generation, resource depletion, public & well-being, drought protection

A.4 List Social and Urban Community KPI's

In this section the social and urban community benefits KPI's are laid out. This criterion is subdivided into the categories justice, process, and public health and well-being. This to make the lists more comprehensible.

Justice

Table 43: Social and Urban Community Benefits (Justice) KPIs

KPI	Description	Assessment method	Scale	Reference
Attachment to neighborhood	Feeling of cohesion in an area	Questionnaire	Neighborhood	Raymond et al. [31]
Control of crime	Indicator of rate of crime in an area	Measurement of frequency of victimization, gender violence, crime	City, neighborhood	Nature4Cities [30]
Control of extra-ordinary events	Possibility to assess how SUDS has affected the risk reduction for extreme events	Quantitative analysis of decrease/increase in insurance claims	City, neighborhood	Nature4Cities [30]
Perceived crime measures	E.g. perception of safety and crime	Survey to obtain average perception of crime types	City, neighborhood, object	Nature4Cities [30] Bouzouidja et al. [57]
Security against violence	Being able to walk freely and safely from place to place	Using statistics to obtain number of violence cases per year	City, neighborhood, object	Raymond et al. [31]
Segregation index	Demonstrates how different social strata are physically separated in an area	E.g., via Duncan index of dissimilarity with correlation analysis with SUDS	City, neighborhood	Nature4Cities [30] Bouzouidja et al. [57]

The indicators laid out in this section, have a direct and indirect focus concerning urban challenges. Table 44 depicts the direct and indirect challenges addressed by the defined KPI's.

Table 44: Social and Urban Community Benefits (Justice) KPIs with corresponding urban challenges

KPI	Direct Urban Challenge addressed	Indirect Urban Challenge addressed
Attachment to neighborhood	Social justice and cohesion	Public health & well-being
Control of crime	People security	Public health & well-being, social justice and cohesion
Control of extra-ordinary events	People security	Public health & well-being, social justice and cohesion, climate adaption and mitigation
Perceived crime measures	Public health & well-being	Social justice and cohesion, people security
Security against violence	People security	Social justice and cohesion, public health & well-being
Segregation index	Social justice and cohesion	Public health & well-being, green economy and inward investment, planning urban space

Process

Table 45: Social and Urban Community Benefits (Process) KPIs

KPI	Description	Assessment method	Scale	Reference
Absolute water consumption	Average annual water consumption	WaterCAD, SewerCAD	City, neighborhood, object	Nature4Cities [30]
Accessibility to green space	Percentage of citizens living within a given distance from accessible, public green space	GIS analysis	City, neighborhood	Raymond et al. [31]
Recreation	Number of enhanced recreational opportunities	Analysis of area via e.g. Google Maps	City, neighborhood	Raymond et al. [31] Ommer et al. [28]
Urban food production	Extra possible food produced by SUDS	Quantitative assessment of food production at e.g., green roofs	Object	Voskamp et al. [76] Raymond et al. [31]
Water scarcity	Lack of water in an area as consumption exceeds delivery of water	Life Cycle Assessment	City, neighborhood, object	Nature4Cities [30]

A list of the introduced KPI's and their addressed urban challenges is depicted in Table 46.

Table 46: Social and Urban Community Benefits (Process) KPIs with corresponding urban challenges

KPI	Direct Urban Challenge addressed	Indirect Urban Challenge addressed
Absolute water consumption	Public health & well-being	Climate adaptation and mitigation, drought protection, water management and quality
Accessibility to green space	Green economy and inward investment	Green spaces and biodiversity, public health & well-being, planning urban space
Recreation	Planning urban space	Public health & well-being, social justice and cohesion, green spaces and biodiversity
Urban food production	Public health & well-being	Green economy and inward investment
Water scarcity	Resource depletion	Drought protection, water management and quality, public health & well-being

Public Health and well-being

Table 47: Social and Urban Community Benefits (Public health and well-being) KPIs

KPI	Description	Assessment method	Scale	Reference
Adaptive Indoor Comfort	Measures people's perception of indoor environment	Quantitative assessment ENVI-met, SOLENE	Neighborhood, object	Nature4Cities [30]
Day-evening-night noise level	Represents daily equivalent sound pressure level	Either via simulation or measurements of decibels	City, neighborhood, object	Nature4Cities [30]
Heat induced mortality	Number of deaths related to temperatures above the 75th percentile of daily mean temperature during summer months	Derivation of risk estimates	City, neighborhood	Nature4Cities [30]
Long term health effects (Air quality)	Estimation of number of deaths due to long term exposure to urban levels of PM2.4 and NO2 with people older than 30 years	Numerical analysis using the formula: formule Output represents number of preterm deaths to ozone long-term exposure	City, neighborhood	Nature4Cities [30]
Mean radiant temperature	Human thermal comfort calculation (mean radiant)	RayMan, SOLWEIG, ENVI-met, FLUENT-ANSYS, SOLENE	Parcel, neighborhood	Bouzouidja et al. [57] Gál and Kántor [77]
Night noise level	Represents average sound pressure level over 1 night	Either in situ measurements or simulation via noise prediction software	City, neighborhood, object	Raymond et al. [31] Nature4Cities [30]
Outdoor Thermal Comfort	Thermal Comfort Score calculation	Sum of weighted PET-category frequencies	City, neighborhood, object	Scharf et al. [39] Bouzouidja et al. [57] Nature4Cities [30]
Physiological Equivalent Temperature (PET)	Human thermal comfort calculation (physiological)	RayMan, ENVI-met, SOLENE	City, neighborhood, object	Bouzouidja et al. [57] Nature4Cities [30]
Population Annoyance index	Describes health effects due to day-evening-night noise level	Development of noise map with buildings and calculated noise contour areas to assess the noise relative to a threshold level	City, neighborhood	Nature4Cities [30]
Predicted mean vote	Human thermal comfort calculation (predicted mean)	ENVI-met, FLUENT-ANSYS, RayMan	Neighborhood, object	Nature4Cities [30] Bouzouidja et al. [57]
Premature deaths and hospital admissions averted	Indicates the population's health	Statistical data analysis	City	Raymond et al. [31]
Quality of life	Represents the perceived global level of quality of life	WHOQOL assessment of the World Health Organization	City, neighborhood, object	WHO [78] Nature4Cities [30] Bouzouidja et al. [57] Kabisch et al. [63]
Reduced percentage of obese people	Indicates how fit a population is	Statistical data analysis	City, neighborhood	Raymond et al. [31] Kabisch et al. [63]
Reduction in chronic stress and stress-related diseases	Provides an indication of the mental health status of a population	Statistical data analysis	City, neighborhood	Raymond et al. [31]
Short term health effects (Air quality)	Estimation of number of preterm deaths due to ozone exposure in urban areas	Calculation similar to long term health effects	City, neighborhood	Nature4Cities [30]
Thermal load of out streaming body	Difference in hourly air temperature flowing in and out of an area on a summer day	ENVI-met	Neighborhood, object	Nature4Cities [30]
Universal thermal climate index	Human thermal comfort calculation (universal)	ENVI-met, TEB, RayMan, SOLENE	City, neighborhood	Schrijvers et al. [79] `http://www.utci.org/`

These indicators address multiple urban challenges. Next to the direct urban challenge they are focused on, they indirectly relate to several other urban challenges as well. In Table 48 the KPI's and their addressed challenges are shown.

Table 48: Social and Urban Community Benefits (Public health & well-being) KPIs with corresponding urban challenges

KPI	Direct Urban Challenge addressed	Indirect Urban Challenge addressed
Adaptive Indoor Comfort	Public health & well-being	Climate adaptation and mitigation
Day-evening-night noise level	Public health & well-being	Planning urban space
Heat induced mortality	Public health & well-being	Social justice and cohesion, climate adaptation and mitigation
Long term health effects (Air quality)	Public health & well-being	Social justice and cohesion, climate adaptation and mitigation, green economy and inward investment
Mean radiant temperature	Public health & well-being	Climate adaptation and mitigation
Night noise level	Public health & well-being	Planning urban space
Outdoor Thermal Comfort	Public health & well-being	Climate adaptation and mitigation, green spaces and biodiversity, planning urban space
Perceived health	Public health & well-being	Social justice and cohesion
Physiological Equivalent Temperature (PET)	Public health & well-being	Social justice and cohesion
Population Annoyance index	Public health & well-being	Social justice and cohesion
Predicted mean vote	Public health & well-being	Social justice and cohesion
Premature deaths and hospital admissions averted	Public health & well-being	Social justice and cohesion, climate adaptation and mitigation, green economy and inward investment
Quality of life	Public health & well-being	Social justice and cohesion, people security, green economy and inward investment
Reduced percentage of obese people	Public health & well-being	Social justice and cohesion
Reduction in chronic stress and stress-related diseases	Public health & well-being	Social justice and cohesion
Short term health effects (Air quality)	Public health & well-being	Social justice and cohesion, climate adaptation and mitigation, green economy and inward investment
Thermal load of out-streaming body	Planning urban space	Public health & well-being, green spaces and biodiversity
Universal thermal climate index	Public health & well-being	Social justice and cohesion

A.5 List Economic KPI's

In this section the economic KPI's are laid out. This criterion is subdivided into the categories monetary and productivity. This creates a better organisation of the KPI's. **Monetary**

Table 49: Economic (Monetary) KPIs

KPI	Description	Assessment method	Scale	Reference
Annual budget of SUDS management	The annual budget spent on green infrastructure management relative to the cities' annual budget	Calculated by dividing the total budget of a city in the past 10 years by the total budget spent on management of SUDS in past 10 years	City, neighborhood, object	Nature4Cities [30]
Energy savings	Expenses saved due to SUDS	E.g., by using an energy saving equation which compares a baseline temperature with the reduced temperature due to SUDS implementation	Object	Ommer et al. [28]
Financial risk/ exposure	Risk of investment of SUDS	Quantitative analysis of associated costs and the total budget available	City, neighborhood, object	Ellis et al. [24]
Life-cycle costs	Operational and capital investment	Calculation of associated operational and capital costs of SUDS	Object	Revitt et al. [34] Ellis et al. [24]
Long term affordability	Financial viability of SUDS	Financial assessment of party that pays for SUDS implementation and management	Object	Revitt et al. [34] Kabisch et al. [63]
Property prices/ House Price Index	Increase or decrease of citizen's wealth due to SUDS implementation in an area	Comparison of house prices before and after SUDS implementation	City, neighborhood, object	Raymond et al. [31] Ommer et al. [28] Nature4Cities [30]
Tax revenue	Change in tax revenue	E.g., calculated based transfer taxes	Object	Ommer et al. [28]
Value of insurance claims	Economic measure of harmful effects of extraordinary events on people's property	Calculated by dividing the total value of insurance claims by the area of scope	City, neighborhood	Nature4Cities [30]

These monetary KPI's aim to tackle multiple urban challenges. Table 50 depicts the direct and indirect urban challenges per KPI.

Table 50: Economic (Monetary) KPIs with corresponding urban challenges

KPI	Direct Urban Challenge addressed	Indirect Urban Challenge addressed
Annual budget of SUDS management	Green economy and inward investment	Climate adaptation and mitigation, planning urban space, social cohesion and justice
Energy savings	Green economy and inward investment	Climate adaptation and mitigation, carbon reduction and sequestration, public health & well-being
Financial risk/ exposure	Green economy and inward investment	Planning urban space
Life-cycle costs	Green economy and inward investment	Planning urban space
Long term affordability	Green economy and inward investment	Planning urban space, social justice and cohesion
Property prices/ House Price Index	Green economy and inward investment	Public health & well-being, social justice and cohesion, green space and biodiversity
Tax revenue	Green economy and inward investment	Public health & well-being, social justice and cohesion
Value of insurance claims	Climate adaptation and mitigation	Public health & well-being, social justice and cohesion

Productivity

Table 51: Economic (Productivity) KPIs

KPI	Description	Assessment method	Scale	Reference
Number of jobs created	Job opportunities created as a result of SUDS implementation	Quantification of the number of employees in SUDS maintenance	City, neighborhood, object	Raymond et al. [31] Ommer et al. [28]
Tourism	Change in revenue of tourism due to increased attractiveness of area with SUDS	Comparison of income before and after SUDS implementation	City, neighborhood	Ommer et al. [28]

These two indicators aim to tackle multiple urban challenges. Next to the direct urban challenge they are focused on, they indirectly relate to several other urban challenges as well. In Table 52 the KPI's and their addressed challenges can be found.

Table 52: Economic (Productivity) KPIs with corresponding urban challenges

KPI	Direct Urban Challenge addressed	Indirect Urban Challenge addressed
Number of jobs created	Green economy and inward investment	Public health & well-being, social justice and cohesion, people security
Tourism	Green economy and inward investment	Green spaces and biodiversity, public health & well-being, planning urban space

A.6 List Legal and Urban Planning KPI's

Table 53: Legal and Urban Planning KPIs

KPI	Description	Assessment method	Scale	Reference
Accessibility	Analysis of the relationship between the residential areas and the spatial organization of green spaces	GIS analysis	Neighborhood	Nature4Cities [30] Bouzouidja et al. [57] Kabisch et al. [63]
Adoption status	Balance between acceptability level and liability of risk	Ideally via analysis of legal documents. Assessment of balance between acceptability and liability of risk	City	Revitt et al. [34]
Local building and development issues	Identification of compatibility of SUDS with location	Analysis of compatibility with planning and development requirements	Object	Revitt et al. [34]
Responsibility	Where do the responsibilities lie for the planning, implementation and maintenance of SUDS	Analysis via either interviews, surveys, focus groups etc.	City, neighborhood	Kabisch et al. [63] Nature4Cities [30]
Social values for urban ecosystems and biodiversity	Active participation and desire for SUDS implementation	Data collection via interviews, surveys, focus groups etc	City, neighborhood	Raymond et al. [31]
Urban storm water management regulations	Analysis of the regulation the development of SUDS has to adhere to	Analysis of legal documentation	City	Revitt et al. [34]

This list on indicators addresses multiple urban challenges. Table 54 shows both the direct and indirect challenges address by these KPI's.

Table 54: Legal and Urban Planning KPIs with corresponding urban challenges

KPI	**Direct Urban Challenge addressed**	**Indirect Urban Challenge addressed**
Accessibility	Planning urban space	Social justice and cohesion, public health & well-being, green space and biodiversity
Adoption status	Planning urban space	Green economy and inward investment
Local building and development issues	Planning urban space	Climate adaptation and mitigation, public health & well-being
Responsibility	Planning urban space	Social justice and cohesion
Social values for urban ecosystems and biodiversity	Planning urban space	Public health & well-being, social justice and cohesion, green space and biodiversity
Urban storm water management regulations	Planning urban space	Climate adaptation and mitigation, public health & well-being, people security

B Climate stress-test

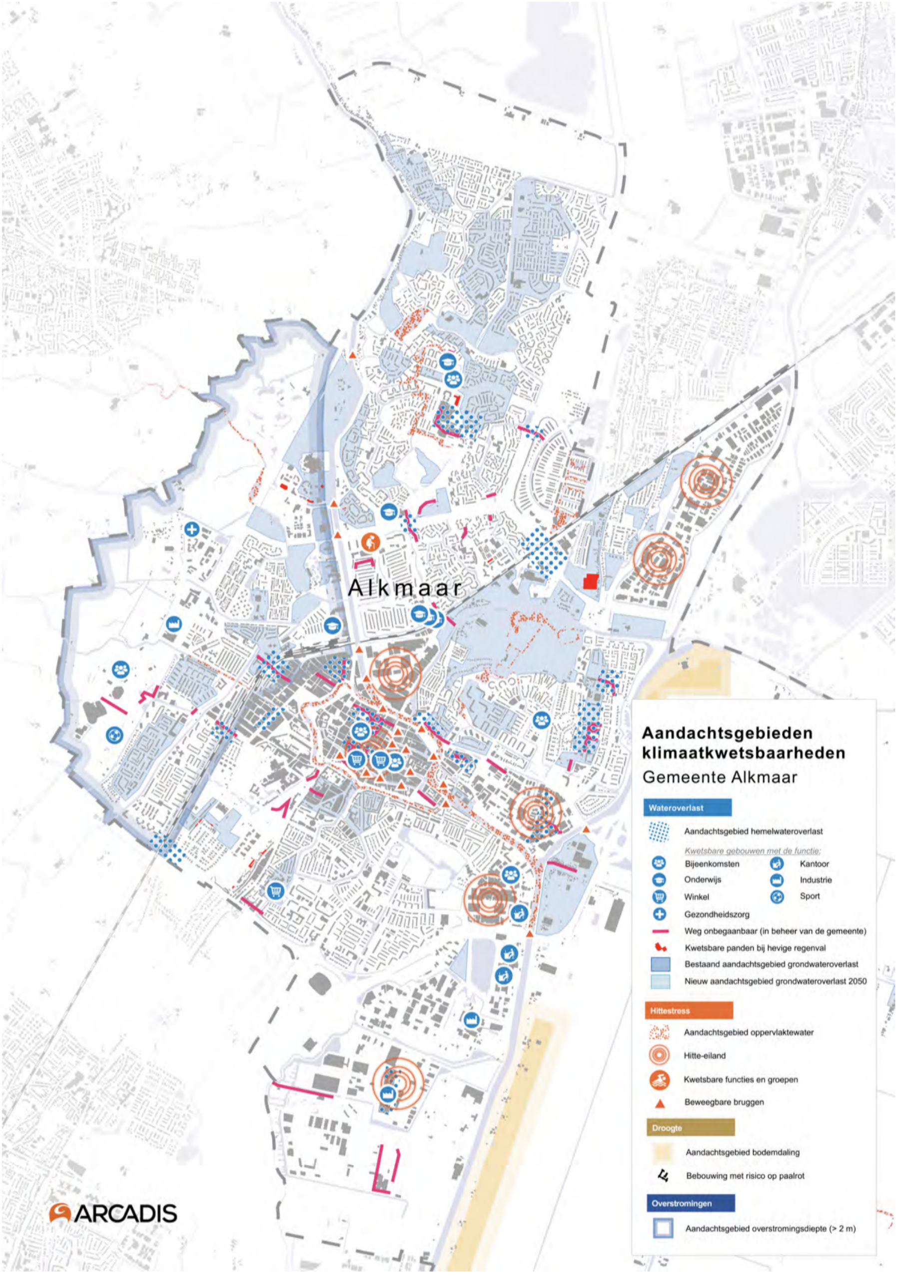


Figure 16: Climate stress-test Alkmaar [80]

C Maps of chosen neighborhoods Alkmaar

Figure 17: Map of de Mare, Alkmaar

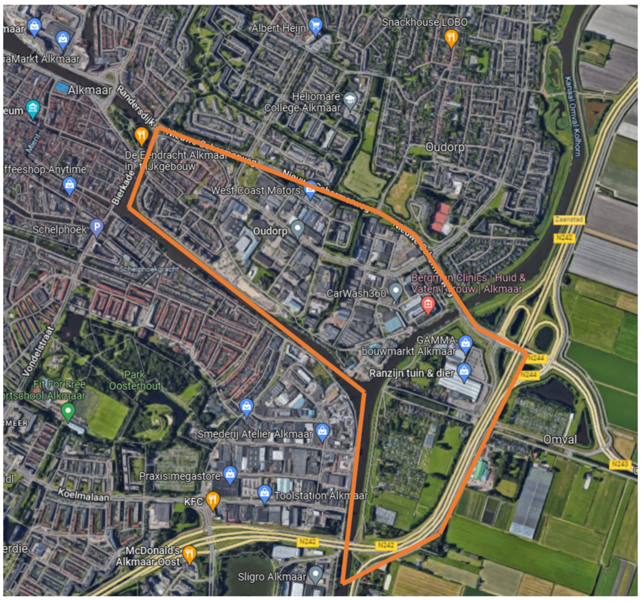
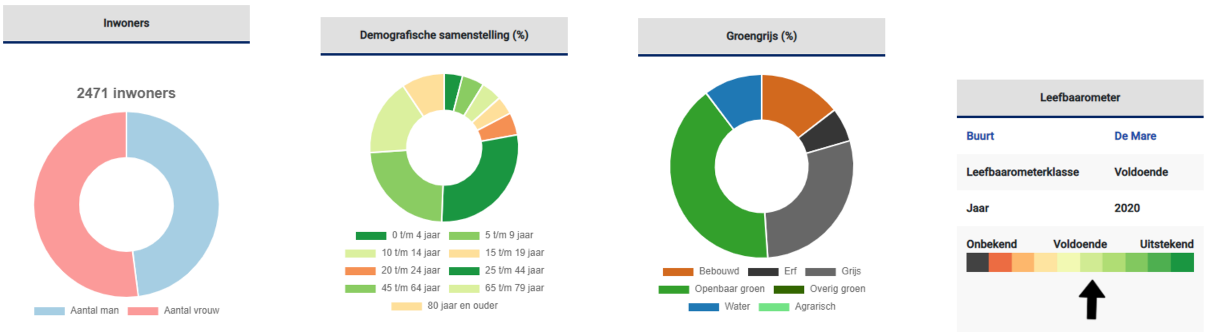


Figure 18: Map of Schermereiland en Omval, Alkmaar

D Background information case study

D.1 De Mare - Alkmaar

De Mare is situated in the North of Alkmaar in the district Huiswaard-Noord. Figure 19 contains the statistics provided by Gemeente Alkmaar [81] on this neighborhood. De Mare's surface area is 61 hectares, of which 3 hectares are surface water. The neighborhood has 2471 inhabitants, of which the largest share, 28.3%, is between 25 and 44 years old. The total percentage of inhabitants above 65 years old is 26%. In Figure 19c it is shown that the largest part, 38.95%, in the neighborhood is public green area. This as the area includes the park Rekerhout, situated in the south of the neighborhood. The style the buildings in the area are built in is from the eighties/nineties, and De Mare is thereby a post-war neighborhood. The livabilityometer (leefbaarometer), depicted in Figure 19d, provides an estimate of the quality of life per neighborhood on the basis of a large number of characteristics of the residential environment, such as the type of facilities, local noise pollution and unsafety [81]. It serves as a signaling and monitoring tool for the municipality, housing associations and other organisations. De Mare is indicated to have a sufficient live-ability.



(a) Inhabitants (b) Demographics (c) Green-gray (%) (d) Live-ability

Figure 19: Statistics neighborhood De Mare [81]

For the public space in this neighborhood, the ratio of green and paved surfaces is 60/40 [82], which is relatively high compared to other neighborhoods in the city, resulting from the presence of Rekerhout. Per household, there is 150-450 m^2 green available [82]. However, Rekerhout is part of this neighborhood having a major influence on this outcome. The available green space per household is high in De Mare because of this park, but the urban design is comparable to the other neighborhoods in Huiswaard. Excluding Rekerhout, the neighborhood contains 25-50 m^2 per household [82], indicating that without the park the area does not include much green.

Following research conducted by SWECO and Gemeente Alkmaar [83], the green municipal main structures (parks, waters, connecting zones, tree structures) are the biodiversity hot spots in Alkmaar. This research expresses biodiversity with nature points. In their research, it is explained that nature points provide a uniform measure of nature quality and are a way of making the added value for biodiversity visible in spatial developments. The south part of De Mare scores high on these nature points, as Rekerhout is one of these biodiversity hot spots. It has a good quality nature for biodiversity. The municipality aspires to invest in preserving and strengthening these natural values. The north part does not score well on this biodiversity measure, as this built-up area does not contain much green.

The climate stress-test conducted by Arcadis [80] designates the area north of Rekerhout as storm water nuisance sensitive (Figure 16, Appendix B). This is also supported by Wareco

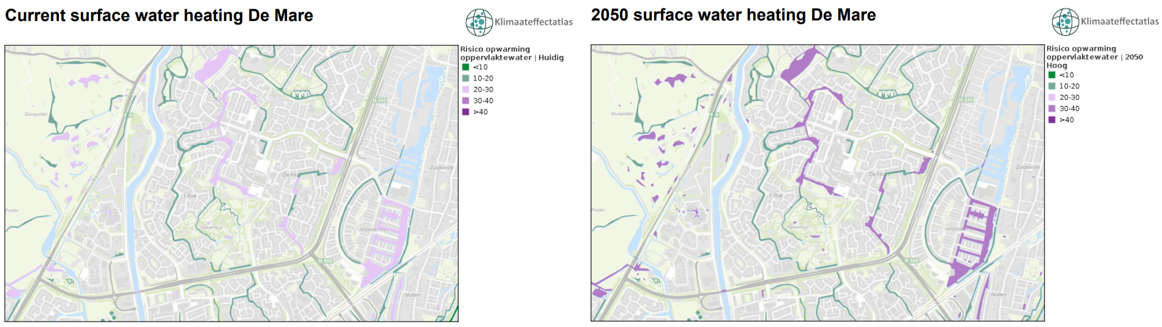
[64], as in the map presented in Figure 28 in Appendix E the risk for water not being able to be drained or infiltrate and thus remaining on the street is also indicated to the area north of the north east corner of Rekerhout. Nowadays, Alkmaar is being tested on precipitation events of 100 mm per 2 hours, having a return period of 1/300-1/500 years. According to Wareco [64] this leads to more than 20 cm water on the streets in this part of De Mare, being a post-war neighborhood. The Klimaateffectatlas [84] investigates an extremer storm, looking at an event with a return period of 1/1000 indicating rainfall of 140 mm per 2 hours. This storm is modelled in the current climate and climate around 2050 according to the KNMI's WH scenario.The WH scenario has the largest number of warm days and nights of the four KNMI'14 climate scenarios, being the scenario with the largest predicted impact of climate change [85]. The darker blue streets in these maps are more prone to have water on the streets during such extreme event.

(a) Water on street current situation [84]

(b) Water on street 2050 [84]

Figure 20: Storm water nuisance due to storm with return period 1/1000

The increase in summer and tropical days caused by climate change has consequences for surface water. During prolonged warm periods, in particular standing surface water can heat up strongly. This affects the water quality, possibly with adverse effects on health, ecology, agriculture, industry and recreation. Increased surface water temperature also contributes to the warming of built-up areas. The surface water in De Mare is pointed out as a vulnerability from heat stress by Arcadis [80]. This means that the surface water in this area is expected to be warmer than 20°C for more than 30 consecutive days in 2050. This is caused by long-term warming of the water, having a strong influence on water quality, resulting in more blue-green algae and botulism, among other things. As is indicated in Figure 28, the surface water is in the area where there is a heat risk. In this map, Wareco [64] indicated that the surface temperature in the area where the surface water is located has the ability to rise above 40°C on a representative summer day in Alkmaar. More detailed information about this increasing surface water temperature is shown in Figure 21. The Klimaateffectatlas [84] shows in these maps the vulnerability of the surface water temperature to increase in De Mare, wherein the model calculates water temperatures for summer periods (April-September) in the current climate and around 2050 according to the KNMI's WH scenario. The longest series of days in which the surface water temperature is higher than 20°C is depicted, whereby these long time periods of high water temperatures negatively affect the quality of the surface water.

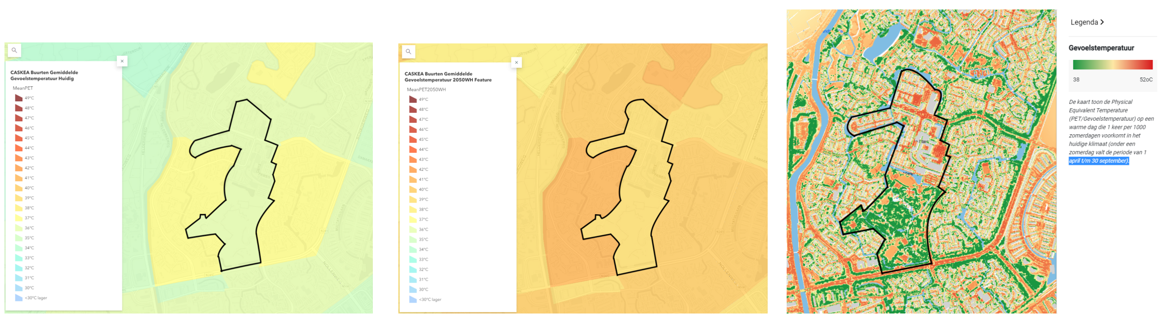


(a) Current surface water temperature [84]   (b) Surface water temperature 2050 [84]

Figure 21: Increase of surface water temperature

Arcadis [80] indicated that for the north-east corner of this neighborhood the area is known to be sensitive to groundwater nuisance (Figure 16, Appendix B). This means that for this location it is expected that the drainage of groundwater in a wet winter situation is structurally smaller than 0.7 m. The predicted future rise of the groundwater level in this area forms a risk. This risk is also substantiated by Wareco [64], as the map in 28 indicates that in the area in the north east corner of De Mare there is the risk of the groundwater level exceeding the depth of 0.7 m - ground level. Additionally, there is a small area where there is a risk of low ground water levels, indicating the risk of a drainage depth more than 1.5m, depicted by the yellow square in Figure 28 in Appendix E.

The heat maps depicted in Figure 22 show the PET in De Mare during an extremely hot summer afternoon. The maps in Figure 22a and 22b present the average PET in ºC for the period 12:00-18:00 local time on a hot summer day. Figure 22a shows the situation in the current climate. Klimaateffectatlas [50] used the weather measurements on the first of July in 2015 to obtain this current situation. This day was used as it was a hot day that occurs approximately once every 5.5 years in the current climate. The map in Figure 22b shows the situation in 2050 with strong climate change, holding the WH scenario of the KNMI. It can be seen that the temperature experienced by the inhabitants is going to increase significantly compared to current state. Figure 22c shows more detailed information on the PET in this neighborhood. As can be seen, the green present in Rekerhout provides considerable cooling locally.



(a) Current PET [50]   (b) PET 2050 prediction [50]   (c) Current detailed PET [81]

Figure 22: PET, De Mare

In general, the city of Alkmaar, and thus De Mare and Schermereiland en Omval, is less vulnerable to drought. Despite the fact that there is a precipitation deficit that affects the groundwater level, this is not a great risk for the city, because the old buildings are not founded on wooden piles [80].

D.1.1 Opportunities

Opportunities for solutions regarding challenges for the themes of heat, groundwater (high and low), soil, and storm water, are investigated by Wareco [64]. These themes are integrally linked in the water system. Their results are shown in Figures 29 and 30 in Appendix E. As is shown in the map depicted in Figure 29, in the part of this neighborhood situated north of Rekerhout the opportunity arises to infiltrate water through the impervious surface. It is a location with a risk of water on the street and the groundwater level here is sufficiently low to consider infiltration possibilities and infiltration to deeper soil layers can be investigated, as is shown in the map in Figure 30. As there is no groundwater contamination present in de Mare, infiltration does not lead to any water quality problems underground and thereby unrestricted. Furthermore, the map in Figure 29 shows the advise for surface storing of water at the locations with the risk for high groundwater levels. Infiltration is not an option for such area and therefore other opportunities need to be explored.

There are several locations that are currently and planned to be under development. In Figure 23 these areas are highlighted by the colour yellow. Momentarily, the area around Urkstraat is redeveloped. At this square, also known as Urkplein, a lot of GI is applied to improve the areas heat stress and storm water nuisance. For the other locations, plans are not final yet. These locations provide additional opportunities to implement SUDS at.

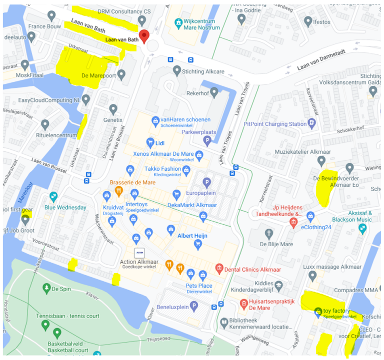
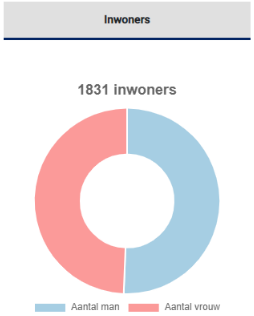


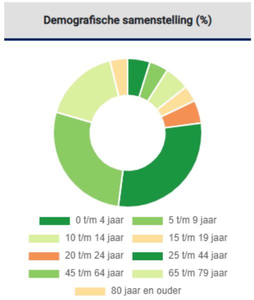
Figure 23: Locations that are going to be redeveloped in De Mare [86]

D.2 Schermereiland en Omval - Alkmaar

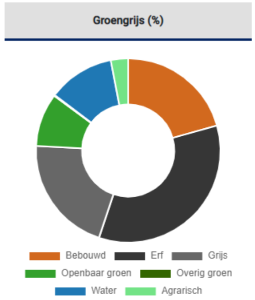
Schermereiland en Omval is located in the central part of Alkmaar, with the western part of this neighborhood being Schermereiland and the area east of Kanaal Omval-Kolhorn (Kraspolderkanaal) being Omval. Detailed statistics provided by Gemeente Alkmaar [81] on this neighborhood are depicted in Figure 24. As is shown, 1831 inhabitants live in this neighborhood. More than half of the people living in this neighborhood are between 25 and 44 years old, 29.1%, and between 45 and 64 years old, 27.5%, as can be seen in Figure 24b. The percentage of inhabitants older than 65 is 20.5%. Shown in Figure 24c, the dominating land use in this neighborhood is property use (erf) with 31.33%. Also, it is shown that the area does not contain much public green space, being only 8.52%. Lastly, the area scores between sufficient and excellent on the livabilityometer depicted in Figure 24d. Schermereiland en Omval thereby scores higher than De Mare.



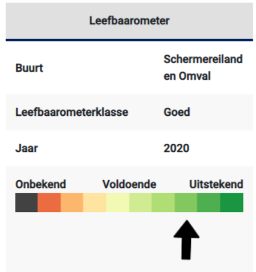
(a) Inhabitants



(b) Demographics



(c) Green-gray (%)

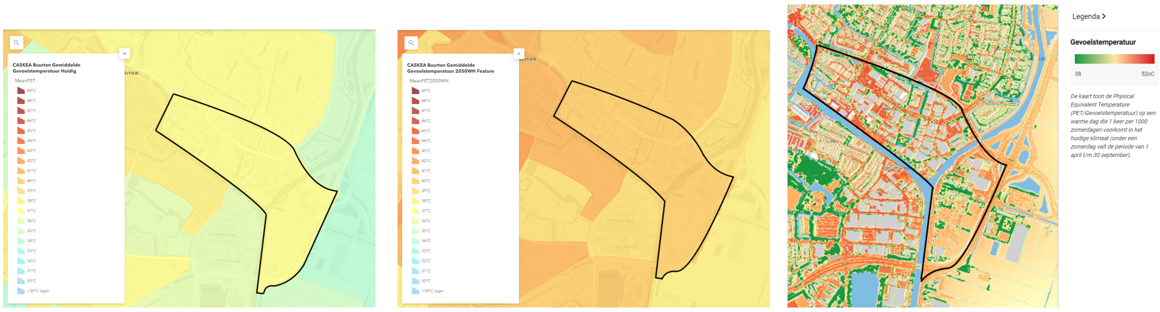


(d) Live-ability

Figure 24: Statistics neighborhood Schermereiland en Omval [81]

The ratio of green and paved surfaces in this neighborhood is 35/65 in the public area [82], whereby Schermereiland en Omval is one of the lower scoring neighborhoods on the amount of green versus paved surfaces, and also has a lot lower ratio than De Mare. The availability of public green area is low, being 25-50 m^2 per household [82]. Consequently, Schermereiland scores the lowest possible outcome on nature points and Omval the second to lowest possible outcome, indicating there is little biodiversity according to the research of SWECO and Gemeente Alkmaar [83]. A lot of profit can be made on industrial estates and strongly petrified areas to increase the areas biodiversity. Furthermore, as is indicated in the research of Wareco [64] in the map depicted in Figure 28 in Appendix E by the yellow square, the entire neighborhood risks low groundwater levels caused by a drainage depth of more than 1.5m.

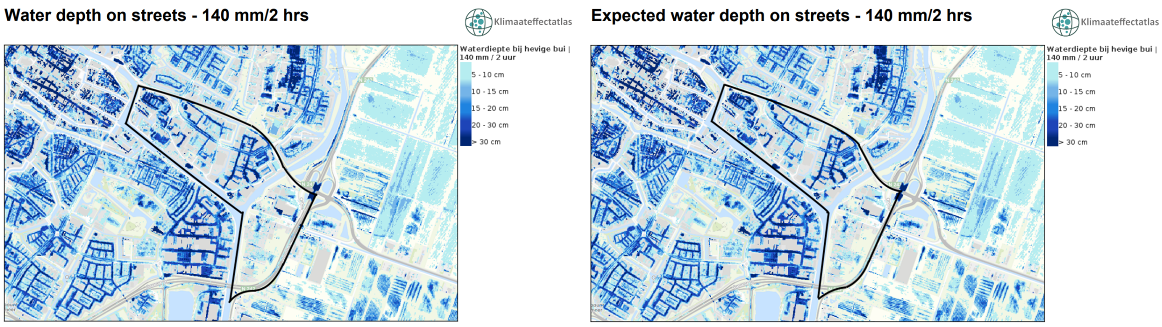
Schermereiland is densely built and dominantly impervious including an business and office area. This area is consequently marked by both Arcadis [80] and Wareco [64] as a location that experiences heat stress. The climate stress-test conducted by Arcadis shows the occurrence of the UHI effect, meaning this area is one of the hottest areas in Alkmaar, which is based on imaging by the satellite Landsat 8. Wareco [64] highlights a risk of heat for almost all of Schermereiland whereby the surface temperatures can become higher than 40°C on a representative summer day in Alkmaar. The heat maps depicted in Figure 25 depict the PET in Schermereiland en Omval during an extremely hot summer afternoon. The maps in Figure 25a and 25b present the average PET in ºC for the period 12:00-18:00 local time on a hot summer day. Figure 25a shows the situation in the current climate for which the weather conditions of the first of July in 2015 are used. The map in Figure 25b shows the situation in 2050 with strong climate change, holding the WH scenario of the KNMI. By looking at the color change between these two maps, it can be seen that for this scenario a significant PET increase is predicted. In Figure 22c more detailed information on the PET in Schermereiland en Omval can be found. It is shown that parts of Schermereiland experience considerable heat stress as the PET is high in a lot of places in this area.



(a) Current PET [50] (b) PET 2050 prediction [50] (c) Current detailed PET [81]

Figure 25: PET, Schermereiland en Omval

As Schermereiland is dominantly impervious, storm water results in nuisance in this area [80]. The area has limited infiltration possibilities for storm water. According to Wareco [64] at parts of Schermereiland there is the risk of storm water not being drained away, leaving water on the street during an heavy storm of 100 mm per 2 hours, being the event used by Alkmaar for modelling the area. The by Klimaateffectatlas [84] investigated more extreme storm, an event with a return period of 1/1000, is depicted in Figure 26. For both the current climate and climate around 2050 according to the KNMI's WH scenario, the results are shown in these maps. The storm water nuisance sensitive streets in this neighborhood can be recognised by the dark blue streets during such extreme event.



(a) Water on street current situation [84] (b) Water on street 2050 [84]

Figure 26: Storm water nuisance due to storm with return period 1/1000

The Omval is a lot less densely built than Schermereiland. In this area there is a lot more green space. This whole area is marked as a known area sensitive to groundwater nuisance by Arcadis [80]. As mentioned earlier, this holds that for this location it is expected that the drainage of groundwater in a wet winter situation is structurally smaller than 0.7 m. Groundwater levels in this area are prone to rise. This is also supported by the research of Wareco [64], wherein the Omval is highligted to be an area with a risk of high groundwater levels.

D.2.1 Opportunities

Considering the findings of Wareco [64] depicted in Figures 29 and 30 in Appendix E, in Schermereiland there is the desire for cooling of the area. Creating additional greenery or more water on the surface should be considered.This is also supported by the climate stress-test of Arcadis [80] indicating the UHI in this area. Furthermore, the map in Figure 29 indicates that improvements in the slope of ground level are desired in the south east end and west end of Schermereiland to minimise the risk of water on the streets during extreme precipitation. As it is a location with a risk of water on the street resulting from extreme precipitation events and the groundwater level here is sufficiently low, infiltration possibilities in shallow and deeper layers can be investigated in Schermereiland, as is shown in the map in Figure 30. This opportunity for infiltration in Schermereiland is also highlighted by Arcadis [80], as it is expected much drainage of groundwater will take place in this area.

The municipality of Alkmaar is planning to redevelop parts of Schermereiland. These locations are shown in Figure 27, highlighted by the colour yellow. As shown, the area around Schermerweg is going to be redeveloped. In this area there is a severe groundwater contamination caused by a past chemical cleaning company. Furthermore, soil remediation needs to be applied to the location highlighted for redevelopment adjacent to Edisonweg and Marconistraat as the soil is contaminated with too high levels of chrome. This is a prerequisite for infiltration in this area. Infiltration into shallow layers is not allowed in this area. The largest part of de Omval contains a community garden. In this part of the neighborhood the municipality of Alkmaar is not currently planning to change the urban design. This thesis thus focuses on implementation of SUDS in Schermereiland.

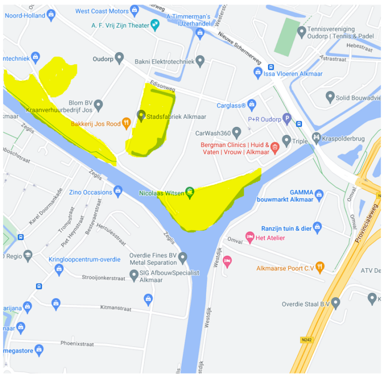


Figure 27: Locations that are going to be redeveloped in Schermereiland [86]

E Water system maps

E.1 Risks

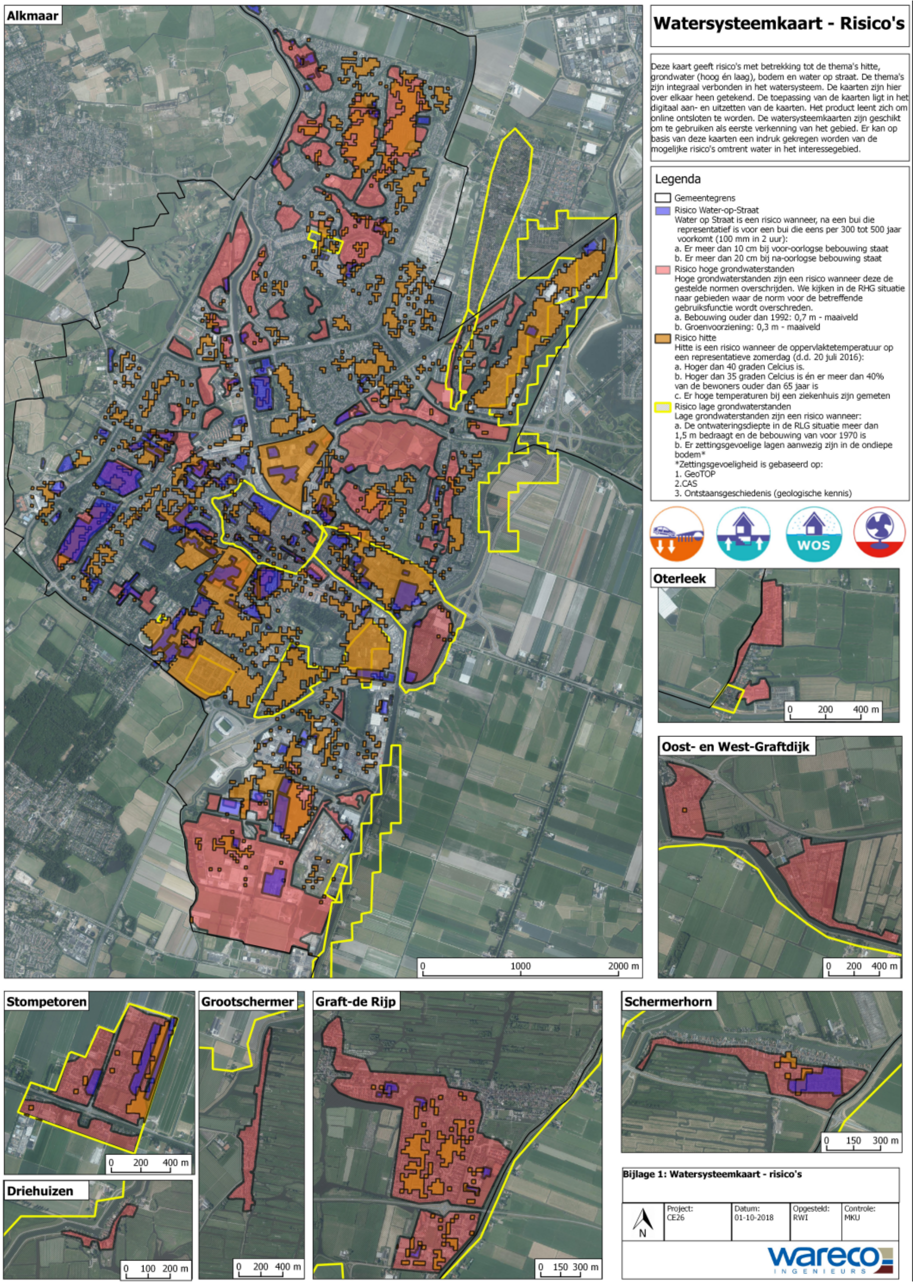


Figure 28: Water system map risks [64]

E.2 Solutions

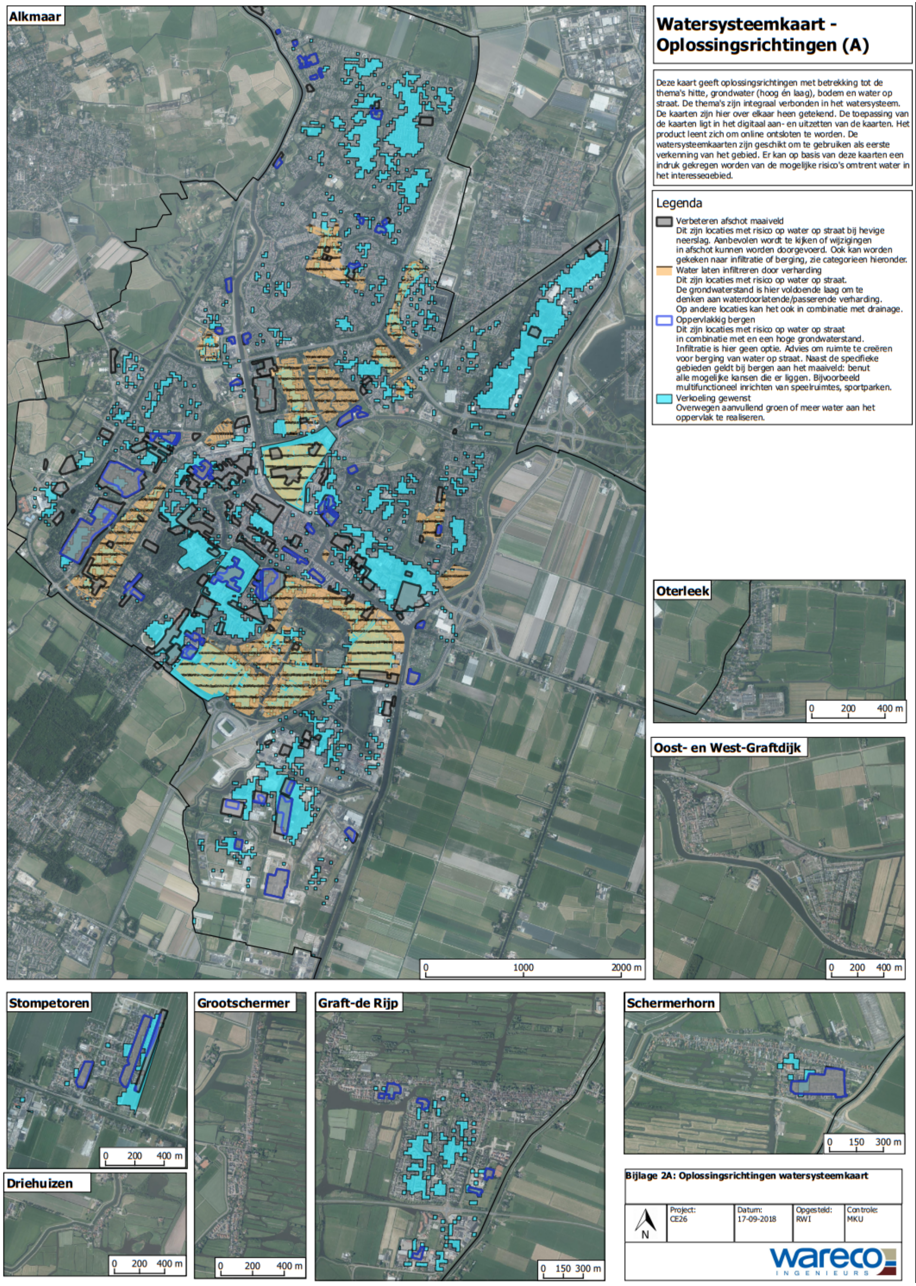


Figure 29: Water system map solutions (A) [64]

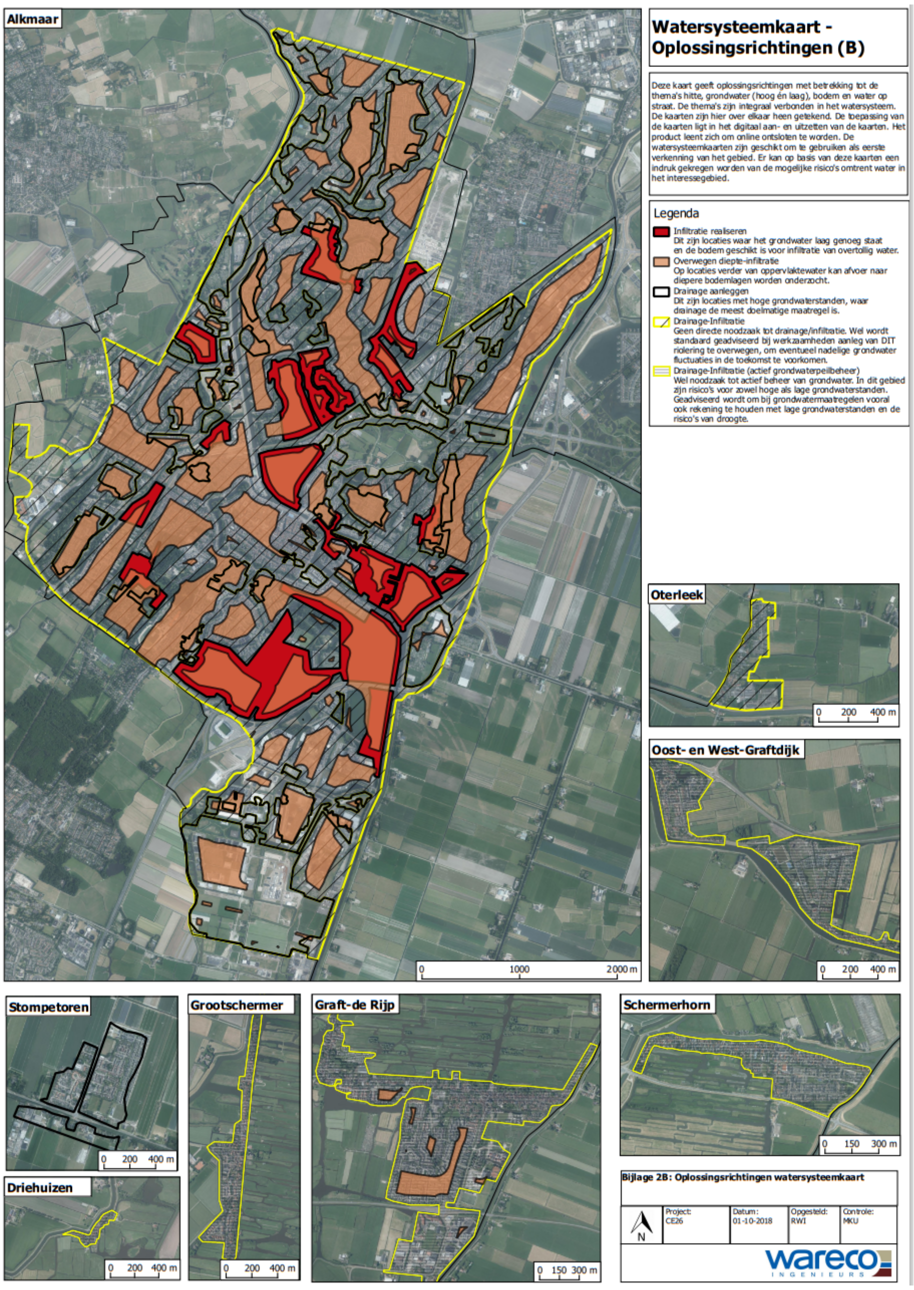


Figure 30: Water system map solutions (B) [64]

F Precipitation statistics the Netherlands

TABEL 2 BASISSTATISTIEK VOOR HET JAAR; NEERSLAGHOEVEELHEDEN (IN MM) BIJ VERSCHILLENDE HERHALINGSTIJDEN EN NEERSLAGDUREN TUSSEN 10 MINUTEN EN 8 DAGEN. NB DE HOEVEELHEDEN IN DEZE TABEL KUNNEN VOOR PRAKTISCH GEBRUIK AFGEROND WORDEN OP HELE MILIMETERS. HIER IS DAT BEWUST NIET GEDAAN OM AFRONDINGSFOUTEN TE VOORKOMEN WANNEER DEZE GETALLEN GEKOMBINEERD WORDEN MET KLIMAATSCENARIOFACTOREN IN DEELRAPPORT 2 EN/OF DE REGIONALE SCHALINGSFACTOREN IN DEELRAPPORT 3

	Neerslagduur										
T [jaar]	10 min	30 min	60 min	2 uur	4 uur	8 uur	12 uur	24 uur	2 dagen	4 dagen	8 dagen
0.5	8.1	10.4	12.6	15.3	18.6	22.2	24.6	30.4	38.6	50.4	68.3
1	10.2	13.5	16.2	19.5	23.4	27.7	30.5	36.8	46.0	59.3	79.4
2	12.2	16.6	20.0	24.0	28.4	33.4	36.5	43.8	54.0	68.6	90.5
5	15.1	21.2	25.8	30.7	35.9	41.7	45.2	54.2	65.5	81.4	105.1
10	17.5	25.3	31.0	36.8	42.8	49.1	52.9	63.0	74.9	91.6	116.1
20	20.3	30.2	37.2	44.2	51.1	58.0	61.9	72.6	85.0	102.1	127.0
25	21.3	32.0	39.5	46.9	54.1	61.2	65.2	75.9	88.5	105.6	130.5
50	24.7	38.2	47.7	56.5	64.8	72.5	76.6	86.9	99.5	116.6	141.5
100	28.7	45.8	57.7	68.4	78.0	86.2	90.2	98.9	111.4	128.1	152.3
200	33.4	55.0	70.0	81.3	88.7	95.0	98.1	112.1	124.2	140.0	163.2
250	35.0	58.4	74.5	86.5	93.9	100.0	102.9	116.7	128.5	143.9	166.7
500	40.8	70.4	90.7	105.0	112.2	117.5	119.6	131.7	142.5	156.4	177.5
1000	47.6	84.9	110.6	127.6	134.4	138.3	139.2	148.2	157.5	169.4	188.3

Figure 31: Precipitation statistics [87]

G Depth-damage curve

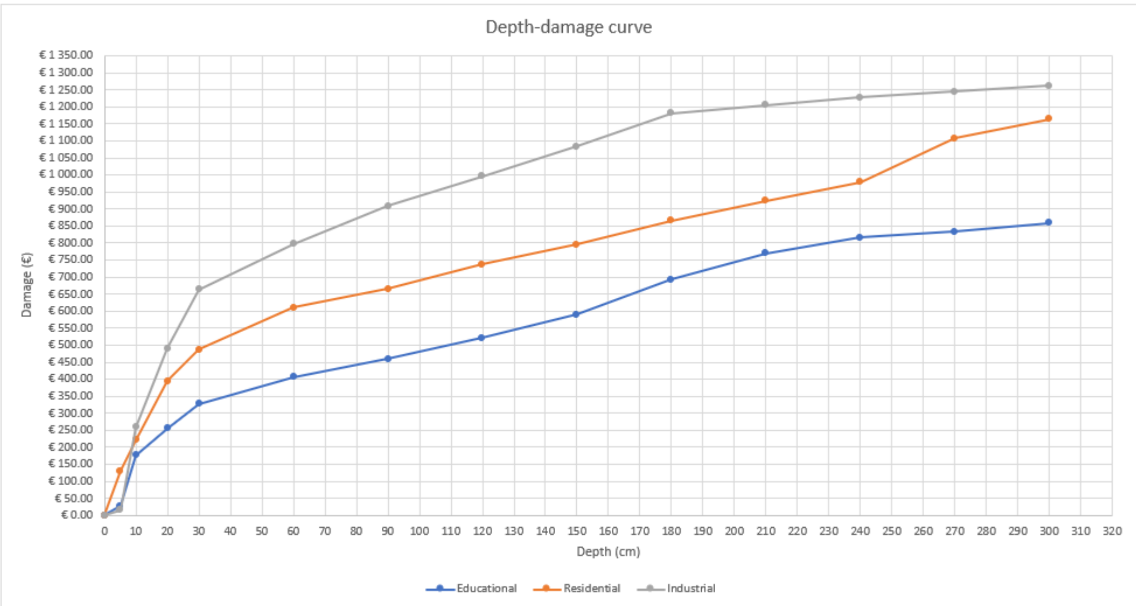


Figure 32: Depth-damage curve [36]

H Pollutant concentrations and loads

BOX 4.2 **Pollutant concentrations and loads**

A peak "flush" of pollutants often occurs during the early stages of a storm event, before the flow rate in the system reaches its peak. It is possible to get a high initial pollution concentration for relatively small rainfall events, as it does not take a great deal of rain to wash off the pollutants. This is why it is important to manage the frequent small events effectively.

Figure 4.1 shows how pollution concentration (red) and cumulative pollution load (green) change over time for sediments transported during a rainfall event, compared to the flow rate (blue). This shows the initial "flush" of pollutants shortly after the start of the event, and then there is a second peak later in the event, which coincides with a further increase in flow rate, as runoff from more distant parts of the site reaches the downstream system.

These peaks in sediment concentration are typical of sediments transported from urban surfaces and also for the pollutants that are predominantly attached to the sediments during an event, such as hydrocarbons, organic compounds and heavy metals. Other pollutants (including dissolved pollutants) can show different runoff patterns, but all show high initial concentrations due to initial wash-off of pollutants from the catchment surface.

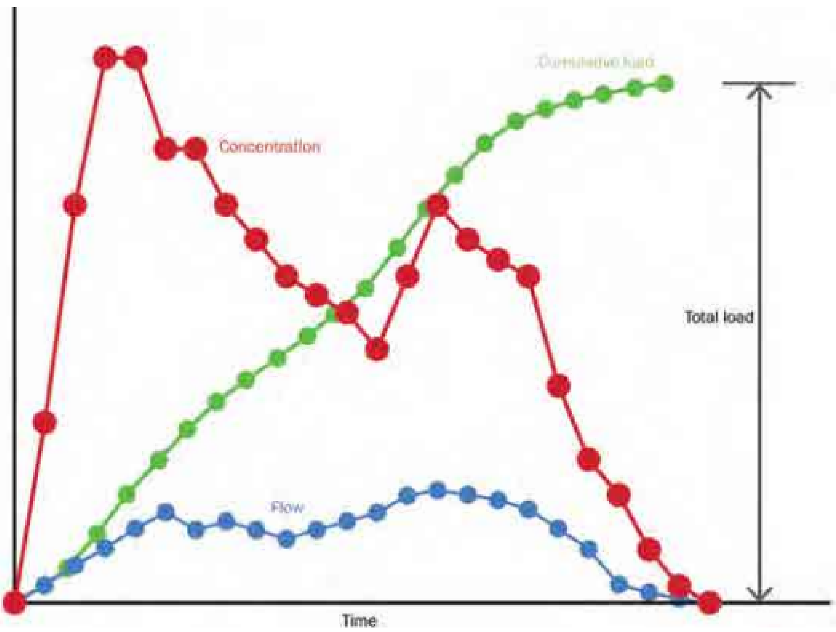


Figure 4.1 Example of flow, pollutant concentration and pollutant load build-up during a rainfall event

Figure 33: Pollutant concentrations and loads urban runoff [5]

I Stormwater quality in the Netherlands

Tabel 6.1 Kwaliteit van afstromend hemelwater afgezet tegen milieukwaliteitsnormen JG-MKN, MAC-MKN en MTR

Parameter	Gemiddeld daken en wegen woonwijken	Gemiddeld daken en wegen bedrijven	JG-MKN***	MAC-MKN***	MTR oppervlakte-water (oud)
Cadmium (Cd)** [µg/L]	0,18	1,4	0,08 – 0,25 ****	0,45 – 1,5 ****	2,0
Koper (Cu) [µg/L]	21	20	2,4	-	3,8
Kwik (Hg)** [µg/L]	0,026	0,26	0,00007	0,07	1,2
Lood (Pb)* [µg/L]	21	68	1,2	14	220
Nikkel (Ni)* [µg/L]	4,1	12	4	34	6,3
Zink (Zn) [µg/L]	144	594	7,8	15,6	40
Antraceen** [µg/L]	0,0076	0,0066	0,1	0,1	
Benzo(a)pyreen** [µg/L]	0,048	0,033	0,00017	0,27	
Minerale olie [µg/L]	102	1813	-	-	
CZV [mg O/L]	36	68	-	-	
P-totaal [mg P/L]	0,30	0,52	-	-	0,15
N-Kjeldahl [mg N/L]	2,1	9,9	-	-	MTR N-totaal 2,2 mg/l
NO_3-N [mg N/L] (Nitraatstikstof)	1,5	0,66	-	-	
TSS [mg/L]	38	48	-	-	
E. coli [#/100 ml]	$2{,}4*10^4$	1135	-	-	$1{,}0*10^3$ *****

* prioritaire stof
** prioritair gevaarlijke stof
*** De JG-MKN en MAC-MKN voor metalen (cadmium, koper, kwik, lood, nikkel, zink) hebben betrekking op de opgeloste concentratie
**** de normwaarde is afhankelijk van de hardheid van het water
***** zwemwaternorm
groen: gemiddelde waarde onder of gelijk aan het JG-MKN;
oranje: gemiddelde waarde boven de JG-MKN, maar onder de MAC-MKN;
rood: gemiddelde waarde boven de MAC-MKN.

Figure 34: Stormwater quality in relation to regulated norms [38]

J Performance of SUDS in reducing urban runoff contamination

TABLE 26.13 Performance of SuDS components in reducing urban runoff contamination

		Concentration ranges: 25%ile – 75%ile				
		TSS (mg/l)	Total cadmium (µg/l)	Total copper (µg/l)	Total zinc (µg/l)	Total nickel (µg/l)
Inflow from urban surface (average values)[1]		20–114	0.2–0.6	6–22	29–112	3–8
Selected environmental standards (Tables 26.1 to 26.5):						
Surface water[5]		25	0.6[6]	6[6]	50[6]	20[6]
Groundwater[5]			0.1	1.5	5	15
Outflows from SuDS components:						
Vegetated/ surface SuDS components[1]	Filter strips	10–35	0.1–0.3	5–12	11–53	2–4
	Bioretention	5–20	0.04–0.1	4–10	5–29	3–8
	Swales	10–43	0.2–0.3	4–15	18–55	2–5
	Detention basins	10–47	0.1–0.4	2–12	6–58	2–4
	Retention ponds	4–28	0.1–0.4	3–7	11–39	2–6
	Wetland basins	4–21	0.1–0.4	2–6	11–33	
	Permeable pavements	14–44	0.3–0.5	4–11	2–29	1–3
Manufactured treatment components[2]	Biological filtration	2–5		N/A[4]	38–221	
	Filtration	7–26		3–10	19–59	
	Hydrodynamic or vortex separators[3]	10–71		6–17	34–107	
	Oil separators	16–87		6–18	60–121	
	Multi-process	2–8		3–16	9–27	

Notes

1 Leisenring *et al* (2014).

2 The above figures for manufactured products are based on a summary of 61 different proprietary systems (Leisenring *et al*, 2012) that passed the stormwater BMP database proprietary device policy. These figures are intended to be indicative of the likely performance of a particular category of proprietary devices. It is recommended that evidence is obtained to support any performance claims of an individual device as outlined in Section 14.5.

3 Referred to as "manufactured device – physical" in WERF (2014).

4 N/A – not available, or fewer than three studies for system.

5 For relevant sources, see Annex 1 Tables 26.8 to 26.12.

6 Standard is for the dissolved metal, at 50–100 mg/l $CaCo_3$ concentration.

Figure 35: Performance of SUDS components in urban runoff contamination [5]

K Intervention strategies

In this section, further information is provided regarding the design of the intervention strategies. Firstly, the implemented SUDS and their areas are provided for de Mare in Table 55. Afterwards, the streets used for the implementation of sustainable road design for each intervention strategy are shown in Table 56. This is followed by the description of the SUDS implemented in Schermereiland en de Omval in Table 57. Lastly, the streets used for sustainable road design in this neighborhood are laid out in Table 58.

Table 55: Implemented SUDS in de Mare

Number #	SUDS type	Area m^2
1	Infiltration crates	10101
2	Green roof	14154
3	Green roof	19542
4	Wadi	3094
5	Wadi	6244
6	Green roof	12508
7	Retention pond	5550
8	Water square	1605
9	Infiltration crates	6410
10	Water square	2089
11	Wadi	5525
12	Wadi	1146
13	Green roof	19783
14	Green roof	8530
15	Green roof	6130
16	Underground reservoir	3915

Table 56: Streets used for SUDS implementation per intervention strategy, de Mare

Streets	Intervention strategy			
	1	*2*	*3*	*4*
Amelandstraat			x	x
Arubastraat				x
Beneluxplein				x
Bonaire straat				x
Duivelandstraat			x	x
Europaweg				x
Europaplein				x
Goereestraat		x	x	x
Hof van Luxemburg				x
Krielenzand				x
Laan van Bath				x
Laan van Troyes		x	x	x
Rottumstraat			x	x
Schiermonnikoogstraat			x	x
Schoklandstraat		x	x	x
Splitstraat		x	x	x
Terschellingstraat			x	x
Urkstraat		x	x	x
Vlielandstraat			x	x
Voornestraat		x	x	x

Table 57: Implemented SUDS in Schermereiland en de Omval

Number	**SUDS type**	**Area m^2**
1	Infiltration crates	11714
2	Green roof	11513
3	Retention pond	5000
4	Green roof	15572
5	Wadi	9263
6	Green roof	3650
7	Green roof	14917
8	Water square	3715
9	Wadi	5071
10	Retention pond	7470
11	Green roof	6609
12	Green roof	1494
13	Wadi	7387
14	Green roof	17361
15	Infiltration crates	12602
16	Wadi	7119

Table 58: Streets used for SUDS implementation per intervention strategy, Schermereiland en de Omval

Streets	**Intervention strategy**			
	1	*2*	*3*	*4*
Alexander Flemingstraat		x	x	x
Boezemsingel		x	x	x
Dijkgraafstraat		x	x	x
Eilandswal		x	x	x
Einsteinstraat				x
Einthovenstraat				x
Heemraadstraat		x	x	x
Heiligland		x	x	x
Ingelandstraat				x
Jaagpad				x
Kamerlingh Onnesstraat		x	x	x
Keesomstraat				x
Kraspolderweg				x
Korte schermerdijk				x
Lorentzstraat				x
Louis Pasteurstraat				x
Madame Curiestraat				x
Marconistraat		x	x	x
Omval			x	x
Oude Trambaan				x
Oudorperdijkje		x	x	x
Prof. van der Waalstraat				x
Scheepjagerstraat				x
Schermeerstraat				x
Schermerpad			x	x
Schermerweg				x
t Hondsbosch				x
t Veentse Eiland				x
Tienenwal		x	x	x
Wagenmakersstraat				x
Waterschapstraat		x	x	x
Westdijk				x

L Results assessment

In this chapter the results of the application of the assessment of the case study using both the conventional framework and extended framework are presented. For all KPI's the results are given. One example is provided for every KPI for which the steps of the assessment methodology as provided in section 4.3 are followed and the full calculation is presented. For each KPI, the other results are obtained following the same steps.

L.1 Investment cost

Based on the design of the intervention strategies, the surface areas on which SUDS are implemented are presented in Appendix K. With these surface areas and the minimum and maximum investment costs per SUDS type shown in Table 8, this range of minimum and maximum costs per SUDS type is calculated. The total minimum and maximum investment cost for each intervention strategy is calculated by obtaining the sum of all individual minimum and maximum costs. Lastly, based on this range of minimum and maximum, the average investment cost per intervention strategy is determined. An example of the calculation conducted for this KPI is presented in Table 59. This Table excludes the minimum and maximum costs laid out in Table 8. This calculation is repeated for each intervention strategy of both neighborhoods.

Table 59: Example calculation average investment cost of intervention strategy B in de Mare

SUDS type	**Area (m^2)**	**Minimum cost**	**Maximum cost**	**Average investment cost**
Green roof	33696	€ 1 684 800	€ 10 108 800	
Wadi	3094	€ 154 700	€ 309 400	
Retention pond	0	€ 0	€ 0	
Water square	0	€ 0	€ 0	
Sustainable road design	8376	€ 167 520	€ 502 560.00	
Infiltration crates	10101	€ 1 515 150	€ 2 525 250	
Total		€ 3 522 170	€ 13 446 010	
Average				€ 8.5 million

L.2 Water storage capacity

This KPI is obtained using the calculation tool provided by Arcadis. This tool, the KA Tool, calculates the water storage capacity based on the storage capacities per square meter presented in Table 10. Additionally, it is assumed most surface types have an initial storage capacity of 0.01 m^3/m^2. Only for open water this storage capacity is higher, for which it is 0.07 m^3/m^2. In this section, an example calculation is provided for intervention strategy B of de Mare. This calculation is repeated for all other intervention strategies in both neighborhoods.

Firstly, the area is divided into surface types, which is shown in Figure 36 for the neighborhood de Mare.

Ruimteverdeling per wijktypologie op basis van BAG en BGT	
Oppervlak t.o.v. totaal oppervlak BGT en BAG	1
Wijktype (voor lookup)	1
Dak - Nieuwbouw	22.01%
Dak - Bestaand	6.17%
Erf	5.31%
Verhard	16.89%
Onverhard	44.69%
Water	4.92%
Totaal oppervlak (m2)	610000.00
	100.00%

Figure 36: Division of de Mare into surface types in the KA Tool for the calculation of the water storage capacity

Secondly, the share of each surface type used for SUDS implementation is calculated and added to the tool. The calculation table in this tool is shown in Figure 37. Based on these percentages and the storage capacities per SUDS type shown in Table 10, the tool calculates the water storage capacity of the intervention strategy in cubic meters. This total storage capacity is divided by the total surface area of the neighborhood and multiplied with 1000 to obtain the water storage capacity of the intervention strategy in mm. For this intervention strategy this calculation is: $(12822.56/610000) * 1000 = 21mm$. This storage capacity excludes the sewer storage.

4				Oppervlak % per maatregel								
Vlak	Opp. % Type 1	Berging/infiltratie oppervlak zonder maatregelen (m3/m2)	Berging oppervlak zonder maatregelen (m3)	Groen dak	Polderdak	Waterdak	Berging(kratten) onder verhard oppervlak (laag; met langzame doorloop naar riolering)	(natuurvriendelijke) Wadi (berging en afwatering) (laag)	Slim ingerichte wegen (laag)	Koel verblijfsplein met vijver	Regenwatervijver	Ruimtegebruik totaal (%)
Dak - Nieuwbouw	22.01%	0.01	1005.91	25.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	25.09%
				5.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Dak - Bestaand	6.17%	0.01	376.57	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
				0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Erf	5.31%	0.01	323.84	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
				0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Verhard	16.89%	0.01	814.66	0.00%	0.00%	0.00%	9.80%	3.00%	8.13%	0.00%	0.00%	20.94%
				0.00%	0.00%	0.00%	1.66%	0.51%	1.37%	0.00%	0.00%	
Onverhard	44.69%	0.01	2726.35	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
				0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Water	4.92%	0.07	2100.00	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
				0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Oppervlak openbare ruimte (m2)			0.00	33696.01	0.00	0.00	10101.00	3094.00	49586.90	0.00	0.00	96477.90
Oppervlak particulier (m2)			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Totaal oppervlak (m2)			0.00	33696.01	0.00	0.00	10101.00	3094.00	49586.90	0.00	0.00	96477.90
Totale berging openbare ruimte (m3)			5641.01	672.78	0.00	0.00	2727.27	1237.60	837.59	0.00	0.00	11116.24
Totale berging particulier (m3)			1706.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1706.32
Totale berging (m3)			7347.33	672.78	0.00	0.00	2727.27	1237.60	837.59	0.00	0.00	12822.56

Figure 37: Calculation of the water storage capacity in m^3 for intervention strategy B in de Mare using the KA Tool

L.3 Maintenance score

To obtain the maintenance score for each intervention strategy equation 1 is applied. In this section, an example calculation of this KPI is provided for intervention strategy B in de Mare. Each SUDS type has their own individual maintenance score, which are laid out in Table 9. Using the data shown in Table 60, the maintenance score for this intervention strategy is calculated. Filling in equation 1 leads to:

$$Maintenance\ score = \frac{3+6+6+7+8}{5*10} = 0.60$$

This is repeated for each intervention strategy in both neighborhoods of the case study.

Table 60: Example calculation for the maintenance score. This example is the calculation conducted for intervention strategy B in de Mare

SUDS Number #	**SUDS type**	**Individual score**		**Maintenance score**
		Appointed	*Out of*	
1	Infiltration crates	3	10	
2	Green roof	6	10	
3	Green roof	6	10	0.60
4	Wadi	7	10	
-	Sustainable road design	8	10	

L.4 Expected Annual Damages

To calculate the EAD for each intervention strategy, the steps laid out in section 4.3.5 are followed. In this section, an example calculation is shown for intervention strategy B in de Mare. These steps are also applied to all other interventions strategies in the case study.

Step 1: Choice of return periods with associated storm events
Increasing the number of storm events modelled improves the representation of the expected damages by the EAD. The choice of return periods and the associated storm events chosen are laid out in section 5.2.2. The storm events that are modelled in Tygron are shown in Table 17.

The subsequent steps are laid for a storm event of 70 mm/hrs, which is a storm with a return period of 100 years of the resilience check. However, these steps are conducted for all return periods chosen for each scenario to be able to obtain the EAD for the intervention strategies.

Step 2: Modelling of rainfall events in both neighborhoods
To model the chosen storm events, the modelling tool Tygron is used. This tool is shown in Figure 38. In this tool, the puddles that occur as a results of a storm event of 70 mm/hrs are shown. For each storm event chosen, a simulation is run in Tygron.

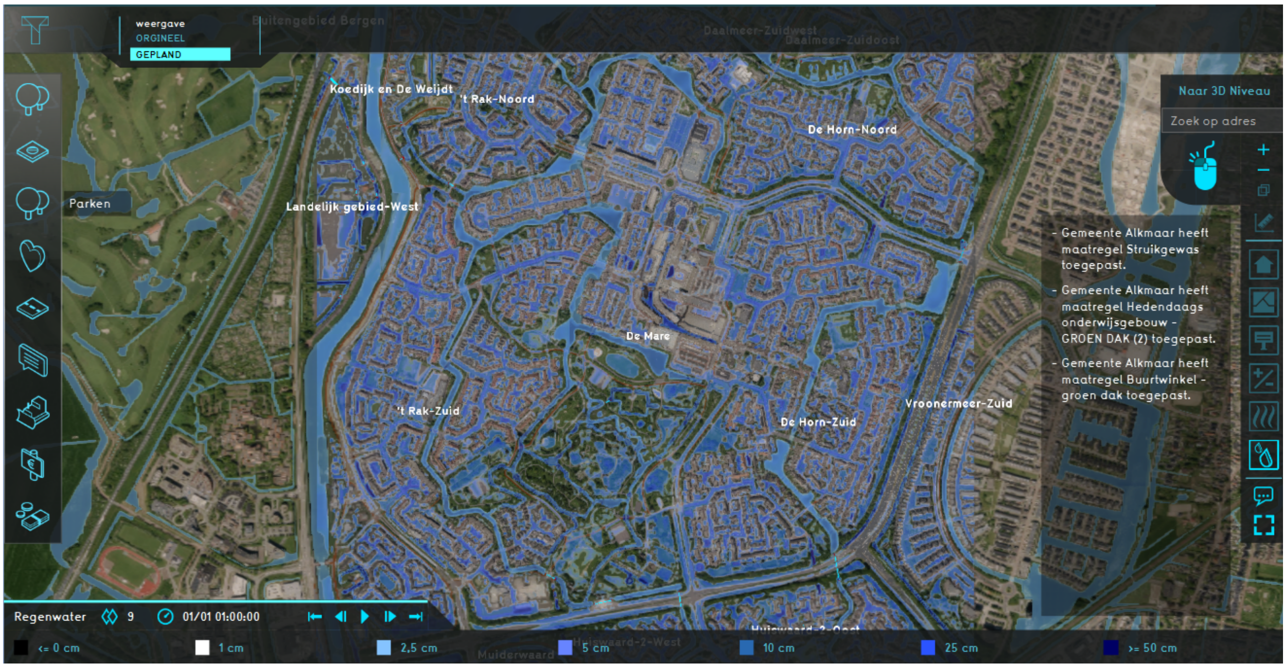


Figure 38: Storm event of 70 mm/hrs modelled in Tygron for intervention strategy B in de Mare

Step 3: Reporting of maximum water level on the streets for each event
Based on the map, shown in Figure 38, obtained in the previous step, the maximum water depths of the puddles are measured in Tygron. Only water depths that exceed the threshold of 20 cm are reported, as only those puddles cause nuisance. The reported water levels that cause damage for a storm event of 70 mm/hrs when intervention strategy B is implemented in de Mare are laid out in Table 61. This is repeated for all other storm events considered.

Step 4: Determination of the resulting damages
With the reported maximum water levels on the streets the damages for each location are calculated. Twenty centimeters are subtracted from the maximum water levels measured, because until that depth no damage is caused to any of the surrounding properties. In de Mare, the locations at which too high water levels occur are all residential. Furthermore, the number of houses per street that are damaged by the storm water are counted in Tygron and reported. Using the water depth in centimeters, the number of houses per location, and the depth-damage curves from engineering practice depicted in Figure 32 in Appendix G, the resulting damage is calculated per location. The damages per location when intervention strategy B is implemented in de Mare resulting from a storm event of 70 mm/hrs are shown in Table 61.

Table 61: Calculation of damages per location where too high water depths occur as a result of a storm event of 70 mm/hrs for intervention strategy B in de Mare

Locations with water level on street >20 cm				**Type**	**Depth (cm)**	**# of houses**	**Damage**
Total locations	*Street*	*Water level (m)*	*Depth causing damage (m)*				
11	Amelandstraat	0.219	0.019	Residential	1.9	1386	€ 68 995
	Duivelandstraat	0.403	0.203	Residential	20.3	497	€ 197 205
	Hof van luxemburg	0.315	0.115	Residential	11.5	10447	€ 2 588 767
	Rottumstraat	0.297	0.097	Residential	9.7	2836	€ 614 107
	Schiermonnikoogstraat	0.246	0.046	Residential	4.6	3727	€ 449 178
	Splitstraat	0.505	0.305	Residential	30.5	5684	€ 2 779 760
	Terschellingstraat	0.31	0.11	Residential	11	2446	€ 585 083
	Urkstraat	1.584	1.384	Residential	138.4	1414	€ 1 087 265
	Vlielandstraat	0.513	0.313	Residential	31.3	2277	€ 1 121 035
	Voornestraat	0.859	0.659	Residential	65.9	2968	€ 1 843 168
	Walcherenstraat	0.236	0.036	Residential	3.6	6240	€ 588 557

Step 5: Calculation of the likelihood
To calculate the likelihood for each storm event equation 3 is applied. For example, the likelihood of the storm event of 70 mm/hrs with a return period of 100 years is: $Likelihood = \frac{1}{100} = 0.01$. This calculation is done for each storm event modelled.

Step 6: Calculation of EAD
The last step is the calculation of the EAD for each intervention strategy. The EAD is obtained using equation 2. Using the likelihood calculated in the previous step and the total resulting damages per modelled storm event, the EAD is determined. Table 62 shows the calculation table for intervention strategy B in de Mare. The EAD for intervention strategy B in de Mare is 0.54 million Euros.

Table 62: Calculation table for EAD in de Mare when intervention strategy B is implemented in the neighborhood

Return period	**Event probability**	**Damage**
2	0.5	€ 0
25	0.04	€ 4 193 197
50	0.02	€ 8 330 209
100	0.01	€ 11 923 120
250	0.004	€ 16 579 731
1000	0.001	€ 23 432 883
	Expected Annual Damages	€ 0.54 million

L.5 Site Pollution Index

To explain how the results of the SPI are obtained, the methodology presented in section 4.3.7 is applied to intervention strategy B in de Mare using the pollutant TSS. The steps explained in this section are repeated for all other pollutants assessed for each intervention strategy modelled in the case study.

Step 1: PI assessment
To apply the PI assessment, the neighborhood is divided into LUSTs. As in intervention strategy B SUDS are implemented, the surface types on which SUDS are applied are split into treated and untreated surface. The areas according to LUST are measured and presented in Table 63. Open water is not included in the categorization of the area. In de Mare there are 3 hectares of open water, leading to the area examined to be 58 hectares.

Step 2: SUDS PMI assessment
Using the available pollution mitigation data, the PMI assessment is conducted. As there are only mitigation indices available regarding the considered SUDS types sustainable road design, green roofs, wadis and retention ponds, this KPI does not take into account underground reservoirs and water squares. The applicable PMIs of TSS per SUDS type, obtained from Table 12, are shown in Table 63.

Step 3: Overall SPI assessment
To obtain the SPI, first the LUPI is calculated using equation 4. Only the PMI's are applied for which the SUDS are implemented on a treated LUST. For example, when using the formula for treated residential roads, only the PMI of sustainable road design is used in the formula as only that specific SUDS affects the pollution in that area. The LUPI is obtained with following calculation: $0.84 * 0.4 * 0.2 = 0.07$. For each of the surface types a LUPI is obtained, which are laid out in Table 63. With the sum of all individual LUPI's, the SPI of TSS for this intervention strategy is determined. This is done by dividing the total LUPI by the neighborhood's area, leading to a SPI of TSS of 0.337.

LUST	Subtype	Area (ha)	PI	PMI sustainable road	PMI green roof	PMI wadi	PMI retention pond	LUPI
Roofs	*Industrial/commercial (untreated)*	4.70	0.3	-	-	-	-	1.41
	Industrial/commercial (treated)	3.37	0.3	N/A	0.85	N/A	N/A	0.86
	Residential	4.33	0.45	-	-	-	-	1.95
Highways	*Motorways*	0.00	0.9	-	-	-	-	0.00
	Major arterial highways	0.00	0.8	-	-	-	-	0.00
	Urban distributor roads	0.65	0.75	-	-	-	-	0.49
	Residential streets (untreated)	2.52	0.4	-	-	-	-	1.01
	Residential streets (treated)	0.84	0.4	0.2	N/A	N/A	N/A	0.07
	Pavements	2.24	0.4	-	-	-	-	0.90
Car parks/hardstanding	*Industrial/commercial*	3.24	0.65	-	-	-	-	2.11
	Driveways (residential)	6.52	0.5	-	-	-	-	3.26
Open areas	*Gardens (all types)*	2.67	0.3	-	-	-	-	0.80
	Parks/golf courses (untreated)	25.44	0.25	-	-	-	-	6.36
	Parks/golf courses (treated)	0.00	0.25	N/A	N/A	N/A	0.6	0.00
	Grassed areas (all types) (untreated)	1.18	0.25	-	-	-	-	0.30
	Grassed areas (all types) (treated)	0.31	0.25	N/A	N/A	0.7	N/A	0.05
	Total area	58						
							Total LUPI	19.55
								SPI 0.337

Table 63: Example calculation table of results SPI TSS intervention strategy B, de Mare

L.6 Pollutant removal capacity

To obtain the PRC, the methodology laid out in section 4.3.8 is applied. In this section the application of the methodology on de Mare to determine the performance of intervention strategy B is presented as an example. The steps elaborated in this section are carried out for each intervention strategy designed in the case study.

Step 1: Determination of pollutant removal capacity per SUDS type
Firstly, the pollutant removal capacities are obtained. In Figure 35 in Appendix J the inflow from urban surface for the 25%ile and 75%ile concentration range for the pollutants TSS, cadmium, copper, nickel, and zinc is laid out. This Figure also includes the outflows from SUDS types when such concentration flow into these types of solutions for this concentration range. Based on this in- and outflow data, the pollutant removal capacity per SUDS type is determined. For example, the pollutant removal capacity of retention ponds for cadmium is: $PRC\ retention\ ponds\ 25\%ile\ = 0.2 - 0.1 = 0.1$ µg/L and $PRC\ retention\ ponds\ 75\%ile\ = 0.6 - 0.4 = 0.2$ µg/L. The pollutant removal capacities per SUDS type can be found in Table 13 in section 4.3.8.

Step 2: Calculation of pollutant load in inflow
The calculation of the inflow loads is based on the design storm of the case study, which is 20 mm/hrs. Based on this design storm, the surface area of de Mare, and the pollutant concentration in Dutch storm water shown in Table 14, the pollutant load for each contaminant in the total inflow is determined for the neighborhood de Mare. For example, the pollutant load in the inflow of storm water in de Mare for the pollutant cadmium is calculated by taking the following steps:

1. Determination of inflow of storm water into the neighborhood:
   (a) 20 mm/hrs = 6 * 10^{-6} $m^3/s/m^2$ = 0.01 $l/s/m^2$ = 56 l/s/ha
   (b) Surface de Mare is 58 ha
   (c) Inflow into area = 56 * 58 = 3.2 * 10^3 l/s
2. Determination of pollutant load in inflow of storm water:
   (a) De Mare is considered to be a residential area. Therefore the average contribution of roofs and roads to the pollutant load is 0.18 µg/L.

(b) Pollutant load in inflow to neighborhood = 0.18 * (3.2 * 10^3) = 0.6 mg

The loads in the inflow per pollutant are shown in Table 64. This is thus the load present in the total inflow of storm water (3.2*10^3 l/s).

Table 64: Pollutant load in inflow in de Mare with a storm event of 20 mm/hrs.

Pollutant	**Pollutant load inflow**	
Cadmium	0.58	mg
Copper	68	mg
Nickel	13	mg
Zinc	0.46	g
TSS	0.12	kg

Step 3: Determination of PRC
Subsequently, the pollutant loads in the total runoff entering the sewer system are determined. Based on the design of intervention strategy B these loads are obtained using the locations and surfaces areas at which SUDS are implemented (Figure 6 with Tables 55 and 56). The amount of pollutant removed by SUDS in this intervention strategy is calculated by multiplying the areas at which they are implemented with the design storm and SUDS removal capacities in Table 13. By subtracting the amount of pollutants removed from the total storm water, the total load per pollutant in the runoff after removal are obtained. For example, the load of cadmium entering the sewer system for the 75%ile is determined with the following calculation:

1. Pollutant presence in treated runoff:

   (a) Firstly, runoff flowing through SUDS is determined. The SUDS types implemented in intervention strategy B for which pollutant removal capacities per SUDS types (step 1) are available are sustainable road design and wadis. Sustainable road design is implemented on 8376 m^2 and wadis on 3094 m^2. For each SUDS type, the runoff treated is calculated by multiplying the design storm (55.6 l/s/ha) with the area on which the SUDS type is constructed. For wadis this calculation holds: $55.6 * (3094/10000) = 17\ l/s$. For sustainable roads the amount of runoff treated is: $55.6 * (8376/10000) = 47\ l/s$

   (b) Per SUDS type the removed load is calculated by multiplying the runoff treated by the SUDS type with the pollutant removal capacities obtained in step 1. Cadmium concentration per liter of runoff is 0.18 µg/L, as de Mare is a residential area. For the 75%ile wadis remove 0.3 µg/L and sustainable roads 0.1 µg/L. In the runoff treated by the wadis (17 l/s), the cadmium load is therefore completely removed. For the runoff treated by the sustainable roads (47 l/s) does still contain cadmium, as per liter 0.08 µg cadmium remains.

2. Determination pollutant concentration per liter of runoff flowing into sewers:

   (a) Firstly, the pollutant loads in the runoff after treatment by SUDS is calculated. Only the runoff flowing through the SUDS are treated. In the remaining runoff of the total inflow of storm water the pollutant load does not change. As an example, the pollutant load for cadmium for the 75%ile after treatment is obtained with the following calculation:
   $(3.2 * 10^3 - 17 - 47) * 0.18 + 17 * 0 + 47 * 0.08 = 0.57\ mg$

   (b) Based on the pollutant loads, the concentration is calculated by dividing the loads with the total runoff. For the 75%ile of cadmium this is: $0.57/((3.2*10^3) = 0.18\ \mu g/L$.

(c) As these steps are also conducted for the 25%ile, the pollutant removal capacities in percentages for this range are determined. For the 75%ile this holds: $\frac{0.58-0.57}{0.58} = -1.34\%$. The average PRC is then obtained by determining the average between the removal percentages of the 25%ile and 75%ile, which results in a PRC of -0.27% for intervention strategy B for cadmium.

In Table 65 the results for this KPI for intervention strategy B in de Mare are depicted. Additionally, the concentration per pollutant per liter of the storm water entering the sewer system is presented.

Noteworthy is to state that the PRC obtained is however independent of choice of storm event. Choosing other storm events to assess this KPI lead to the same results.

Table 65: Pollutant concentrations in storm water that enters the sewer system when intervention strategy B is implemented in de Mare and the average PRC for each contaminant for this intervention strategy.

Pollutant	**Concentration of pollutant in storm water after removal**		**Unit**	**Average PRC of intervention strategy B**
	25%ile removal	*75%ile removal*		
Cadmium	0.18	0.18	µg/L	-0.27%
Copper	21	20.8	µg/L	-0.56%
Nickel	4.07	4.01	µg/L	-1.49%
Zinc	144	143	µg/L	-0.68%
TSS	37.9	37.3	mg/L	-1.17%

L.7 Impervious area

Based on equation 6, this indicator is calculated. The surface is considered to be impervious when it is sealed and does not contribute to the aesthetic appreciation of the area. This led to the surface areas presented in Tables 66 and 67. The results are obtained by dividing these areas with the total area, respectively 61 ha for de Mare and 97 ha for Schermereiland en de Omval.

Table 66: Calculation table of impervious surface for the intervention strategies designed for de Mare

Intervention strategy	**Impervious area (ha)**	**Impervious area (%)**
A	28	47%
B	25	41%
C	23	37%
D	18	30%

Table 67: Calculation table of impervious surface for the intervention strategies designed for Schermereiland en de Omval

Intervention strategy	**Impervious area (ha)**	**Impervious area (%)**
A	65	67%
B	62	64%
C	59	61%
D	55	57%

L.8 Thermal Comfort Score

In this section, an example is provided to explain how the TCS is obtained for all intervention strategies. For intervention strategy B of de Mare the method by which the result is obtained is presented.

Step 1: PET analysis of chosen heat day
Firstly, the PET analysis of July 1st in 2015 is modelled in Tygron for the period 12:00-18:00 local time. In Figure 39 the modelled heat map for this day at 12:00 is shown.

Figure 39: Tygron modelling of PET analysis in de Mare for intervention strategy B

Step 2: Assignment of thermal sensation classes
Based on the heat map shown in Figure 39, thermal sensation classes are assigned to the area. This thermal sensation class is assigned based on the average PET of the modelled time frame. Table 68 depicts the thermal sensation classes per measured PET values from the heat map.

Step 3: Calculation of area ratio
Subsequently, the area ratio is calculated by dividing the area with an average temperature with the total area. The results obtained are shown in Table 68.

Step 4: Expression of physiological stress
Using the heat map modelled in the PET analysis, physiological stress levels are assigned to the temperatures measured in de Mare.

Step 5: Assignment of weighting factors
Based on Table 15, weighting factors are assigned to the measures PET categories found in the PET analysis of de Mare when intervention strategy B is implemented.

Step 6: Determination of TCS
Lastly, the TCS is determined. Firstly, the weighting factors are multiplied with the area ratio leading to the average points. Secondly, the sum of the average points is calculated to obtain the total TCS for the area. For intervention strategy B of de Mare the TCS is 58.33.

Table 68: Calculation table TCS for intervention strategy B for de Mare

Area (m^2)	Temperature (Celsius) *12:00*	*13:00*	*14:00*	*15:00*	*16:00*	*17:00*	*18:00*	***AVERAGE***	Area ratio	Thermal Sensation	Grade of physiological stress	Weighting factor	Average points
1783.35	45.91	46.33	46.53	46.56	46.48	46.3	46.07	46.31	0.38%	Very hot	Extreme heat stress	0	0
1533.37	43	43.32	43.5	43.6	43.67	43.7	43.74	43.50	0.33%	Very hot	Extreme heat stress	0	0
1666.39	43.55	43.83	44.01	44.13	44.25	44.35	44.48	44.09	0.36%	Very hot	Extreme heat stress	0	0
313.98	43.62	43.91	44.09	44.2	44.31	44.38	44.49	44.14	0.07%	Very hot	Extreme heat stress	0	0
1746.55	45.79	46.2	46.4	46.44	46.39	46.24	46.05	46.22	0.38%	Very hot	Extreme heat stress	0	0
308.88	45.67	46.08	46.28	46.33	46.27	46.1	45.9	46.09	0.07%	Very hot	Extreme heat stress	0	0
86305.61	33.15	33.29	33.44	33.65	33.99	34.41	34.94	33.84	18.58%	Warm	Moderate heat stress	0.75	13.93
160779.87	33.91	34.04	34.2	34.41	34.74	35.17	35.7	34.60	34.61%	Warm	Moderate heat stress	0.75	25.95
5627.93	47.82	48.34	48.55	48.53	48.33	47.95	47.48	48.14	1.21%	Super hot	Extreme heat stress	0	0
4762.7	47.46	47.94	48.16	48.15	47.98	47.65	47.24	47.80	1.03%	Super hot	Extreme heat stress	0	0
4308.64	49.22	49.83	50.07	49.99	49.65	49.07	48.35	49.45	0.93%	Super hot	Extreme heat stress	0	0
7097.32	47.11	47.59	47.8	47.8	47.65	47.34	46.97	47.47	1.53%	Super hot	Extreme heat stress	0	0
3062.08	46.99	47.45	47.69	47.68	47.54	47.27	46.93	47.36	0.66%	Super hot	Extreme heat stress	0	0
192.68	47.64	48.15	48.37	48.35	48.15	47.77	47.31	47.96	0.04%	Super hot	Extreme heat stress	0	0
5465.32	34.32	34.45	34.6	34.82	35.15	35.57	36.09	35.00	1.18%	Warm	Moderate heat stress	0.75	0.88
1445.05	48.44	48.99	49.22	49.17	48.9	48.43	47.84	48.71	0.31%	Super hot	Extreme heat stress	0	0
1803.48	46.03	46.53	46.74	46.72	46.51	46.14	45.67	46.33	0.39%	Very hot	Extreme heat stress	0	0
742.4	47.45	47.96	48.17	48.14	47.93	47.54	47.06	47.75	0.16%	Super hot	Extreme heat stress	0	0
1328.46	48.34	48.9	49.12	49.08	48.81	48.34	47.75	48.62	0.29%	Super hot	Extreme heat stress	0	0
4300.46	47.32	47.81	48.02	48.02	47.86	47.55	47.16	47.68	0.93%	Super hot	Extreme heat stress	0	0
1987.1	46.93	47.39	47.6	47.62	47.48	47.21	46.87	47.30	0.43%	Super hot	Extreme heat stress	0	0
1842.81	47.8	48.31	48.53	48.51	48.3	47.91	47.43	48.11	0.40%	Super hot	Extreme heat stress	0	0
667.91	48.35	48.92	49.15	49.1	48.81	48.31	47.7	48.62	0.14%	Super hot	Extreme heat stress	0	0
1134.9	48.83	49.41	49.64	49.58	49.28	48.76	48.12	49.09	0.24%	Super hot	Extreme heat stress	0	0
1250.5	47.76	48.28	48.5	48.47	48.26	47.87	47.39	48.08	0.27%	Super hot	Extreme heat stress	0	0
163143.26	34.69	34.82	34.96	35.17	35.5	35.91	36.43	35.35	35.11%	Hot	Strong heat stress	0.5	17.56
												TCS:	58.33

L.9 Biotope Area Factor

To determine the BAF the methodology explained in section 4.3.13 is applied. In this section, the three steps of the methodology are elaborated for intervention strategy C of de Mare. The methodology is applied to all the intervention strategies designed in the case study.

Step 1: Classification of subject area according to surface types
Firstly, the neighborhood is divided into surface types. In Table 69 the surfaces areas corresponding to the surface types in de Mare for intervention strategy C are shown.

Step 2: Assignment of ecological value factors
Secondly, the ecological value factors, or weighting factors, are assigned to the surface types.

Step 3: Calculation of BAF
Using equation 7, the BAF score is calculated for this intervention strategy. The sum of the surface areas multiplied with their corresponding weighting factors is divided by the total area of de Mare, leading to a BAF of 0.528 for intervention strategy C. The calculation holds:

$$BAF = \frac{(0*168811)+(0.1*57565)+(0.2*2056)+(0.4*41588)+(1*258226)+(0.5*35550)+(0.5*46204)}{610000} = 0.528$$

Table 69: Example calculation table BAF, intervention strategy C de Mare

Surface type	**Weighting factor**	**Surface area (m^2)**	**Area de Mare (m^2)**	**BAF**
Sealed	0	168811	610000	0.528
Partially sealed	0.1	57565		
Semi-open	0.2	2056		
Greened	0.4	41588		
Surfaces with vegetation, unconnected to the soil below, small substrate thickness	0.5	0		
Surfaces with vegetation, unconnected to the soil below, medium substrate thickness	0.6	0		
Surfaces with vegetation, unconnected to the soil below, large substrate thickness	0.7	0		
Surfaces with vegetation, unconnected to the soil below, very large substrate thickness	0.9	0		
Surfaces with vegetation, connected to the soil below	1	258226		
Rainwater infiltration per m2 of roof area	0.2	0		
Water surface	0.5	35550		
Vertical greenery with connection to the ground	0.5	0		
Vertical greenery without connection to the ground	0.7	0		
Extensive roof greening	0.5	46204		
Semi-intensive roof greening	0.7	0		
Intensive roof greening	0.8	0		

M Performance improvement intervention strategies

In Figures 40 and 41 the improved performance for subsequent intervention strategies including more SUDS is shown. The more SUDS implemented, the better the performance on the KPIs assessing the multi-objectivity of SUDS. In Figure 40 the KPIs water storage capacity, EAD and impervious area are scaled to the right orange axis. The other KPIs are scaled to the left blue axis. In Figure 41 only the water storage capacity is scaled to the right orange axis.

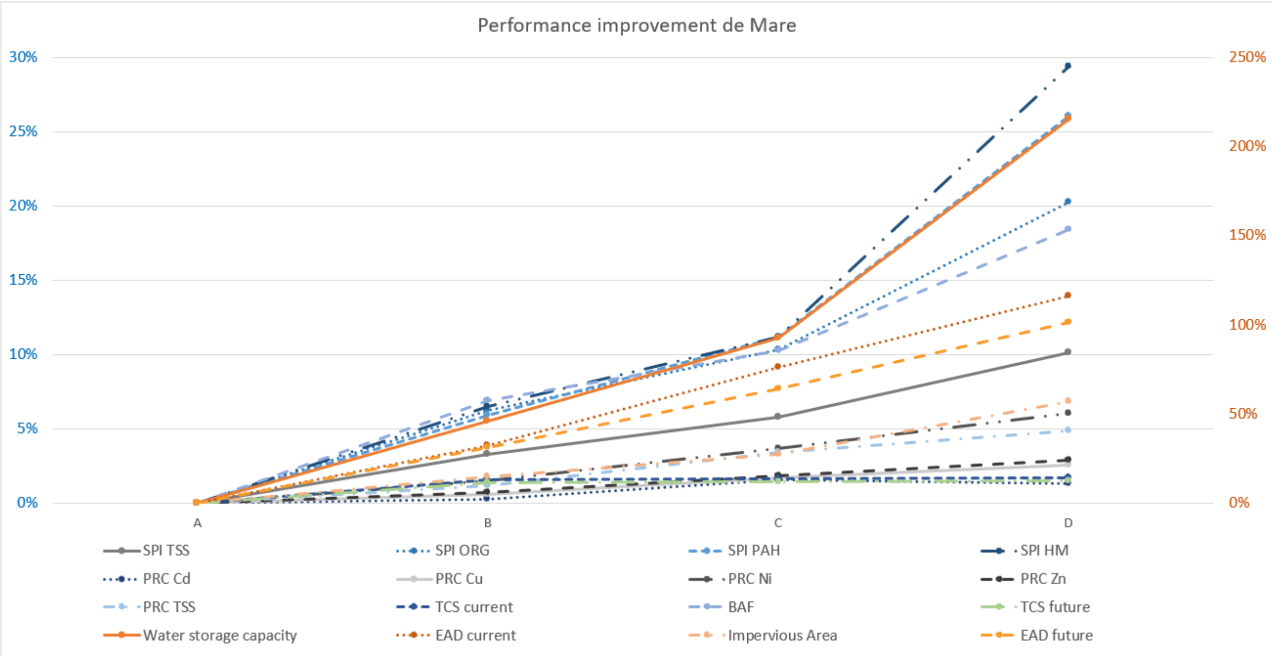


Figure 40: Performance improvement intervention strategies B, C and D compared to intervention strategy A (no SUDS) on the KPIs applied in the neighborhood de Mare.

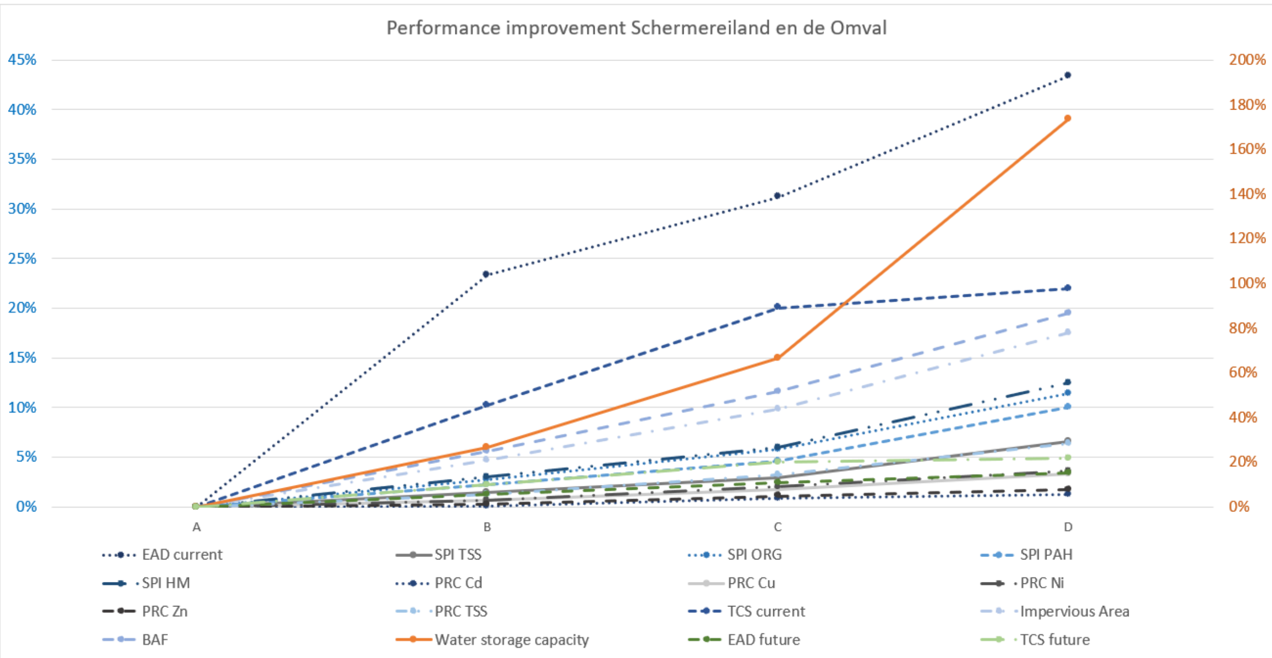


Figure 41: Performance improvement intervention strategies B, C and D compared to intervention strategy A (no SUDS) on the KPIs applied in the neighborhood Schermereiland en de Omval

N Pollutant removal capacities in Dutch urban areas on object scale

Tables 70, 71, 72, 73, and 74 show the calculation tables to determine the removal capacities of cadmium, copper, nickel, zinc, and TSS. This calculation is done on object scale for the SUDS types of which the needed input data was available.

Table 70: Removal capacity of cadmium per liter inflow on object scale

	Inflow concentration				**Outflow concentration**				**Removal capacity**			
SUDS type	**Dutch Residential area (µg/L)**	**Dutch Business area (µg/L)**	**Removal capacity (µg/L)**		**Residential area (µg/L)**		**Business area (µg/L)**		**Residential area (%)**		**Business area (%)**	
			25%ile	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*
Filter strips	0.18	1.4	0.1	0.3	0.08	0	1.3	1.1	-56%	-100%	-7%	-21%
Bioretention	0.18	1.4	0.16	0.5	0.02	0	1.24	0.9	-89%	-100%	-11%	-36%
Swales	0.18	1.4	0	0.3	0.18	0	1.4	1.1	0%	-100%	0%	-21%
Detention basins	0.18	1.4	0.1	0.2	0.08	0	1.3	1.2	-56%	-100%	-7%	-14%
Retention ponds	0.18	1.4	0.1	0.2	0.08	0	1.3	1.2	-56%	-100%	-7%	-14%
Wetland basins	0.18	1.4	0.1	0.2	0.08	0	1.3	1.2	-56%	-100%	-7%	-14%
Permeable pavements	0.18	1.4	-0.1	0.1	0.28	0.08	1.5	1.3	56%	-56%	7%	-7%

Table 71: Removal capacity of copper per liter inflow on object scale

	Inflow concentration				**Outflow concentration**				**Removal capacity**			
SUDS type	**Dutch Residential area (µg/L)**	**Dutch Business area (µg/L)**	**Removal capacity (µg/L)**		**Residential area (µg/L)**		**Business area (µg/L)**		**Residential area (%)**		**Business area (%)**	
			25%ile	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*
Filter strips	21	20	1	10	20	11	19	10	-5%	-48%	-5%	-50%
Bioretention	21	20	2	12	19	9	18	8	-10%	-57%	-10%	-60%
Swales	21	20	2	7	19	14	18	13	-10%	-33%	-10%	-35%
Detention basins	21	20	4	10	17	11	16	10	-19%	-48%	-20%	-50%
Retention ponds	21	20	3	15	18	6	17	5	-14%	-71%	-15%	-75%
Wetland basins	21	20	4	16	17	5	16	4	-19%	-76%	-20%	-80%
Permeable pavements	21	20	2	11	19	10	18	9	-10%	-52%	-10%	-55%

Table 72: Removal capacity of nickel per liter inflow on object scale

	Inflow concentration				**Outflow concentration**				**Removal capacity**			
SUDS type	**Dutch Residential area (µg/L)**	**Dutch Business area (µg/L)**	**Removal capacity (µg/L)**		**Residential area (µg/L)**		**Business area (µg/L)**		**Residential area (%)**		**Business area (%)**	
			25%ile	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*
Filter strips	4.1	12	1	4	3.1	0.1	11	8	-24%	-98%	-8%	-33%
Bioretention	4.1	12	0	0	4.1	4.1	12	12	0%	0%	0%	0%
Swales	4.1	12	1	3	3.1	1.1	11	9	-24%	-73%	-8%	-25%
Detention basins	4.1	12	1	4	3.1	0.1	11	8	-24%	-98%	-8%	-33%
Retention ponds	4.1	12	1	2	3.1	2.1	11	10	-24%	-49%	-8%	-17%
Wetland basins	4.1	12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Permeable pavements	4.1	12	2	5	2.1	0	10	7	-49%	-100%	-17%	-42%

Table 73: Removal capacity of zinc per liter inflow on object scale

	Inflow concentration				**Outflow concentration**				**Removal capacity**			
SUDS type	**Dutch Residential area (µg/L)**	**Dutch Business area (µg/L)**	**Removal capacity (µg/L)**		**Residential area (µg/L)**		**Business area (µg/L)**		**Residential area (%)**		**Business area (%)**	
			25%ile	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*
Filter strips	144	594	18	59	126	85	576	535	-13%	-41%	-3%	-10%
Bioretention	144	594	24	83	120	61	570	511	-17%	-58%	-4%	-14%
Swales	144	594	11	57	133	87	583	537	-8%	-40%	-2%	-10%
Detention basins	144	594	23	54	121	90	571	540	-16%	-38%	-4%	-9%
Retention ponds	144	594	18	73	126	71	576	521	-13%	-51%	-3%	-12%
Wetland basins	144	594	18	79	126	65	576	515	-13%	-55%	-3%	-13%
Permeable pavements	144	594	27	83	117	61	567	511	-19%	-58%	-5%	-14%

Table 74: Removal capacity of TSS per liter inflow on object scale

SUDS type	**Inflow concentration** Dutch Residential area (µg/L)	Dutch Business area (µg/L)	**Removal capacity (µg/L)**		**Outflow concentration** Residential area (µg/L)		Business area (µg/L)		**Removal capacity** Residential area (%)		Business area (%)	
			25%ile	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*	*25%ile*	*75%ile*
Filter strips	38	48	10	79	28	0	38	0	-26%	-100%	-21%	-100%
Bioretention	38	48	15	94	23	0	33	0	-39%	-100%	-31%	-100%
Swales	38	48	10	71	28	0	38	0	-26%	-100%	-21%	-100%
Detention basins	38	48	10	67	28	0	38	0	-26%	-100%	-21%	-100%
Retention ponds	38	48	16	86	22	0	32	0	-42%	-100%	-33%	-100%
Wetland basins	38	48	16	93	22	0	32	0	-42%	-100%	-33%	-100%
Permeable pavements	38	48	6	70	32	0	42	0	-16%	-100%	-13%	-100%