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Designing green and blue infrastructure to support healthy urban living

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Summary

There is a growing awareness in cities throughout the world that green and blue infrastructure can offer a wide range of ecosystem services to support a healthy urban environment. For example, landscape architects explore possibilities in their design of the urban landscape to use the potential of green elements for regulating air temperature, air quality, water storage and drainage, and noise reduction.

However, the potential benefits of green and blue infrastructure are probably only partially utilized because of a lack of both scientific knowledge and practical understanding of what these benefits are, and how green and blue infrastructure can best be implemented. Hence there is a need for a translation of scientific knowledge on the functionality of green and blue infrastructure into design principles and how to integrate these principles into the design of multifunctional green and blue infrastructure.

This report focuses on developing concepts and design principles for blue and green infrastructure that not only support climate resilience but also contribute to a healthy and liveable urban environment. A healthy and liveable urban environment contributes to the strengthening of the socio-economic climate in cities. The objective is to assess and show how the functional use of urban blue and green infrastructure contributes to a liveable and healthy city. The premise is that liveability can be improved with a variety of ecosystems services.

First, the functional use of blue and green infrastructure was assessed on the basis of available literature and experience from the city of Utrecht. Secondly, design principles were formulated for the design of blue and green infrastructure in the urban landscape. The design principles are compiled in a number of infographics that provide information on the effectiveness of green spaces as part of the green infrastructure to deliver ecosystem services.

The design principles focus on a variety of ecosystem services such as temperature regulation, air quality regulation, storm water runoff mitigation, noise reduction and recreation. In this way, relevant ecosystem services are linked to principles that help to optimize the design of green spaces for the selected services. The design principles for green infrastructure are classified into five key aspects of green spaces that influence their effectiveness: volume, shape, location, dispersion and maintenance.

For blue infrastructure we distinguish three categories of health aspects of water and ecosystem services that support human health: 1. direct exposure to water contributing to medical health; 2. encouraging healthy living by creating possibilities to exercise, and 3. aesthetical aspects of water contributing to mental health. Design principles for healthy blue infrastructure have a stepwise approach. Basic quality needed for almost all urban activities is to create clear water with some visible life (vegetation, fish). On top of this, design principles are created to facilitate leisure activities or to enable direct contact like swimming and paddling.

Next, we analysed economic benefits that can be derived from the ecosystem services. This analysis will help to better compare green infrastructure with alternative (grey) infrastructures in cities, in this way supporting the decision making on investing in urban design. This

analysis was limited to green infrastructure. Benefits of blue infrastructure will be analysed at a later stage.

We organized a series of workshops with the municipality of Utrecht, the first of which focused on discussing and improving design principles, and demonstrating and applying a number of tools to support the design process. In a second workshop, we incorporated the design principles into the conceptual design of a city district that visualizes healthy urban living. In a final workshop we identified the state of knowledge on climate adaptation and healthy urban living, which we will incorporate in a strategic research agenda for the city of Utrecht.

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1 Introduction

1.1 Healthy urban living

Worldwide more than half the world's population live in cities and this number is rising rapidly. Increase of population density and the ambition to prevent urban sprawl lead to densification of cities. Many cities are situated in coastal or delta areas where flood risk increases. This is firstly a result of climate change, including rising sea levels, increased river discharge and extreme precipitation. Secondly, this results from land use changes such as the increase of sealed surfaces and buildings and from subsidence. Frequent flooding and the consequent damage are a threat to a healthy and vital urban environment. Furthermore, heat waves become more frequent because of climate change. This may lead to health problems in cities since these areas face higher temperatures than the rural surroundings (urban heat islands). Associated health risks are heat stress and an increase in mortality among the elderly and people with cardiovascular disease.

Well planned and designed green infrastructure, including water and soil, can contribute to climate change adaptation and at the same time promote and support healthy urban living. Effective application requires design principles that address the direct relationship between green infrastructure and impacts of climate change is important (flood risks, flood, heat, water supply and drought), but also the quality of the ecosystem (water, soil and air quality) and its relationship with health (increased mortality and morbidity by unhealthy air and heat stress, spread of pathogens, drug residues and hormones, sanitation, green and blue infrastructure contribution to environmental quality).

Research has shown that the urban environment in which people live, work and play affects their health. Characteristics of a healthy and sustainable environment include:
- a clean and safe environment;
- sufficient green space, nature and water;
- healthy and sustainable homes;
- attractive and varied public spaces;
- wide range of public services (housing, schools, shopping, culture, business, sports, health).

Historically, health has often been the driver for investment in urban infrastructure. Around the turn of the 20th century public health was decisive for urban planning (sewers). This resulted in the greatest possible health improvement for the Dutch urban environment. Air quality has improved greatly as well through the use of cleaner fuels and improved technology. Nevertheless, loss of open space, traffic congestion, noise and poor air quality are still the factors that determine the quality of life in the city. In the case of air quality there is epidemiological evidence that adverse effects on human health still exist. It is therefore important to identify how urban planning and design affect environmental quality.

Improvement of water and/or air quality is a means of improving public health and thus principally to lower costs in the public health sector. With the recent change of legislation in the Netherlands a significant part of public health care responsibilities shifts from the central government to the municipalities. Investments in the physical realm at the municipal level (cost) can lead to health improvements and therefore to lower public health expenses (benefit) at the same municipal level. Health insurers may benefit as well from environmental improvement if we can demonstrate that such an improvement will contribute to reducing healthcare costs.

Green and blue infrastructure
The European Commission has adopted a Green Infrastructure Strategy (COM, 2013) and states that green infrastructure (GI) 'can make a significant contribution to the effective implementation of all policies where some or all of the desired objectives can be achieved in whole or in part through nature-based solutions. There is usually a high return on GI investments and overall reviews of restoration projects typically show cost-benefit ratios in the range of 3 to 75'. Well planned and designed green infrastructure, including water and soil, can contribute to climate change adaptation and at the same time promote and support healthy urban living.

The commission defines GI as the spatial structure of natural and semi-natural areas but also other environmental features which enable citizens to benefit from its multiple services. The underlying principle is that the same area of land can offer multiple benefits if its ecosystems are in a healthy state. GI serves the interests of both people and nature. Green infrastructure includes 'blue' elements such as rivers, streams and ponds. Sometimes this is stressed by the term green-blue infrastructure and this report, the surface water part of green infrastructure is referred to as blue infrastructure. The reason for the latter is that functions of green and blue elements from the green infrastructure have been assessed separately.

Ecosystem services
The term 'ecosystem services' is mentioned throughout this report and refers to the goods and services that are provided by ecosystems and that are beneficial to humans. Ecosystem services are related to natural capital, which consists of all natural resources available to humans.

Figure 1.1 shows a visualization of part of a city that is designed according to principles of healthy urban living.

Typical aspects of a city:
- Crowded / limited space
- A lot of waste produced
- A lot of resources imported

Challenges relevant for Water quality and health:
- Close the circles: what use to be waste can be a new resources
- Create (blue/green) space to play/rest/sport, (multiple use of space); use the city for short distances / daily use, use the boundaries for regional use e.g. for a day out
- Invite to live healthy (attractive tracks to cycle/walk/public transport/skate/row)

Blue infrastructure can contribute to:
- Healthy living: swim, play, row, sail
- Mental health: social interaction, resting, leisure, restaurants, design
- medical health: no toxic compounds, bacteria, pathogens

Figuur: POSAD

Figure 1.1   Visualization of a city district designed according to principles of healthy urban living (POSAD, 2014)

1.2 Aim

The objective of this report is to assess and show how the functional use of urban blue and green infrastructure (BGI), both at the street and city level, can contribute to a liveable and healthy city. Liveability can be improved with a variety of ecosystems services, such as water retention and temperature regulation.

We will first assess the effectiveness of blue and green infrastructure on the basis of available literature and experience from the city of Utrecht. Secondly, we will formulate principles for the design of blue and green infrastructure in the urban landscape.

Next, we will identify and partly quantify the benefits of BGI in order to support the decision making on investing in urban design.

1.3 Project scope

In an assignment for the Dutch Ministry of Economic Affairs, the Dutch research institutes Deltares, TNO, DLO and ECN have combined forces in a research project called Adaptive Circular Cities (ACC) to address major challenges for urban areas:

- Implementing climate change mitigation
- Adaptation to climate changes and sea level rise
- Sustainable use of natural resources and ecosystems
- Finding alternatives for valuable resources
- Transition to circular economies.

The objective of the Adaptive Circular Cities project is to develop innovative combinations of existing solutions with added value, using state of the art expertise, tools and models that the institutes have to offer. Optimal combinations should simultaneously contribute to climate change mitigation, climate change adaptation and resource efficiency.

The project is divided into work packages in which a number of closely related subjects are addressed. The present report is the result of the work package Healthy urban living (safe, sanitary and healthy), focusing on developing options, measures and design principles for blue and green infrastructure that not only support climate resilience but also contribute to a healthy and liveable urban environment. A healthy and liveable urban environment contributes to the strengthening of the socio-economic climate in cities.

1.4 The pilot area of Utrecht

The city of Utrecht is located in the middle of the Netherlands. The municipality has the ambition to achieve a healthy urban environment for its citizens. It is a hub of transport connections, being its central railway station the largest train hub of the country. Compared to other municipalities in the Netherlands, Utrecht has a relatively young and highly educated population. Inhabitants perceive their health and living environment as 'good' and the number of doctors' visits is relatively low (Position paper Utrecht for Agenda Stad; http://agendastad.nl/). The city of Utrecht has 334,295 inhabitants (2015); the population is expected to grow to almost 400,000 in 2030. Accommodation of the growing population needs to take place between fixed city boundaries, which implies densification of the urban structure. This also means that there is a growing number of people that could benefit from ecosystem services provided by green infrastructure and at the same time less space will be available for green areas. Utrecht is currently nr 29, out of 31, in the ranking of green cities in the

Netherlands[1]. This list is based on the amount (m^2) of green space per household in the built up areas. However, the municipality is working very hard to improve the amount of green spaces, as is shown by an increase of 24% in the area of green per household from 2009 to 2014. Five knowledge institutes based in Utrecht (TNO, the National Institute for Public Health and the Environment RIVM, University Utrecht, the Royal Netherlands Meteorological Institute KNMI and Deltares), cooperate to support the development towards a larger and denser but healthy city in the joint Knowledge Center for Healthy Urban Living[2]. Municipality Utrecht is candidate for the European Green Capital Award.

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[1] (http://www.wageningenur.nl/nl/nieuws/Heerlen-Emmen-en-Lelystad-groenste-steden-van-Nederland.htm)

[2] http://www.kchul.nl/

2 Methodology: from impact on urban challenges to design principles for healthy urban living

2.1 Optimizing green infrastructure

Municipalities in Europe are rediscovering the value of green spaces in their urban areas. The main societal functions for which municipalities design green spaces (including surface water elements) are the aesthetic value of green spaces and recreation. There is a growing awareness that green infra can be more beneficial to society than merely serving aesthetics and recreation. For example, the municipality of Utrecht is interested in making better use of green infrastructure in the search of measures that can help to achieve a healthy city. Landscape architects want to take the capacity of green elements for regulating temperature, air quality, water storage and drainage and noise reduction into account. In order to be able to do so, there is a need for translation of scientific knowledge on functionality of green infrastructure into practical design principles. It also requires practical guidelines for how to integrate these principles into the design of multifunctional green infrastructure.

This report describes the results of a first attempt to formulate practical design principles for optimization of green infrastructure.

Relevant ecosystem services were translated into to rules or principles that support the design of green spaces for the selected services. These design principles were then classified into five key aspects of green spaces that influence their effectiveness: volume, shape, location, dispersion and maintenance, see Figure 2.1. We defined two spatial scales, the entire city and street level, to be able to make a distinction in designing green infrastructure at these spatial levels. The formulated design principles were compiled in a visual representation of infographics shown in Figure 2.2 and Figure 2.3. These two infographics thus present the key factors on the effectiveness of green spaces as part of the green infrastructure to deliver ecosystem services.

Chapter 3 can be seen as the substantiation of the infographics, containing an extensive synthesis of available scientific knowledge and detailed background information that has been used for the development of the design principles.

Figure 2.1   Classification of design principles into five key aspects of green spaces that influence effectiveness: volume, shape, location, dispersion and maintenance
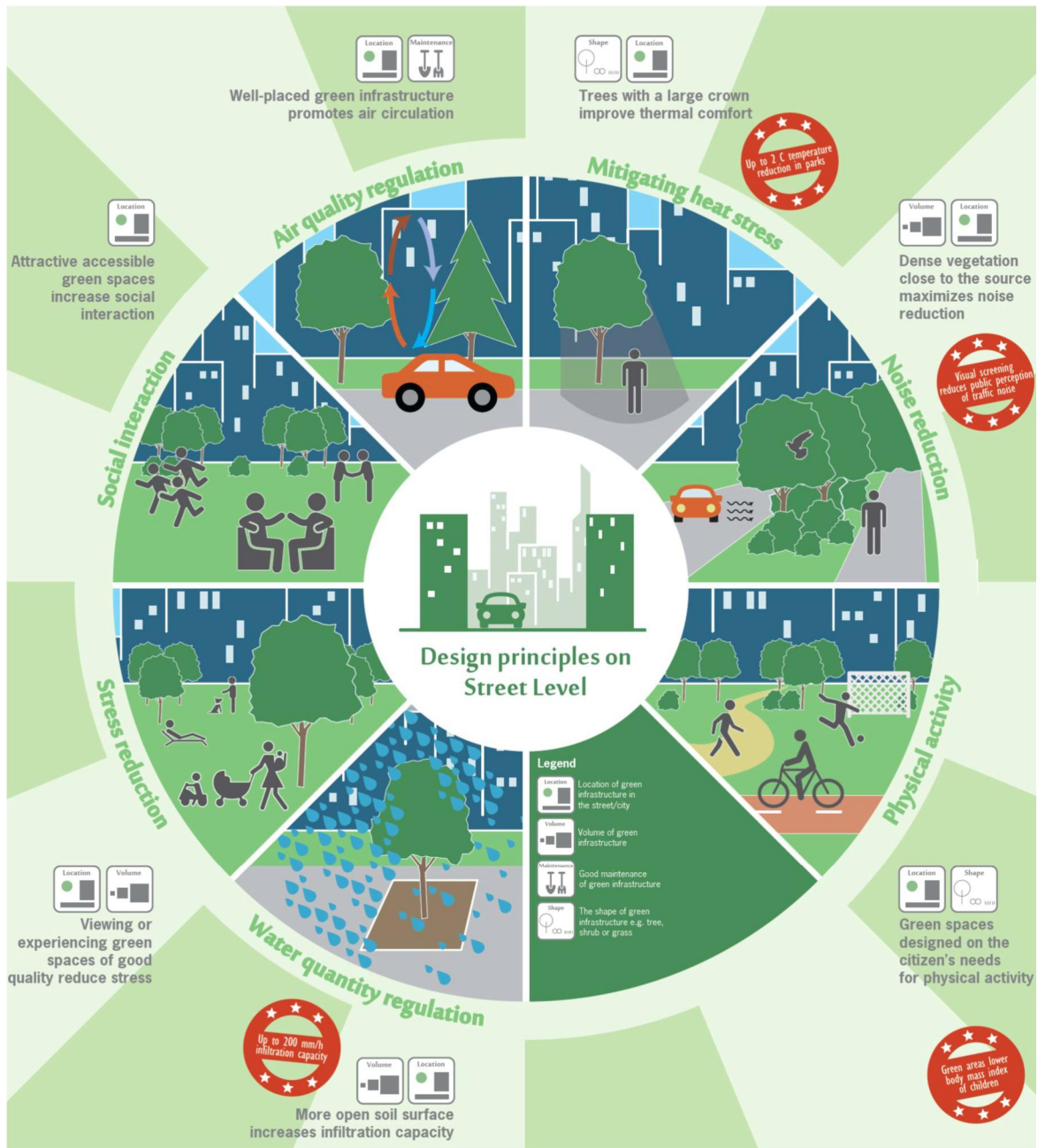
Figure 2.2   Infographics summarizing design principles for green infrastructure at street level
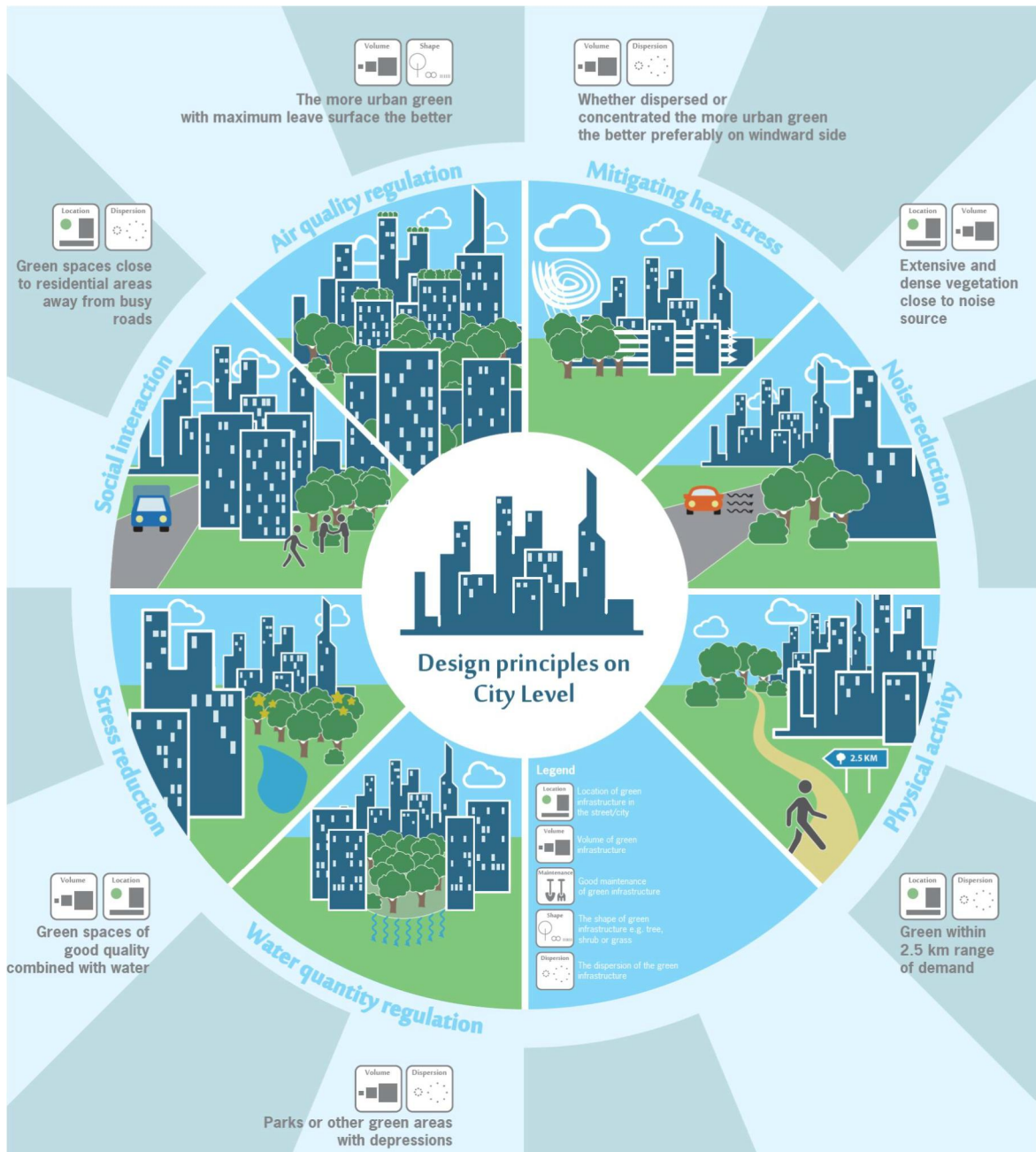
Figure 2.3   Infographics summarizing design principles for green infrastructure at city level

2.2 Optimizing blue infrastructure

2.2.1 What is the impact of blue infrastructure quality on healthy urban living?

A well-functioning blue infrastructure requires a thorough vision in the beginning of the design process, because water is a dynamic substance which flows, evaporates, runs off the soil, and leaches. It requires an integrated approach to create a network that prevents floods and draughts, but also has a good water quality. The water quality provides a lot of ecosystem services as is shown in Figure 2.4.

Figuur:
http://www.dutchwatersector.com/news-events/news/5312-landscape-architecture-west-8-designs-master-plan-with-ecological-water-system-for-guangzhou-china.html

Figure 2.4   Some examples of urban measures and water related ecosystem services that promote human health.

All functions mentioned in Figure 2.4 are closely connected to city design, for example: locations of restaurants and industry, opportunities for swimming (apart from the fact whether the location is formally appointed as a swimming location), what are rational cycling tracks, etc.

2.2.2 Methodology

Our methodology starts with the existing design frame work developed by POSAD[3] and links these to design principles and the urban water system requirements. In this section we describe the conceptual method we apply to link human health to the design principles and to the urban water system.

Human health ("gezondheid" in the Figure 2.5) is influenced by the city ("stad", physical system) and the behavior of the inhabitants ("mens in Utrecht", see Figure 2.5).

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[3] See http://posad.nl/en/projects/gezonde-verstedelijking/
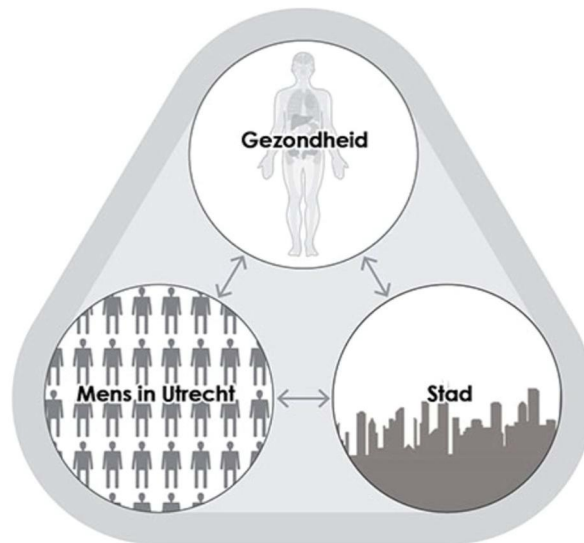
Figure 2.5   Basic concept in which urban human health ("gezondheid") is both influenced by the physical city ("Stad") and human behaviour ("Mens in Utrecht"). (Source: POSAD)

The city (physical system)

The city can provide **basic health conditions**, such as clean air or low noise pollution. The city can also provide **incentives for healthy living**, such as swimming opportunities, green spaces to reside in, places to meet, or places for urban farming. However, the individual's behavior (lifestyle) determines if the incentives are used to improve personal health.
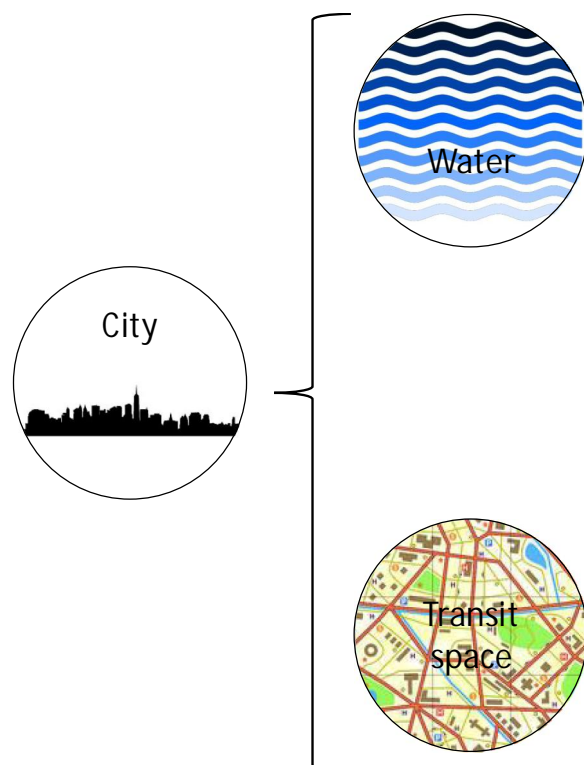
Figure 2.6   The city consists of several layers or types of infrastructure. Here the water layer or blue space, green space and transit layer or public space are shown.

The physical system (city) is composed of all kinds of layers/spaces that together form the physical city. Figure 2.7 shows some examples of these layers like the water infrastructure, green infrastructure and the physical transit infrastructure. We focus on **(public) space**: roads,

bike roads, walk ways, play grounds, etc.; **blue space** like water, canals, ponds, sewer, drainage, etc.; the **green space** such as parks, tree lines, meadows, etc.

Networks and flows

The physical infrastructure connects locations and can be viewed as **networks**. These networks conduct different kinds of flows: flow of people in the physical city; flow of water in the water network; flow of people and other species in the green network.

Figure 2.7   Cities are networks (images POSAD).

Thinking in networks is a necessity for water as it always flows from a source to a sink, but it also provides design opportunities in which you can utilize the urban design to **guide** flows of people, water, or species. When the flow is known, **use it** to improve design to achieve more effect.

A **network** view is the first principle in water management. The city is an interconnecting water system consisting of surface and ground water. There are separated water networks but mostly these are interlinked like sewers to surface water ("riooloverstorten"). A change in water quality disperses through the water system and influences the quality and functionality of urban water elsewhere. Also water **quantity** change disperses through the network and is not a local phenomenon. This has repercussions for the green infrastructure that depends on availability of water.

For working with other flows than water, a useful analogy from river restoration is "let the river (flow) do the work (of designing the landscape)". In urban design we could, when appropriate, reinforce existing societal developments (flows) to achieve the design goal. You do not design the end-result but **design the initial pattern** and let the usage define the end-result. Like linking bike routes into longer routes because of higher mobility by the increasing amount of electric bikes, and allow for space to let (recreational) business activity development along routes.

Design Principles

Design principles (Figure 2.8) are basic building blocks of the city public space. They provide the most basic elements in design that have a meaning in themselves.
- The principles are **additions/changes** to the physical city making use of water, green elements, etc.
- We aim for design principles or basic building blocks to **have a positive effect on human health** (see image).
- They either **influence health directly** (for example air quality regulation) **or through incentives for healthy behavior** (like social interaction, physical activity).
- They need to be of a **certain quality** to work effectively.
- The functionality is **dependent on flow and quality** of the blue/green and human network.

Figure 2.8   An example of the design principles that are a product of this study.

This report provides many design principles linked to the green space that provide human health benefits.

Connecting design principles – using the network

Thinking in networks can lead to a string of connected design principles that together achieve more impact on city human health. Some practical examples to illustrate this point are:

- Connect water from **rooftop farming** or green roofs (clean, nutrient poor) to **streams and ponds in parks**.
- For swimming, use **nutrient lowering reed bed filters** in a flowing urban stream/canal. This **increases biodiversity**, while simultaneously **improving water quality** further downstream for swimming.
- Connect / direct people flows through urban green corridors. Use recreation and social interaction design principles along the route.

Design principles and urban water system requirements

The design principles all have water quality requirements for them to function properly or to function sustainably. These requirements can for example be flow, nutrient status, water clarity, or water quantity needed. Since water is part of a network, these water quality requirements have consequences for the water quality in other parts of the water network/city. Figure 2.9 shows the conceptual link between design principles that alter the city physical structure and the water system and its urban water system requirements.
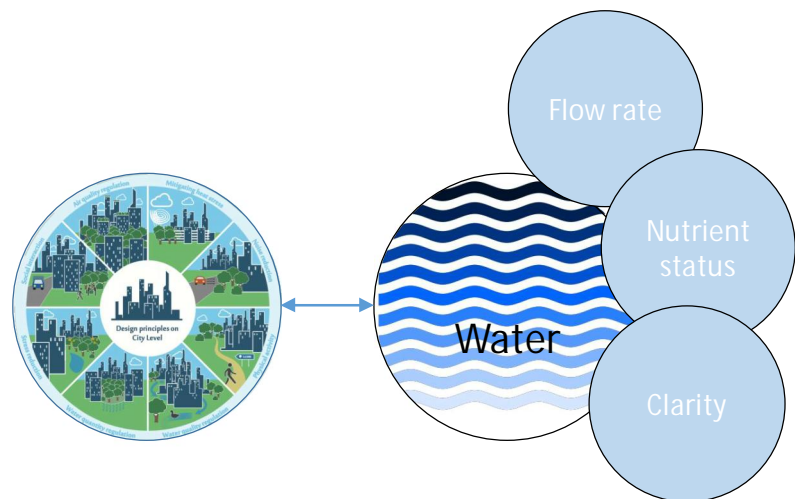
Figure 2.9   The conceptual link between human health ("gezondheid", human behaviour ("mens in Utrecht" and design principles that alter the city physical structure. The design principles depend on the urban water system and have specific urban water system requirements.

For human health we distinguish three categories of water to human health services (as shown in Figure 2.4): 1. Direct exposure to water contributing to **medical health**; 2. **encouraging healthy living** by creating possibilities to move, and 3. Aesthetical aspects of water contributing to **mental health**.

Design principles for healthy blue infrastructure will be elaborated within these three categories. However, to work effectively, the health services have to be connected to water quality aspects the water manager can understand. Figure 2.10 aims to link somewhat abstract **health services** to simple **water quality requirements in use by water managers**. **Error! Reference source not found.** shows (1) mental health, healthy living and medical health as pies; (2: inner circle) the the functions of water that provide mental health, healthy living and medical health; (3: second circle) the simple requirements for urban water that promote health and (4: outside the circle) the linked physical/ecological requirements for urban water as used by water managers. These requirements are translated into design principles in Sections 3.6, 3.8 and 0.
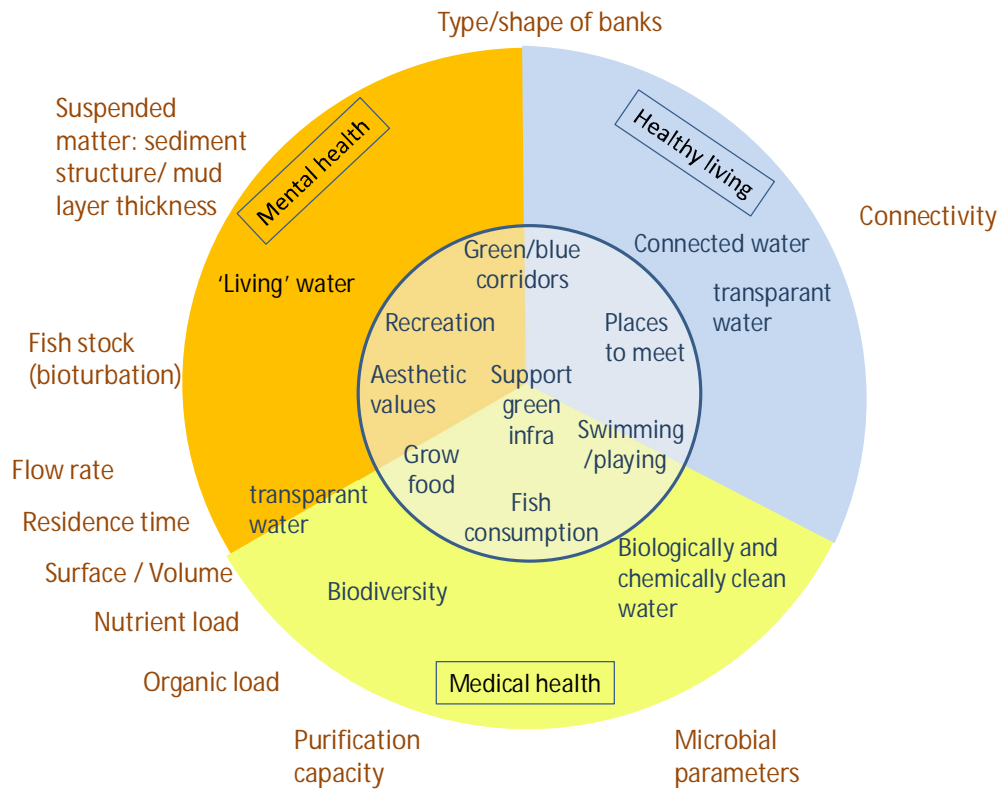
Figure 2.10 Infographic for Blue infrastructure. The 3 essential contributions of blue infrastructure (healthy living, mental and medical health) are shown in pies. The functions are shown in the centre. The requirements to the water system are presented in the outer circle. The relevant parameters as used by water managers for design principles are shown outside the coloured areas.

3 Impact of blue and green infrastructure on healthy urban living and design principles for optimization

3.1 Introduction

This chapter provides a synthesis of available knowledge on mechanisms and effectiveness of blue and green infrastructure for selected ecosystem services based on extensive literature review and professional expertise. Based on this synthesis design principles have been formulated for the purpose of supporting landscape architects and urban planners to optimize the functionality of green infrastructure for the selected ecosystem services.

The identification of ecosystem services follows from experience, interviews and workshops with policy makers and specialists (landscape design, spatial planning, environmental management and health) from the city of Utrecht and other municipalities. Detailed information on the impact of green infrastructure on water regulation, air temperature regulation, air quality regulation, noise reduction and stress reduction is provided in Sections 3.2 through 0. Elaboration of the impact of blue infrastructure on human health services (medical health; healthy living; mental health) is given in Sections 3.6, 3.8 and 0.

3.2 Water regulation

3.2.1 Impact of green infrastructure on water regulation

The function of green infrastructure for water regulation that is described here is reduction of storm water runoff. This reduction is caused by the storage capacity and water loss through evapotranspiration of green infrastructure. Due to this runoff reduction, less water is discharged to for instance:
- surface water, thereby increasing storage capacity for runoff from other areas;
- the sewer system, thereby increasing storage capacity for runoff from other areas;
- the waste water treatment plant, thereby increasing the efficiency and reducing costs for treatment;
- groundwater, which can have both positive and negative effects based on local conditions,

The effectiveness of green infrastructure in water regulation depends on rainfall intensity and frequency, vegetation and soil characteristics.

The main influence of vegetation and soil on the urban water balance is through:
- canopy interception and evaporation;
- infiltration of precipitation and runoff;
- root water uptake and transpiration;

Although the functioning of green roofs largely depends on the above processes, green roofs are treated as a separate topic as these are not in direct contact with the soil.

In the temperate climate of the Netherlands rainfall events are not intense. This can make green infrastructure very suitable for water regulation. To summarize a few statistics on extreme events in the Netherlands (Buishand, 2007):

- a one hour event of more than 5 mm or more occurs only 10 times per year,
- an event of more than 14 mm once per year,
- an event of more than 43 mm occurs once in 100 year.

On a daily basis over half of the precipitation falls on days on which it rains less than 10 mm per day.

3.2.1.1 Canopy interception and evaporation

Canopy interception in urban areas has not been studied extensively. However it has been studied exhaustively for forest canopies. Typical interception capacities of 1-2 mm for deciduous trees and up to 3.8 mm for coniferous trees have been reported (Gerrits, 2010). Before the interception capacity has been reached a fraction of the precipitation is intercepted by leaves, branches and stem. The rest of the precipitation reaches the ground as throughfall. The interception capacity is mainly determined by the density of the canopy which is expressed in a Leaf Area Index which is the ratio of the area of leaves per area of land surface.

The interception capacity has a large influence during small, but frequent rainfall events.
For a 15 minute rainfall event that occurs twice per year (6 mm) we can estimate that 20-30% of the rainfall is intercepted. However for a one hour precipitation event that occurs once in two years only 6-12% would be intercepted. In the Netherlands 20-30% of precipitation that falls on forests is intercepted on a yearly basis.

3.2.1.2 Infiltration

The main contribution of green infrastructure for reducing stormwater runoff and preventing pluvial flooding is through the infiltration of stormwater into open soils underneath vegetation (in contradiction to sealed soils). Distinction must be made between trees within the street scape where the open soil is often much smaller than the canopy and root area and open soil that has a similar footprint as the vegetation in e.g. parks.
In the first situation the infiltration surface and thereby runoff infiltration/discharge capacity is limited. In this case the limited storage capacity can be increased by using permeable pavements around trees.
In the second situation the infiltration can be expected to be highest and is mainly determined by the soil type, compaction and antecedent soil moisture conditions. Often applied tree pit sand consists mainly of loamy sand that has an average infiltration capacity of about 250mm/h and can range between 150 and 500mm/h depending on exact composition and degree of compaction. For clay soils this varies between 25-250 mm for compacted and uncompacted soils respectively. These numbers show that a one hour rainfall event of 64 mm (1/1000 year) does not generate runoff in a loamy sand. Additionally, a paved surface equal to 7 times the open soil surface could be stored during a 1/10 year event (27mm).

3.2.1.3 Root water uptake and transpiration

Transpiration of urban vegetation in Dutch cities has hardly been measured. 170l/day has been reported for Common lime trees in Rotterdam (Jacobs, 2014). However based on forests transpiration can be assumed to be 300-500mm per year. Thereby vegetation is a major consumer of water in the urban water system, thereby lowering the soil moisture content and often the groundwater levels. These effects are highly variable and depend on vegetation density, soil and subsurface conditions and the groundwater situation. In polder systems transpired water does not need to be pumped out of the polder.

Root water uptake and transpiration mainly occur during the growth season when deciduous trees have leaves and potential evapotranspiration is high. Coniferous trees can transpire all year although much less in winter due to low potential evapotranspiration rate.

3.2.1.4   Green roofs

Green roofs are treated separately as they are not in direct contact with the soil. In densely build urban areas (blue-)green roofs can help to temporarily store precipitation, increase evapotranspiration and thereby reduce stormwater runoff. The effectiveness of a green roof depends mainly on:
- growth medium
- drainage layer

To describe the effectiveness of green roofs for water regulation a distinction can be made between the effectiveness on a seasonal or yearly timescale and on the timescale of a single rainfall event.

On a yearly timescale the maximum runoff reduction of a green roof is equal to the actual evapotranspiration of the vegetation. The rainfall that does not evapotranspire runs off to another drainage system. In theory the runoff reduction of a green roof could equal the potential evapotranspiration if all stormwater is available for transpiration by vegetation.

On a timescale of a single rainfall event a green roof contributes to reducing stormwater runoff by temporally storing rainfall and reducing and delaying the peak discharge. Because water is discharged to the drainage system at a smaller rate and during a longer period after the rainfall event it reduces the pressure on the drainage system. As the stormwater is still discharged to the drainage system the annual sum of discharge does not reduce dramatically however flooding can be reduced significantly.

Often a distinction is made between extensive green roofs having a thin layer (<15 cm) of growth medium and intensive green roofs with a thicker layer (>15 cm) of growth medium. For extensive green roofs a growth medium of 3-10 cm is very common.

Extensive green roofs have a relatively small maximum storage capacity. This storage capacity will relatively often be reached and excess water runs off to another water system and is not available for transpiration. The water available to vegetation for transpiration will decrease rapidly in dry periods due to the limited storage capacity. Therefore drought tolerant species like sedum with a limited transpiration rate are often used on green roofs. The storage capacity of intensive green roofs (thicker than 15cm) is larger. These roofs can store and transpire more water during dry periods and less drought tolerant species can be planted.

Research on green roofs in Germany (Mentens, 2006) shows that the annual runoff of intensive and extensive green roofs is on average 25% and 50% of annual rainfall (Figure 3.3). This means that respectively 75% and 50% of the precipitation is stored on green roofs, after which it evaporates. For the Dutch situation STOWA / Rioned (2015) showed that for a 25 year rainfall series of De Bilt the evaporation and thus stormwater runoff reduction increases from about 30% for 3mm substrate storage to 50% at 15 mm and 70% at 130mm substrate storage.

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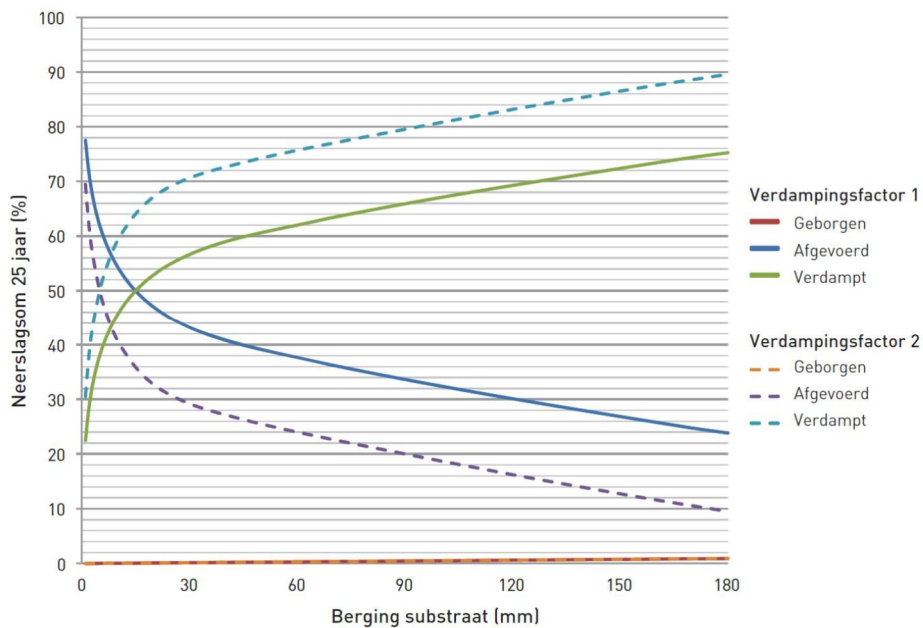
Figure 3.1   Effect of water storage capacity of substrate on evaporation based on Penman for standard evaporation factor (1) and a double evaporation factor (2). Source STOWA / Rioned (2015)
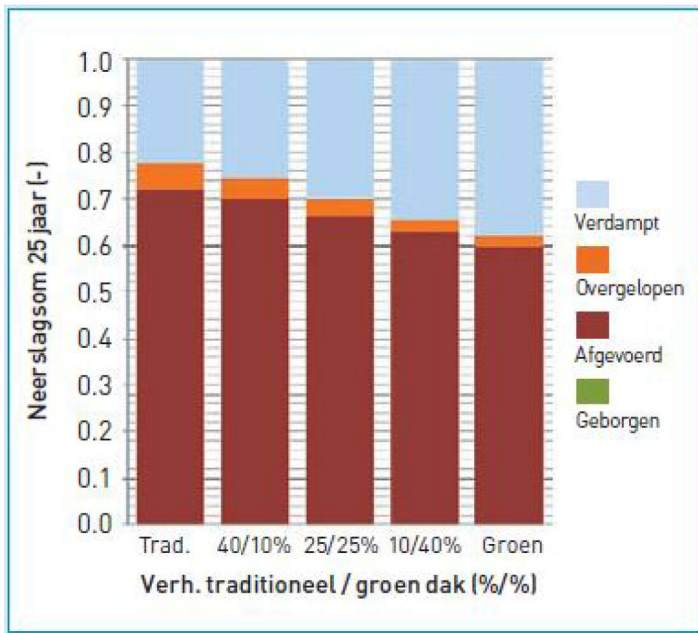
Figure 3.2   Hydrological functioning of district with varying fractions of green roofs. The roof surface area is equal to the road surface area and the green roof substrate has a storage capacity of 20 mm and a drainage storage layer of 50mm with a discharge rate (delay) of 1.8mm / hr. Source STOWA / Rioned (2015).
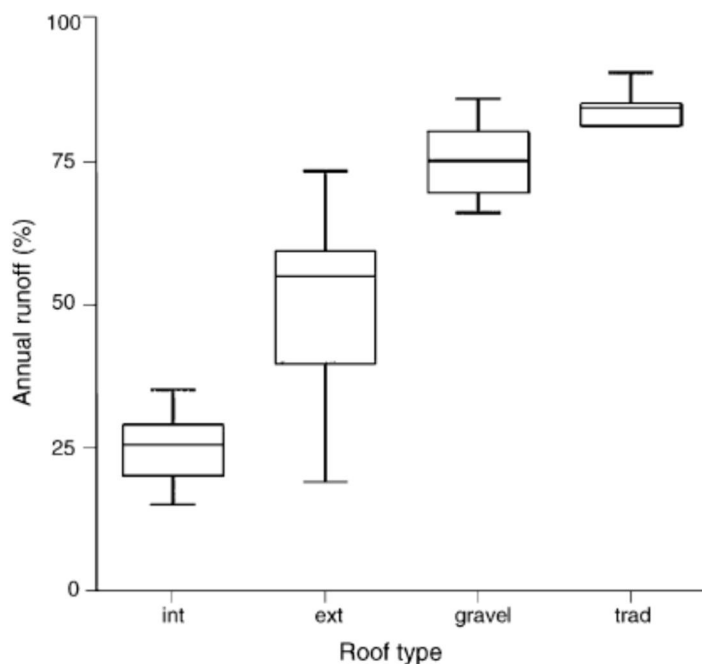
Figure 3.3   Annual runoff for different types of roofs in Germany as a percentage of the precipitation. From left to right: intensive green roofs, extensive green roofs, gravel roofs and traditional roofs. Shown is the median, 25th and 75th percentile and the minimum and maximum value. Source: Mentens, 2006

The study of STOWA / Rioned also shows that the overflow volume of the sewage diminished by 50% by implementation of green roofs in an area where the runoff generation surface consists for 50% of roofs and 50% off roads.

A growth medium is designed to retain sufficient water for dry periods. This water is stored within the medium, and the occupied volume is not available for storage of new rainfall events. A series of rainfall events causes the maximum storage capacity of the roof to be easily exceeded, especially in winter when evapotranspiration is low.
The porosity of the growth medium, and thereby the storage capacity (25-30% of volume) is relatively low. To compensate for this a relatively thick layer is required to store extreme events, causing higher construction costs.

Besides storage, precipitation is the most important factor that determines the retention of extreme precipitation and delay of rainfall runoff. The retention and delay reduce damage and nuisance of the runoff downstream. Extensive green roofs quickly reach the maximum storage space at field capacity after which additional rainfall is drained almost instantaneously. Intensive green roofs with a thicker growth medium can store more water. The water retention on green roofs that were monitored in New York (Carson, 2013) ranged from 80% in the case of rainfall events of less than 10 mm up to about 25% in case of and event of more than 50mm of precipitation (Figure 3.4). These roofs did not have a discharge delay in the drainage layer.
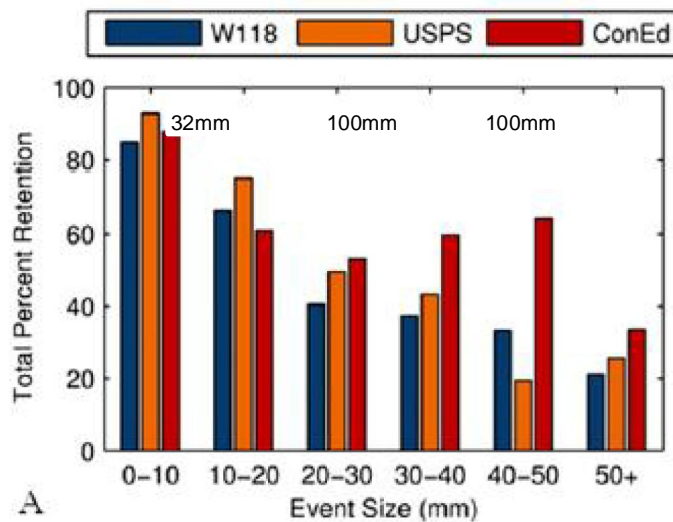
Figure 3.4   Measured discharge reduction as a percentage of precipitation for three green roofs with a thickness of 32, 100 and 100mm in New York. Source: Carson, 2013

3.2.2   Design principles

3.2.2.1   Canopy interception and evaporation

Vegetation interception can be maximized by increasing the surface area of the vegetation and by increasing the density. Coniferous trees have a larger interception capacity and evapotranspiration rate than deciduous trees. But also differences exist between different deciduous tree species. Density of vegetation can be increased by allowing for multiple vertical layers to maximize interception and evapotranspiration, for instance trees over grass.

3.2.2.2   Infiltration

Infiltration can be maximized by increasing the surface area of open soil, by increasing the infiltration capacity of the soil and by temporarily storing water to allow it to infiltrate during a longer period.

Creating more non-paved surfaces increases infiltration capacity and thereby reduces runoff.

Increasing the infiltrating capacity can be achieved by using more coarse grained materials to raise land or replace existing soil and by improving the soil structure of existing soils. Clogging of soils by dispersed solid particles should be prevented. This can be done by only draining runoff from secondary roads and sidewalks or purifying runoff prior to infiltration.

The capacity to infiltrate to runoff can be enlarged by creating depressions in the surface or create subsurface bodies of coarse material to temporarily store water prior to infiltration. This can be done in green zones like parks or wider vegetation strips, but also underneath infrastructure.

In situations with high groundwater levels and consequent low storage capacity extra storage capacity can be created by implementing or intensifying groundwater drainage systems.

3.2.2.3   Root water uptake and transpiration

Also root water uptake and transpiration can be maximized by increasing the surface area of green infrastructure. Selecting species to maximize transpiration and thereby evaporative cooling can be an option. However higher transpiration can also cause soil moisture depletion to occur earlier during meteorological drought and thereby lowering the transpiration rate and

increasing drought stress. In general planting drought tolerant species results in an opposite effect as these tend to transpire less.

3.2.2.4 Green roofs

A green roof can consist of many different layers. The main layers that are relevant for water storage are from top to bottom: the vegetation layer; the growth medium in which the roots of the vegetation are and water is stored; a drainage layer to discharge excess water to prevent saturation and a water sealing layer to prevent the water to get in contact with the building construction.

The vegetation layer of the green roof intercepts part of the precipitation as described in 3.2.1.1 and 3.2.2.1. The interception capacity can be maximized by using plants with a high interception capacity. The interception capacity is generally low for extensive roofs as the density of the vegetation and thereby the leaf area index is generally quite low. Intensive green roofs can bare more vegetation and have a higher leaf area index and can have a higher interception capacity.

The largest storage of stormwater is within the growth medium. In general green roofs with a thicker growth medium can store more water. Extensive green roofs (thinner than 15cm) have a relatively small maximum storage capacity that will relatively often be exceeded after which excess water runs off to another drainage system. The storage capacity is limited and the water available for transpiration low. The storage capacity of intensive green roofs (thicker than 15cm) is larger and therefore these roofs can store and transpire more water and during longer during dry periods. The annual transpiration rates result in lower annual runoff rates.

The growth medium is designed to retain sufficient water for plants to transpire. The volume that is used for water storage is not available for storage of new rainfall events. The porosity of the growth medium is relatively low. To maximize runoff reduction during extreme rainfall events a relatively thick growth medium is needed. This requires a stronger construction of the building which results in higher construction costs.

A drainage layer is used to drain stormwater in case the storage capacity of the roof is exceeded. In general this layer drains at a high rate towards another drainage system. Additional peak flow reduction can be achieved by delaying the discharge from the drainage layer and store the water temporally within the layer. This solution can also limit the volume of required growth medium. The storage capacity that is available within the drainage layer can be controlled by the drainage rate and is easier to predict than the water storage that is available within the growth medium.

3.3 Air Temperature regulation

3.3.1 Urban heat island effect and heat stress

During heat waves, it is warmer in every city in the Netherlands, large or small, than it is in the surrounding area. This so-called 'urban heat island (UHI) effect' is clearly noticeable and can reach a difference of more than 7 ˚C, especially in the evening. The urban heat island effect is caused by the absorption of sunlight by (stony) materials, the lack of evaporation and the emission of heat caused by human activities ('anthropogenic heat'). With global warming continuing throughout the next decades, the number of days, and especially nights, with high temperatures possibly leading to heat stress in the city can increase substantially.

Within an urban area, the UHI varies substantially. The properties of the direct surroundings turn out to be of great influence here. The most influential factors are the proportion of built surfaces, paved surfaces and the proportion of vegetated surfaces. In addition, the average building height has a clear effect. The ratio of building height to street width also influences the absorption of sunlight, thermal emissions from buildings and other surfaces into the atmosphere, and the transportation of heat within the street

Above a certain limit, high temperatures lead to heat stress. This heat stress can lead to a decreased thermal comfort, sleep disruption, behavior changes (greater aggression) and decreased productivity. In general, productivity decreases by 2% per degree of temperature increase with temperatures above 25 °C (Seppanen et al., 2004).

However, heat stress can also lead to serious heat-related illnesses such as skin rashes, cramps, exhaustion, strokes, kidney failure and breathing problems. Heat stress can sometimes even lead to death (Howe and Boden, 2007). During heat waves both hospital admissions (for emergencies) and death rates increase significantly (Kovats and Hajat, 2008). In the Netherlands, death rates increase by 12% during heat waves (approximately 40 deaths more per day) (Huynen et al., 2001). The people who are the most sensitive to heat-related illnesses and death are the elderly over the age of 75 and the chronically ill, especially if they have heart, breathing and kidney diseases (Kovats and Hajat 2008; Hajat et al., 2010).

Factors influencing thermal comfort

Next to *air temperature* (T_{air}), thermal comfort of humans depends on solar radiation, infrared radiation emitted by objects surrounding a person (including the atmosphere, buildings, etc.), humidity and wind speed, as well as on personal characteristics like clothing and activity. The effect of radiation (solar plus infrared) is often quantified by means of the so-called *mean radiant temperature* (T_{mrt}). A commonly used measure to quantify human thermal comfort is the so-called *physiologically equivalent temperature* (PET), which is computed from the total energy exchange between a human body and its environment.

During the day, the thermal comfort in the city is largely determined by the differences in wind velocity; the average differences in humidity and radiation are too small to have a noticeable effect. Locally however, the effect of radiation can be significant (e.g. walking on the sunny side of the street or in the shadow of street trees). After sunset, air temperature plays a more important role in thermal comfort, and factors that influence the air temperature are important in determining the thermal comfort.

3.3.2 Impact of green infrastructure on temperature

Urban vegetation can reduce heat in the built environment by providing shade and evaporative cooling. In addition, green elements have a significant positive influence on the human perception of temperature.

The cooling effect of different types of green elements has been assessed by several studies. In many cases the results are based on model calculations, in some cases observations have been carried out. Studies show, for instance, that within parks, also relatively small ones, air temperature can be up to approximately 3 °C lower than in the surroundings. This 'Park Cool Island' effect has a limited influence on the air temperature in the surrounding built area. For some green elements, the cooling effect in terms of air temperature (T_{air}) is limited (less than 1 °C), but a clear reduction of the mean radiant temperature (up to 25 °C) and PET (up to

15°C) is measured or predicted by models, especially because of the shadow of large tree crowns. Applying green roofs in simulations does not result in a noticeable reduction of the air temperature at pedestrian level.

The mechanisms behind cooling by vegetation and the results from quantification studies are described in more detail below; the information mostly originates from 'Final Report Climate Proof Cities 2010-2014[4]' (Rovers et al., 2014) and directly refers to results obtained in the Dutch climatic and urban context. Occasionally, results from other parts of the world are discussed to put these Dutch results in a proper context.

3.3.3 Mechanisms behind urban temperature regulation

Reduction of solar radiation by providing shadow
Tree crowns provide shade and can thus reduce the effect of solar radiation on thermal comfort. Also, shading of the surface and other objects lowers the temperature of these objects and therefore their emission of infrared radiation. Trees can also indirectly affect thermal comfort by, for instance, casting shadow on buildings, thereby reducing the accumulation of heat indoors. To optimize the effect of shading by trees it is important to carefully consider the situation. For example, playgrounds require different functionalities than shopping centers.

Reduction of air temperature through evapotranspiration
Evapotranspiration transforms radiation energy absorbed by vegetation into evaporation of the water present in or on plants. Thus, it reduces the amount of energy available for heating of the atmosphere, which generally results in somewhat lower air temperatures over evaporating surfaces. A first requirement of the evaporative cooling effect obviously is the availability of water. In extended periods of warm and dry weather the water balance of the city is therefore of crucial importance.

3.3.4 Quantification of the impact on temperature and thermal comfort

In general, measurements in the Netherlands indicate that, when 10% of the paved and built surface is replaced by vegetation, the maximum value of the UHI can be reduced by approximately 0.4-0.6°C (Steeneveld et al., 2011; Heusinkveld et al., 2014; Van Hove et al., 2015). The fraction of green surface area is determined at neighborhood level, in a radius of several hundreds of meters around a measurement point. No distinction is made between between various types of green. Below, separate studies of various types of urban vegetation and their cooling effect are considered, but those results apply at much smaller scales.

Street trees
Observations at street level in Utrecht show a limited cooling effect for street trees in terms of air temperature (T_{air}), but a clear reduction of the mean radiant temperature, T_{mrt} was found., especially because of the shading by large tree crowns. The average T_{mrt} in a street with a 54% surface of tree crowns was 4.5 °C lower than in a street without trees. Ten percent more tree crowns in a street leads to a reduction of T_{mrt} by 1 °C T_{mrt} (radiative temperature) (Klemm et al., 2013a; Klemm et al., 2014b). Effects may depend on the weather conditions.

Measurements during central European summer conditions in Freiburg (Germany) revealed that larger effects may be possible. When comparing sunny with shaded places a reduction of T_{mrt} and PET by over 30°C and over 15°C, respectively, were found (Matzarakis et al., 1999; Lee et al., 2013; see textbox in 2.2.1 for a brief explanation of T_{mrt} and T_{air}). The effect of tree crowns was examined in terms of the percentage of the East – South – West sky blocked by the trees by Lee et al. (2013): in summer conditions between 10 and 16 hour, T_{air} reduced with 0.2°C per 10% of blocking by crowns, T_{mrt} by 3.8 °C and PET by 1.4 °C. Another study in Tel-Aviv analysing 11 sites with trees (ranging in width from 20-60 meters) measured an average cooling effect of 2.8 °C mostly due to shading, with little variation between the sites (Shashua-Bar and Hoffman, 2000).

Returning to the Dutch context, using model simulations for the J.P. van Muijlwijkstraat in the city centre of Arnhem (based on the warm summer day of 16 July 2003) a reduction of the average and maximum temperatures of respectively 0.6 °C and 1.6 °C was obtained for street trees in comparison with the situation without trees in the street (Gromke et al., 2015).

Street gardens
Measurements show a limited influence of street gardens on the local climate conditions in outdoor areas, such as on air temperature or mean radiant temperature, excepting when large trees are present that offer shade. However, green gardens do show a significant positive influence on human temperature perception. Seeing green elements at different heights (low shrubs, hedges, tree crowns) makes heat more bearable for people, and they also appreciate such streets more from an aesthetic point of view (Klemm et al., 2013a, Klemm et al., planned for 2014).

Green facades
CFD simulations show that applying green facades results in relatively low reductions of the air temperature in the street: an average of 0.1 °C and a maximum of 0.3 °C (Gromke et al., 2015). The effect of green facades on the outdoor temperature strongly depends on the type of green facade, but for each façade type the effect is only noticeable very close to the facade. In a study in Singapore, where different green facades were examined, it turned out that the vegetation gave a reduced temperature of around 2 °C at around 30 cm away from the façade (Wong et al., 2010). The facades with a good substrate seem to be the most effective for this.

In order to prevent overheating of buildings indoors, a green facade is certainly not the most effective measure. There is a limited effect for poorly insulated buildings, and the effect is negligible for well-insulated buildings (Van Hooff et al., 2014). Due to their visual impact, green facades or climbing constructions for plants do contribute to a better temperature perception outdoors (Klemm et al., 2013a; Klemm et al., planned 2014).

Green roofs
Applying green roofs in model simulations did not result in a noticeable reduction of the air temperature at pedestrian level in the street (Gromke et al., 2015). In general, the cooling effects were limited to a distance of a few meters from the vegetation. These results are consistent with the differences in temperature measured in earlier studies (e.g. Alexandri and Jones 2008, Errel et al. 2009).

When applying green roofs at city scale (i.e. greening 80-90% of the roofs), however, an analysis of existing simulation studies showed that they may reduce the average ambient temperature between 0.3 and 3 °C (Santamouris, 2014).

Extensive green roofs with growing material with a height of 15 cm or less (sedum roof, grass roof, etc.) should reduce the heat transfer from outdoors to indoors due to (1) more reflection of shortwave radiation; (2) better insulation; (3) facilitation of heat transfer away from the building; (4) evapotranspiration. However, in the simulation study, applying an extensive green roof only had a very limited effect on the number of hours the indoor temperature is uncomfortably high (Van Hooff et al., 2014). The positive effects are countered by the adverse effect of insulation: it traps heat more effectively. The effect of applying a green roof on indoor temperature is greater the lower the insulation rating of the building's shell is.

Parks
The results of measurements carried out in a small park in Rotterdam illustrate that on summer days (days with a maximum temperature of 25 to 30 °C) the average air temperature in a park can be up to 3 °C lower than outside the park (Slingerland, 2012). This makes the air temperature equal to or even lower than the air temperature outside the city. The measurements also indicate that this 'Park Cool Island' effect only has a limited influence on the air temperature in the surrounding built area. Comparable results were found with mobile measurements (Heusinkveld et al., 2010, 2014) and are reasonably consistent with results obtained in other parts of the world (Bowler , 2010).

Results of observations at city level in Utrecht show an average difference in air temperature in a park compared to its direct built surroundings of 1 °C (measured in the afternoon of a hot summer's day). The average PET in parks is on average 2 °C lower than in the city and 5 °C lower than in the countryside. 10% more tree crowns in a park leads to a cooling of 3.2 °C T_{mrt} (radiative temperature). This turns parks into cool islands during daytime in the city (Klemm et al. 2013b, Klemm et al. 2014a). Green spaces in the city are also more popular for outdoor visits on a warm summer's day than areas with water or surface spaces in the city. Green spaces are therefore highly important for outdoor recreation on warm summer's days (Klemm et al., 2014a).

The vegetation on the windward side (the side where the wind comes from) lowers the air temperature in parks during the day and at night (Klemm et al.2014a; Heusinkveld et al. 2014). The same can be applied at city scale: vegetation on the windward side can distribute lower air temperatures over the city. This means that not only large green spaces in the city contribute to a lower air temperature, but that the accumulated effect of all green spaces (consisting of private and public green spaces and elements) also has a positive effect.

3.3.5   Design principles

Summarizing, placing trees along the side of the street improves local human thermal comfort on hot days, in particular via reduction of the mean radiant temperature. In addition, the trees and other plants use a significant part of the incoming shortwave solar radiation for evaporation (Jacobs et al., 2015), depending on the growing conditions (soil, availability of water; e.g., Rahman et al., 2011). Evaporation will help preventing a rise of the air temperature in the city, although the effect will mainly be noticeable at the city to neighbourhood scale.

Street trees are an effective way of improving thermal comfort in existing streets that catch a lot of sun. But street trees are not needed everywhere. Depending on the orientation of the street or the street profile (height-width ratio) buildings themselves can create shade for

pedestrians with comparable effects on T_{mrt} (Lee et al., 2013). In streets with busy traffic too many trees can even have a negative effect. Tree crowns in a dense canopy can create a 'tunnel effect' so that the air cannot circulate and the exhaust fumes linger in the street.

All green elements in streets, such as front gardens, facades and tree pits, have a psychological effect. Pedestrians looking at vegetation experience better thermal comfort and find the heat more bearable.

When examining a street or a square the local context plays a decisive role: where is it convenient to have sun/shade, and where should there be shelter/ventilation? Also, the physical circumstances determine the effect of, for instance vegetation. Various relatively small, local measures can make the street/neighbourhood less vulnerable to heat stress. A number of general guidelines are summarized below:

- Maintain and increase the percentage of green in the city, especially at the windward side during hot conditions (wind direction during hot periods typically differs from the prevailing wind direction during most of the year). To prevent overheating of the urban environment, spreading out green elements is more effective; however, for offering cool spaces, recreation and biodiversity, parks are very important. Variation in green elements (height, species) helps to create various microclimates, thereby not only allowing inhabitants to choose themselves what they prefer, but also offering the best strategy for optimal evaporative cooling without blocking ventilation zones. Despite the fact that more research is needed about the working and application of cool wind corridors, it is worth looking at the possibilities of developing cool spots (>90% vegetation) around the city. Vegetation on the side of the city or a park that is windward during heat waves has the most effect. The prevailing direction of the wind in the Bilt during sustained heat waves is mainly north-easterly (Kleerekoper et al., in review a).

- Add trees with large crowns in streets, parks or squares with a lot of solar radiation. Considering that the shade effect of (large) tree crowns plays an important role, the location of trees, types of tree and maintenance policy (o.a. irrigation) should be taken into account, specifically during the design phase, in order to place trees as effectively as possible. Use deciduous trees in particular: they provide shade in summer, without hampering beneficial effects of sunlight in the winter.

- Take vegetation maintenance into account from the start. The effectiveness of the adaptation measures mentioned depends completely on good construction *and* good maintenance. Therefore, during the design and construction process the maintainability of the adaptation option must already be taken into detailed account. Many of the options will be situated in open spaces and must fit into maintenance schedules for vegetation, roads, drainage, sewers and waterways belonging to municipalities and water boards.

- Apply infiltration to ensure sufficient soil moisture content for vegetation. In many cities with sandy substrates, little water is retained naturally, so that there is a lack of moisture in dry periods and the effect of evaporative cooling through vegetation is limited. By not draining away rainwater straight away but allowing it to infiltrate and stay in the soil, the evaporation from the vegetation can be kept at an appropriate level in dry periods. The infiltration can be improved by applying less impermeable pavement. Measures against

heat stress and flooding (section 2.1.2) can be linked. Sometimes, dense and stony city soil can be replaced by more natural soil, improving water availability for plants.

3.4 Air quality regulation

3.4.1 Mechanisms and quantification of impact of green infrastructure

In principal there are three mechanisms by which air quality is influenced by green infrastructure. These are
1. Increase in deposition of pollutants
2. Altering the wind flow
3. Emitting biogenic volatile compounds and pollen

These three mechanisms influence the air quality on different scales. Mechanisms one and three influence the air quality on city scale, while mechanism two influences the air quality on a local scale. In addition, there are also indirect effects. An example is the effect of shading on ambient temperature and vehicle emissions, which will be briefly introduced in the text.

3.4.1.1 *Increase in deposition of pollutants*
Several model studies investigate the influence of increased deposition of pollutants caused by green on air quality (among others Nowak et al., 2006 and Yang et al., 2008).These studies assume that the dry deposition of a pollutant is a function of the deposition velocity, the height to which the pollutant is well mixed, and the concentration of a pollutant. The deposition velocity of green is in general higher than that of other urban surfaces due to the metabolic uptake by plants, the "stickiness" of the leaf surface, the large surface area of green, and the aerodynamic properties of green (Broadmeadow, M.S.J and Freer-Smith, P.H,1996 cited in Pugh et al. 2012). This increased deposition velocity is also supported by measurements (among others Rondón et al., 1993 and Hesterberg et al., 1996). The higher the deposition velocity, the more deposition, and the lower the concentration of a pollutant in the air will become. The concentration itself also influences the deposition, the higher the concentration the more deposition. Thus some studies suggest to place green infrastructure at locations were the emissions, and thereby also the concentration of pollutants, is high (Nowak et al.,2006). The study of Nowak et al. (2006) found that for ten American cities the estimated air quality improvement due to removal of pollutant by urban trees was 1 % or less. For the city of Portland, with 42% of tree cover, the air quality was 0.003% improved for CO, 0.6% for NO_2, 0.8% for O_3, 1% for PM_{10}, and 0.7% for SO_2. Although the improvement is small other designs than green might worsen the air quality.

It must be noted that part of the removed pollutants can be re-suspended into the atmosphere. This re-suspension is mainly driven by wind. The study of Nowak et al. (2013) assumes that the deposited $PM_{2.5}$ are removed from green infrastructure when rain intensity exceeds a storage capacity, which was calculated as 0.2 x leaf area index. They concluded that trees indeed improved the $PM_{2.5}$ air quality of ten cities in the United States of America, ranging from 0.05% to 0.24%. However, the effect of rainfall on the removal of for example particulate matter has not been investigated thoroughly. Ottelé et al. (2011) found that for leaves of the common ivy, rainfall did not have a significant effect on the number of particles retained on the leaf. These findings might be different for other types of leaves. Assuming that rainfall does have an effect on the removal of particulate matter, in the city of Utrecht there are on average 135 to 140 days with 1 mm of rain or more (KNMI, 2011). Thereby if rainfall removes deposited pollutant, on many days the deposited air pollutant will be washed off by rain and not re-suspended into the atmosphere.

3.4.1.2 Alter the wind flow

In urban areas the dense amount of buildings limits the air exchange between roof-top and street level. This in combination with the high amount of emissions at street levels due to for example traffic causes high amount of pollutants at street levels. At urban street canyons (tall buildings at both side of the street) with wind perpendicular on the street a wake vortex is formed. This vortex causes the concentrations of air pollutants to be higher at the leeward site of the street (Gromke et al., 2008).

To what extent the wind flow in an urban environment is altered due to green, depends on the type of green infrastructure (trees, shrubs, or grass), the lay-out of the urban environment, and the wind direction. The wind tunnel experiment carried out by Gromke et al. (2008) showed that trees limit the amount of ventilation, and thereby increase the concentration level of pollutants in a street. Several computational fluid dynamics (CFD) model studies also show that in an urban street canyon the residence time of air can increase due to trees (Vos et al., 2012, and Amorim et al., 2013). Thus the altering of the wind flow caused by trees might have a negative effect on air pollution in street canyons, especially when the emissions in the canyon is high. Pugh et al. (2012), however, show with a CFD model that green walls in a street canyon have a positive effect on both NO_2 and PM_{10} concentrations.

The deposition and altering of the wind flow are seen as the most important factors of green to alter the air quality. Several modelling studies take into account both factors (Pugh et al., 2012, Vos et al., 2012, and Amorim et al. 2013). However, the conclusions drawn from these studies differ from each another. Pugh et al. (2012) and Amorim et al. (2013) both report a reduction in air pollution in urban canyon due to green. The study of Pugh et al. (2012) even reports reduction values up to 40% for NO_2 and 60% for PM_{10}. While Vos et al. (2013) concludes that urban vegetation leads to an increase of air pollutants, as a result of a decrease in ventilation. They found that only impermeable green screens decreased concentration of pollutants at street level. Nevertheless, these screens had to be 3-4 m tall, which might be undesirable in urban areas. Note that the study of Vos et al. (2013) did not take into account green walls as an alternative to plant green inside a street canyon.

Green roofs can be an alternative to planting green inside the urban canyon. In principal green roofs should influence the flow at the street level of an urban canyon less than green planted inside the canyon. Yang et al. (2008) used a dry deposition model to quantify the effect of green roofs on the air quality in Chicago (United States of America). They found that the annual removal of pollutants for Chicago was 85 kg ha^{-1} yr^{-1}. It should be noted that the efficiency of green to remove pollutants depends on the concentrations of the pollutants; the higher the concentration the more of the pollutants will be removed.

Experimental data on the influence of green on air quality in an urban environment is still lacking. Weijers et al. (2007) did investigate experimentally the influence of a green strip on the air quality (PM and NO_x) near a motorway. They found that immediately behind the green strip the concentrations of $PM_{2.5}$ and PM_{10} were lowered. No such relation was found for NO and NO_2. A similar study was carried out by Erbrink et al. (2009) along a motorway. They found higher concentrations of NO and NO_x close by the road when vegetation was planted. However, the concentrations of NO_2 were lower when vegetation was planted due to the less mixing in of O_3. For fine dust they did not find that the concentration decreased when vegetation was planted.

3.4.1.3 Emit biogenic volatile compounds and pollen

Biological sources also emit biogenic volatile organic compounds (VOCs). The majority of VOCs are produced by plants. A major class of VOCs is terpenes. Emissions are affected by a variety of factors, such as temperature, which determines rates of volatilization and growth, and sunlight, which determines rates of biosynthesis. Emission occurs almost exclusively from the leaves, the stomata in particular. The VOCs can react with nitrogen oxides and carbon monoxide to form ozone, which is a photochemical reaction (i.e., occurs when there is sunlight). Thereby, green might increase the concentration of O_3 in cities, especially in summertime. Nowak et al. (2000) modelled the consequence of green on O_3 concentrations above a city, and found that in urban areas the O_3 concentrations decreased when green infrastructure is added. However, the average O_3 concentration over the overall domain increased. It is advisable to use diverse plant types to ensure that the O_3 does not increase due to planting green infrastructure.

Besides biogenic volatile organic compounds green also emit pollen, which has a negative effect on the health of people with hay fever symptoms. Note that the size of pollen is in general higher than 10 µm, thus it does not contribute to the concentration of PM_{10} in the atmosphere. Cariñanos et al. (2014) introduced a quantitative index to estimate the allergenic potential of urban green. This index is based on allergenic potential, pollination strategies, duration of the pollination period, tree size, and number of individuals per species. It enables policy makers to estimate the allergenic potential of urban green and test different designs (Cariñanos et al., 2014).

3.4.1.4 Lower emissions due to shading

Indirectly, urban green can lower emissions due to lowering the temperature by shading. More details about the influence of green infrastructure on temperature can be found in Section 3.3. For example, the use of air condition in a car leads to an increase of CO_2 emissions and fuel consumptions of cars. Weilenmann et al. (2005) found during tests of different cars a maximum increase of extra CO_2 emissions due to the use of an air conditioning system of 82.7 g/km (26%), for urban driving at 37 ^{o}C with the sun shining. Urban green can help shade cars and thereby decrease the temperature and the use of air conditioning in cars. It is unknown to what extent this indirect lowering of emissions influences the air quality in the urban area.

Steiner et al. (2010) show that the concentration of O_3 increases with 2 to 8 ppb for every increase of air temperature of 1°C. Thus lowering the air temperature by shading can help reduce O_3 concentrations. However, for extreme temperature above 312 K (39°C) the O_3 concentrations actually decreases or diminishes (Steiner et al. 2010). Such extreme air temperatures are rarely observed in the urban climate in the Netherlands, thus in principal lower air temperature should lead to lower concentrations of O_3.

3.4.2 Design principles

The design of green infrastructure in a city should be carefully considered, since when wrongly designed the air quality can worsen due to green. Thus there are a few design principals to consider:
1. Residence time
2. Type of green infrastructure
3. Maintenance

In Figure 3.5 some advisable design principals are shown, for street canyons, green roofs, and horizontal surfaces. For street canyons it is advisable to place trees only sparsely, so that the polluted air at street level is mixed with cleaner air atop. Another solution for street canyons is using green walls. For green roofs it is advisable to use intensive green in multiple layers to ensure mixing of air and removal of dust. For horizontal surfaces it is advisable to use coarse green structure which can potentially remove dust instead of flat smooth surfaces.
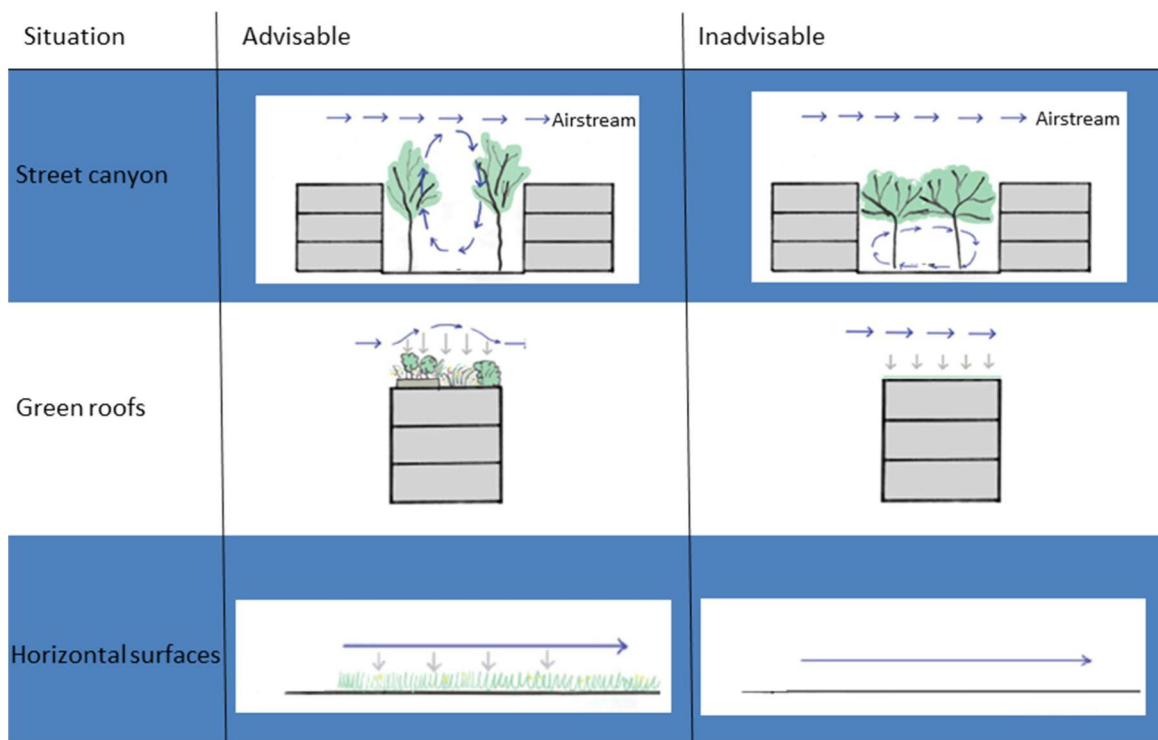
Figure 3.5: Design principles for three different situations. These pictures are adopted from Vries et al. (2011).

3.4.2.1 Residence time

The air quality can worsen locally due to an increase in residence time of air in a city due to alteration of the wind flow caused by green infrastructure. Especially in street canyons with a high amount of emissions green infrastructure needs to be carefully designed. Large trees can easily block the air exchange between in and outside the street canyon, and thereby increase the residence time and the concentrations of air pollutants in the street canyons. Thus in these situations the use of trees with large crowns should be avoided. Green walls and shrubs are better options. Furthermore, green-infrastructure should be placed in line with the street-alignment so that wind can be channeled in the street canyon to achieve maximum ventilation. This advice does not necessarily apply for a street with little traffic and a reasonably good air quality.

Vos et al. (2013) found that in street canyons the concentration at the footpath (1.5 m height) only diminished significantly when green impermeable screen of 3-4 m were placed between the road and footpath. It is questionable if such high impermeable screens are desirable in urban areas. Vos et al. (2013) also adviced to use green infrastructure in street canyons that has a limited impact on the air flow (i.e., low hedges and isolated trees). Note that there is difference between air quality improvements due to green when viewed from a local and a city scale. On a local scale it is advisable to place urban trees away from emissions of pollutants (Vos et al., 2013), while on a city scale it is advisable to place trees close to the

emissions of pollutants as suggested by Nowak et al. (2006). Studies that combine these two effects are still lacking.

3.4.2.2 Type of green infrastructure

When selecting the type of green infrastructure different aspects should be considered. Important is that the species survive the circumstances. In highly polluted areas a pollutant tolerant species should be planted, while if there is a lack of water or space the species should be able to overcome these stresses. There is the potential removal of pollutants, though this does not only depend on the species, but also on the size, growth, form, and health condition of an individual plant (Jim and Chen, 2008). Also the possible negative influence of plant species by the emission of volatile organic compounds should be considered. In order to minimize the emissions of these compounds a variety of species should be used.

In principal conifer trees are best in removing fine dust, because the dust are deposited on the needles and on the branches. Furthermore, these trees in general stay green throughout the winter, making it possible to remove fine dust all year round. For gases, deciduous trees with leaves with large stomatal openings remove most pollutants. However, in winter the uptake of pollutants by plants are minimal. Thus, the type of tree chosen depends on which problem of air quality has to be diminished.

When designing green infrastructure also allergenic potential for people with hay fever can be taken into account. As mentioned in Section 3.4.1.3. Cariñanos et al. (2014) developed a quantitative index which can be used to estimate the allergenic potential of different designs. They state that diversity is a key aspect to minimize allergenic potential. This diversity is taxonomic (genera and species), morphological (size, shape), and biological (pollination strategies, pollination periods).

3.4.2.3 Maintenance

Structural maintenance of green infrastructure is necessary if it is to improve air quality due to potential filter capacity of green. In street canyons it is important that urban green does not hamper ventilation. Thus the size of trees should be minimized and overhanging tree crowns besides one another should be avoided. On the other hand, for other situation where enough ventilation exist trees should be allowed to grow tall and big, since large healthy trees can take up 60 to 70% more air pollutants than small trees (Nowak, 1994).

The overall health of urban green is also important to ensure optimal pollutant removal. Timely pruning, watering on dry days, and pest monitoring and control, could improve plants health and thus their intensities of photosynthesis and respiration (Yang, 1996 cited in Jim and Chen, 2008).

To minimize allergenic potential, maintenance of green infrastructure is also important. For example, frequent adequate mowing of grass hinders flowering, and thus reduce the amount of pollen emitted by grasses (Cariñanos et al., 2014).

3.5 Noise reduction

3.5.1 Impact of green infrastructure on noise reduction

Noise pollution is stated to be one of the four major pollution problems worldwide (Dzhambov and Dimitrova, 2014). In the European Union about 250 million residents suffer from noise exposure higher than 55 decibel of which 80 million are exposed to noise levels higher than 65 decibels, a level that is considered unacceptable (European Commission, 1996). Hindrance from noise has a damaging effect on living comfort, the work environment and liveability of residents. Noise nuisance can seriously increase the risk of major health problems like loss of hearing and cardiovascular diseases (Bolund and Hunhammar, 1999; Ising and Kruppa, 2004). Noise can also significantly affect the quality of living of people, even when no direct psychological and or medical symptoms are caused (Dzhambov and Dimitrova, 2014).

Green infrastructure can reduce traffic noise by serving as a natural sound barrier. Both direct and indirect effects are provided by vegetation. Direct functions imply the attenuation of noise due to adsorption and dispersal and scattering of sound waves. Indirect functions imply the adsorption capacity of open soil and the noise reducing effect of decreasing wind speed (Aertsens et al., 2012). Besides the direct en indirect physical noise reduction mechanisms, vegetation also provides noise reduction services via psychological effects. Just visually screening the noise source by providing a view on a green barrier makes that noise is perceived as less annoying. Also alteration of noise perception by the sound derived from urban green spaces, like bird singing, leaves rustling, water flowing, or bird singing makes that the annoying background noise is masked (Derkzen, 2015; Irvine et al., 2009).

3.5.1.1 *Physical noise reduction*
The precise mechanisms that participate to these noise reduction and to which extent the various factors influence is researched by different studies (Reethof, 1973). Noise reduction by vegetation is influenced by various factors. i) The <u>location</u> of the vegetation belt regarding the noise source, the closer the vegetation is planted to the noise source, the more effect. ii) The <u>frequency of the noise</u> determined by the traffic intensity (Huddart, 1990). Vegetation does not have an effect in the reduction of low noise frequencies (< 500 hertz), delivered by engines. Noise with frequencies between 500 and 2000 hertz will mostly be scattered by the vegetation. Vegetation is most effective in reducing high noise frequencies (>2000 hertz), mostly delivered by the friction between car tires and the road deck (Heutinck and Kopinga, 2009). iii) The vegetation and soil characteristics that affect noise reduction. Other factors that affect the noise reduction efficiency of vegetation are soil type and climatic circumstances, such as wind speed, wind direction, temperature and humidity (Derkzen, 2015; Van Renterghem et al., 2012). In the next paragraphs, some crucial characteristics of green structures are discussed in more detail.

3.5.1.2 *Density and depth of green structures*
A single row of trees or shrubs does not have much of an effect (1-3 dB) in attenuating traffic noise (Samara and Tsitsoni, 2011). When more extensive and dense vegetation structures are applied, combining multiple layers, a reduction of multiple decibels (3-8 dB) can be achieved (Reethof, 1973; Samara and Tsitsoni, 2011).

A study by Aylor (1972), researching the sound adsorption of maize fields with different planting densities found that the most important aspect in noise attenuation is the plant density (including leave and stem density), especially for high frequency noise attenuation. Reethof (1973) suggests, based on field measurements and a literature study, an attenuation

of 8 dB per 30.48 m (100 ft) may be achieved. The study does not signify any species differences. The paper states planting density is of more importance.

A field study by Huddart (1990) showed that a 10-meter strip of dense vegetation close to the road (noise source) could result in an attenuation of 5 dB in comparison with grass and 8 dB in comparison with pavement. The paper states that a similar dense belt of 20 meter results in an attenuation of 6 dB in comparison with grass and 10 dB in comparison with pavement. So, increased depth of vegetation gives only small improvements in noise attenuation. The results of a study by Harris and Cohn (1985) found that a reduction of 2 to 3 dB is possible with narrow belts (9.1m) of vegetation. The manual for measurement and calculation of industry noises (TNO, 2004) provides values that can be used to calculate noise reduction levels of one dense strip of vegetation (see Table 3.1). The manual gives the restriction that calculations can be made for a maximum of 4 vegetation strips. Thus, vegetation can, with the condition that it is applied in the right manner, make that traffic noise is attenuated.

Table 3.1   Noise reduction of one strip of dense vegetation (TNO, 2004)

Noise frequency in Hz	63	125	250	500	1000	2000	4000	8000
Noise reduction of one dense vegetation strip in dB	0	0	1	1	1	1	2	3

3.5.1.3   Vegetation types

Woody vegetation and open soil start absorbing noise frequencies at lower levels than leafy vegetation (Chaparro and Terrasdas, 2009; Samara and Tsitsoni, 2011). Also coniferous trees are less efficient in noise reduction than broadleaved deciduous trees and trees with thin trunks are less efficient than trees with thick trunks (T. Van Renterghem, Botteldooren, and Verheyen, 2012).

A field study by Van Renterghem et al. (2014), researching (light vehicles) noise attenuation effect of hedges in the UK, Germany and France found that relatively thick hedges only provide minor physical noise reduction. In controlled pass-by experiments hedges gave median noise reduction levels of 1.5 to 3.6 dB. In a spectral analysis an improved ground effect was found between 250 and 1000 Hz due to the presence of a hedge. The effect was strengthened by a small piece of grassland right in front of the hedge. Twigs, branches and foliage were found to be responsible for noise reduction above 1000 Hz with increased scattering and adsorption by increased sound frequencies. At high frequencies (higher than 5000 Hz) noise reductions between 2 and 10 dB were measured. The results in the study suggest that hedges offer limited noise reductions of light vehicles (A-weight).

3.5.1.4   Vegetation compared to solid noise barriers

For the use of vegetation instead of conventional 'grey' measures, the paper by Huddart (1990) states that a 10 meter belt close to the road would be a "reasonable compromise" between using green infrastructure as noise barrier and the higher land costs. In comparison, a solid barrier is expected to reduce 8dB directly behind it (Huddart, 1990). Recent Dutch research studied the noise reduction effect of a thick layer of bamboo. The study concluded that a thick layer of bamboo of 5 meters in height and 6 meters in depth had the same noise reduction effect as a massive screen of 3 meters height (Van Leeuwen and Waarts, 2015).

3.5.1.5 Physiological effect on noise perception

Besides the physical aspects of vegetation on noise reduction, literature also describes a psychological effect; visually screening traffic and providing a 'green' view can make that noise is perceived as less annoying (Dzhambov and Dimitrova, 2014) (Heutinck and Kopinga, 2009; Li, Chau, and Tang, 2010). Yuen-mei (2012) has been researching the effect of green barriers on noise perception in Hong Kong and found an improved public perception of traffic noise due to visual screening by vegetation. Green noise barriers were preferred by residents over concrete solutions due to the aesthetic benefits. The paper also states that people (86% of respondents) are willing to pay for green noise barriers. In a case study by the New Zealand Transport agency, visually screened traffic by trees provided subjective noise benefits (NZ transport agency, 2012). Remarkable is that the psychological effect of vegetation on noise perception is not optimal when the noise source is completely screened. A study to the effect of vegetation on traffic noise perception found that best result can be achieved when the noise source is partially visible (Anderson, Mulligan, and Goodman, 1984; Aylor, 1972).

3.5.2 Design principles

When designing green infrastructure for the purpose of noise reduction, some key design considerations have to be taking into account. The U.S. guideline booklet for designing buffers and corridors by the NSDA (2008) provides some key considerations:

- "Locate buffer close to the noise source while providing an appropriate setback for accidents and drifting snow.
- Evergreen species will offer year-around noise control
- Create a dense buffer with trees and shrubs to prevent gaps
- Select plants tolerant of air pollution and de-icing methods
- Natural buffers will be less effective than planted buffers.
- Consider topography and use existing landforms as noise barriers where possible"

A study by Fan et al. (2010) researching the *"noise attenuation by plants and the corresponding noise-reducing spectrum"* concluded with three suggestions for designing vegetative sound barriers:

- Use a combination of plants with noise reducing spectrums similar to the environmental/source noise spectrum in order to achieve the most efficient noise reduction.
- Plant the vegetation in a crossings arrangement to optimize the reduction of low frequency noise. Crossing arrangements were determined to be more effective in the level of noise attenuation over an abreast design.
- Make sure the vegetative sound barrier fulfils the basal requirements of length, width and height. *"An effective noise reduction can be expected within a distance of eight times the tree height"* (Fang and Ling, 2005).

A paper by Heitinck and Kopinga (2009) provides a list of species that are suitable for traffic noise attenuation (see Table 3.2).

Table 3.2   Some applicable species that can be used for noise attenuation (Heutinck and Kopinga, 2009)

Trees with a dense crown	Small trees and evergreen shrubs	Evergreen small shrubs
Acer platanoides	Taxus baccata	Cotoneaster spp.
Ilex aquifolium	Juniperus spp.	Mahonia spp.
Chamaecyparis ssp.	Ligustrum spp.	Symphoricarpos spp.
Cupressocyparis leylandii	Prunus laurocerasus	Rosa rugosa
Thuja ssp.	Pinus Mugo	Caragana arborescens
		Philadelphus spp.
		Potentilla fructucosa

3.6   Mental health

3.6.1   Impact of green infrastructure on mental health

A study by Hartig et al. (2014) gives an extended research overview about the relation between health and nature. It describes an array of benefits resulting from contact with nature, and shows that evidence regarding some benefits is strong, but direct cause and effect evidence is limited. Research has clearly established that contact with nature in or outside cities reduces levels of stress. KPMG shows that the benefits of nature do not only significantly reduce healthcare costs, but also avoid labour cost due to reduced sickness leave (absence) and increased productivity. They indicate that the benefits of more green infrastructure can reach up to 400 million euros for a population of 10 million people (KPMG, 2012). However, in their study they assume direct cause-results mechanism for which there is no scientific proof yet. De Vries (2010) concluded that some findings indicate that applying beliefs about those benefits should be done with care, and shows that substantial gaps in knowledge remain, especially about the long-term effects of a "daily dose" of exposure to green elements on stress-related health complaints.

3.6.1.1   Mechanisms

Research considers health in many ways, such as beneficial change in emotional and physiological markers of stress measured during visits to natural areas (Barton and Pretty, 2010, Hartig et al., 2003). De Vries (2010) stated that especially people exposed to stress are likely to benefit most from nearby nature in their residential environment. The two main mechanisms that could be responsible for stress reduction are:
- Visual contact with green infrastructure
- Access to green infrastructure

Visual aspects of experiencing green and nature
Based on findings of (mostly experimental) research, seeing green elements already has a positive relation with stress reduction. This effect occurs even with images of parks and green landscapes (Van den Berg, Winsum-Westra, 2006). De Vries (2010) argued that one potentially beneficial option would be to maximise people's visual contact with green elements. A study of Honold et al. (2015) finds that participants whose homes had views of high amounts of diverse kinds of vegetation had significantly lower cortisol levels (a hormone to measure stress). Taylor et al. (2015) showed in their study a decrease of 1.18 antidepressant prescriptions per thousand people per unit increase in trees per km of street.

Results from Kardan et al. (2015) suggest that people who live in neighbourhoods with a higher density of trees on their streets report significantly higher health perception and significantly less cardio-metabolic conditions.

The theory of stress reduction also indicates that aquatic environments can have a particular restorative potential. White et al. (2010) used a set of 120 photographs of natural and built scenes, half of which contained "aquatic" elements. Both natural and built scenes containing water were associated with higher perceived restorativeness than those without water. However, Triguero-Mas et al. (2015) did not find consistent results on blue spaces.

Access to green spaces
Some studies connected access to nature to health impact. Dense urban settings, without accessible green space, may reduce opportunities for stress-reducing nature contact as well as increased exposure to environmental stressors (Hartig et al., 2011). Beliefs about stress-reducing effects of park visits are widespread and long-standing (Olmsted, 1970). In a Dutch study, the relationships between stressful life events in the previous three months, both health complaints and perceived general health were weaker among those people with more green space within 3 km of the home (Van den Berg et al., 2010).

In most cities, people visiting a natural environment for health-restoring purposes must engage in some form of physical activity to do so. Accordingly, results of experiments show that "green exercise" is more psychologically beneficial than the same exercise in settings with relatively little nature (Mitchell, 2013, Pretty et al., 2005, Bratman et al., 2015). Thus, being active in natural settings may yield health benefits over and above the benefits of physical activity in other environments. De Vries et al. (2014) argued that there is a significant relation between the amount of walking as a form of physical activity and the amount of green infrastructure. Citizens walk 20% more if the green infrastructure is sufficient.

Hartig et al. (2014) argued that community gardening supports restoration from stress associated with work or other demands. The Japanese practice of Shinrin-yoku, or forest-bathing, involves beliefs about the salutary values of certain substances in the air, and it entails behaviors that ordinarily promote stress reduction (e.g., distancing oneself from everyday demands, adopting a meditative stance) (Tsunetsugu et al., 2010). Participants who regularly used a vegetated trail along a canal had significantly lower cortisol levels and reported significantly higher life satisfaction than less frequent users (Honold et al., 2015).

Some studies (Brown et al., 2013, de Bloom et al., 2014) also indicate the improved mental health during lunchtime walking in the nature.

Overall, the reviews generally agreed that beneficial effects from contact with nature do occur, but that the evidence is not yet sound enough to state when, where, and for whom given effects will occur or how large or long-lasting they will be.

3.6.1.2 Design principles
De Vries (2010) distinguished two design principles for stress reduction: maximising visual contact with green elements and offering high-quality, immersive restorative experiences in green space.

Stress reduction through visual contact with green could be established by planting trees and shrubs along frequently used routes to work, school or shops. Building facades overgrown with creepers and climbers would be a very efficient way to maximise visual contact with

green on a street level (de Vries, 2010). More commonly, green spaces between residences and heavily trafficked roads can reduce occupant noise annoyance (Nilsson, Berglund, 2006), vegetation can conceal displeasing structures (Smardon, 1988), and landscaping around housing can help residents maintain privacy and avoid feelings of crowding (Day, 2000). Honold et al. (2015) argued that vegetated routes or paths play an important role in the restorative activities and daily commutes of participants. They recommend more consideration of greenways in urban development. Taylor et al (2015) suggest that street trees may be a positive urban asset to decrease the risk of negative mental health outcomes. Kardan et al. (2015) found in their research that having 10 or 11 more trees in a city block on average, improves health perception.

The qualities needed for an environment to be restorative depends partly on the motives people have to visit green infrastructure. Gerritsen and Goossen (2003) distinguished five motives people have to visit green spaces: amusement, have a break, interest, nature dedication and physical challenges. Each motive is related to a design principle. Research in the Netherlands (Goossen et al., 2009) shows that people with the motive 'amusement' are mostly visiting with friends and relatives and prefer a green environment that is more familiar and well maintained. They prefer green spaces where they can meet and play. Flowering plants and fragrant shrubs are in favour. They dislike environments which attract mosquitoes (Goossen and Hommel, 2003). People with 'having a break' as motive prefer a green space that suggests the opposite of a built environment, which implies that vegetation conceals displeasing structures and prevents feelings of crowding. People with 'interest' as motive prefer a green infrastructure with a "story such as restored old sightlines or re-use of not used spaces such as the Highline in New York. People with 'nature dedication' as motive prefer more wilderness and they dislike well maintained green infrastructure. People with 'physical challenge' as motive prefer a green infrastructure which stimulates them to exercise, like tree climbing or a rough mountain bike parcours.

De Vries (2010) argued that the design of green spaces seems to be a major factor, as some green spaces invite exercise while others invite more passive forms of recreation.

3.6.2 Impact of blue infrastructure on mental health

Urban waters enable a number of leisure activities like boating, fishing, ice-skating but is also considered as a pleasant environment to look at (from a house, terrace or park), and to walk, cycle, skate along. This all contributes to a pleasant area to live, which reduces stress. This is very much comparable to the effects attributed to greens infrastructure.

With respect to look at green and blue infrastructure, White et al. (2010) used a set of 120 photographs of natural and built scenes, half of which contained "aquatic" elements. Both natural and built scenes containing water were associated with higher perceived restorativeness than those without water. Not all authors found beneficial effects of watching blue spaces (Triguero-Mas et al., 2015). More studies support the beneficial effects if people have access to nature (blue and green).

The value of blue infrastructure is only valid if the water quality is good enough for the function the water has. Except for eutrophic fish ponds (described in 3.6.2.4), containing a lot of carp and bream, all functions of urban water benefit from clear water. Clear water may thus be considered as a basic requirement for urban waters. Also stench (mostly because of

rotting of organic materials) should be prevented. There are a number of key factors determining the transparency and smell of water.

3.6.2.1 Mechanisms and quantification

Clear and freshwater
The penetration of light into surface waters is determined by water itself and by dissolved and particulate compounds in the water. The most important substances are shown in Table 3.3.

Table 3.3   The substances that reduce light penetration

Dissolved	Particulate
Water (background extinction)	Mineral suspended solids (inorganic suspended solids including clay < 2 μm)
Humic acids (dissolved organic carbon; DOC)	Living algae
	Detritus (dead organic suspended solids)

The extinction can be calculated if the concentrations of these particles are measured by using the UITZICHT-model[5]. The background concentration is stable. Dissolved organic matter is generally considered as a natural phenomenon, e.g. water in peat areas has a yellow brownish colour, and never manipulated by water managers, though the composition of the water (hardness, salinity, pH) definitely influences the DOC-concentration. The concentration of suspended particulate matter is influenced by two mechanisms:

- Algae growth. High concentrations of nutrients cause algae blooms, the temperature is also an important factor. It is worth mentioning that in recent years the Quagga mussel filters a lot of algae resulting in clear waters at relatively high nutrient concentrations.
- Resuspension of sediments (inorganic and organic) to the water layer by organisms (fish like bream and carp, and benthic invertebrates), shipping, wind, water flow and runoff from land and recreation

A part of the turbidity, the so-called background turbidity, cannot be influenced, e.g. as a result of natural suspended solids, iron-rich seepage and dissolved humic acids (especially in peat bogs).

The transparency is also limited by the occurrence of floating layers caused by blue-green algae or duckweed, due to large supply of nutrients. These layers also cause other water quality problems. Below the floating layer the water temperature is lower, and the exchange of oxygen between the air and the water is blocked. Submerged plants don't receive sunlight this decreases the photosynthesis (oxygen production) and can cause anoxic conditions. A concentration of at least 4 to 6 mg O_2 per liter indicates a good water quality. Sensitive fish species may be disturbed by an oxygen content lower than 4 mg/l.

Above mentioned aspects lead to the following key factors to obtain or maintain clear and odourless water:
- Limit algae growth and prevent floating layers
- Limit resuspension
- Avoid oxygen shortage

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[5] See http://www.andriks.net/uitzicht/nl/uitzicht.html

3.6.2.2 Design principles

Limit algae growth and prevent floating layers of duckweed or algae

Flow rate and residence time
Stagnant water is more sensitive for algae blooms. Ecology in stagnant waters is process-controlled, indicating a cycle of nutrients to organisms to detritus and again to nutrients. If the flow rate increases, the system transforms into a flow-controlled system. The nutrients are transported to the downstream area. The high flow generally hampers algae growth and also growth of floating vegetation like duckweed. If the velocity further increases, particles can resuspend and hamper the transparency.

Recommended: create a flow. It needs to be elaborated what the minimal or optimal flow rate should be.

An example of the effects caused by different flow rates is shown in Figure 3.6. It is not easy to see, but the blue line is the Binnenrotte (the water is black), whereas the red line is a diamond shaped stagnant branch of the Binnenrotte (the water is completely green by a cover of duckweed).
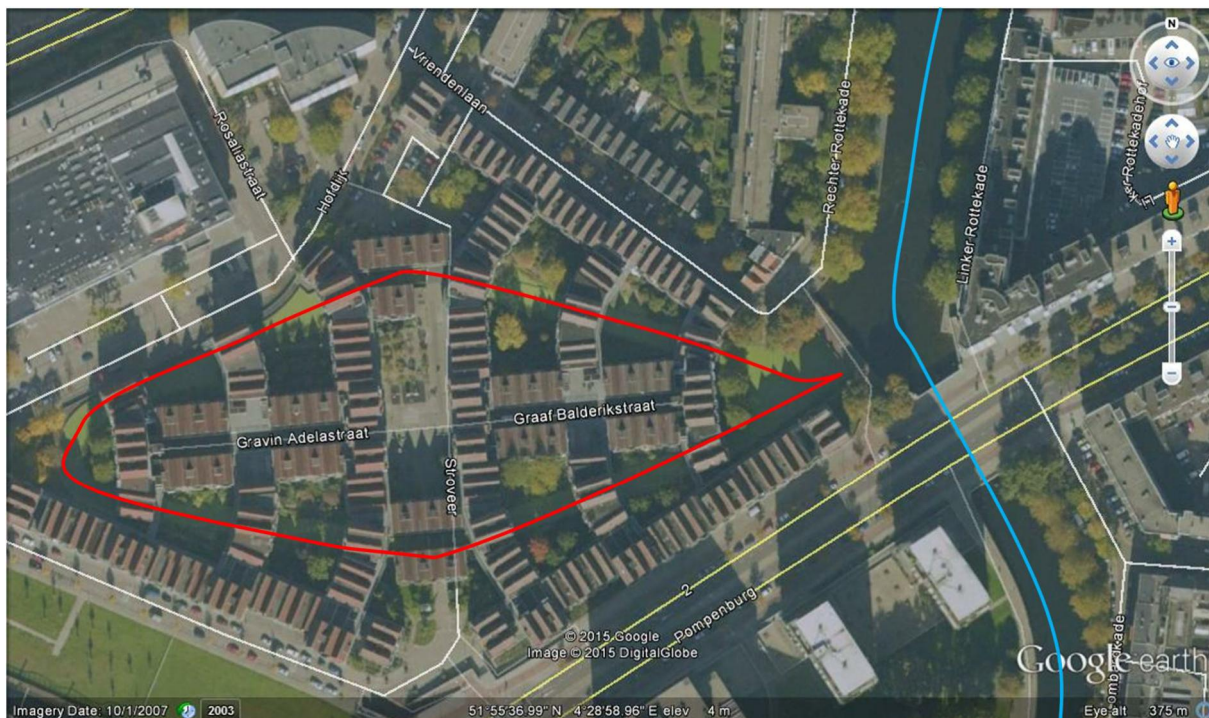
Figure 3.6   Photograph of the Binnenrotte in Rotterdam (source: Google Earth).

Water depth
Recommended: the minimum water depth should be 1 meter to have sufficient buffer for temperature and incidental input of nutrients.

Nutrient load
Most urban waters suffer a nutrient excess. In almost all cases, the challenge is to reduce the external nutrient load as much as reasonably possible. That requires attention for the inlet

water quality, the direct inputs, such as dog shit, duck food (bread), stormwater overflows, and discharges of waste water treatment plants.

The acceptable load of nutrients differs for each water body and quantification requires expert knowledge. However, to get more insight in the acceptable load, you should start with the compilation of a water and nutrient balance. How much comes in? Which processes take place (degradation, sedimentation, etc.)? And how much goes out? The next step is to use simple or advanced models to simulate the (proposed) water system.

Recommended: <u>reduce the external nutrient load as much as possible.</u>

Limit Resuspension

The turbidity of the water is basically influenced by two mechanisms (Penning et al., 2014):
- The stability of the top layer of the sediment
- The forces on the sediment by water movement.

The composition (organic fraction, grain size distribution) of the top layer is very important for the stability. A peaty sediment generally has a fluffy top layer that can erode easily, but also a muddy layer on top of consolidated sediment may be sensitive to erosion. The top layer is often influenced by the materials that enter the water body, such suspended matter from adjacent waters, leaves, and other (organic) loads. Furthermore, the physical and biological activity in the sediment determines to what extent the sediment can consolidate. Particularly, small sediment fauna can keep the sediment less resistant to erosion.

The forces on the sediment can be a result of: flow rate, (wind)waves, recreation, ships, biological activity (fish, benthic invertebrates). In (mostly small and stagnant) urban waters, flow rate, ships and wind induced erosion will play a minor role. Recreation (swimming, boating) might play a role, but fish is probably the main cause

Recommended: <u>keep the sediment low in organic matter content (e.g. sand cover)</u>
Recommended: <u>create favourable conditions for aquatic vegetation.</u>

Sediment and nutrient load
Nutrient-poor sediments, regular dredging and removing organic matter (water plants, duck weed, dead animals) limit the organic load and therefore the availability of detritus and humic acids. Regular flushing of the water system with clean water improves water quality, lower the nutrient content. Avoid churning up sediments by fish (especially carp and bream), wind, dog walking along the shores, recreation and boats.

Oxygen conditions
Oxygen is important for aquatic life. Aquatic plants have a major effect on the availability of oxygen in the water layer and in the soil (through photosynthesis and respiration directly and indirectly through decomposition of organic matter) which in turn has a major effect on the nutrient content of the water. Especially dense vegetation of submerged aquatic plants can cause large fluctuations in oxygen concentration during photosynthesis and respiration. During daytime photosynthesis dominates with increasing and even oversaturated oxygen levels, in the dark respiration dominates and takes the oxygen away. Daily fluctuations of 10 mg / l are no exception. Especially at high temperatures oxygen deficiency may occur. Floating aquatic plants and duck weed can limit diffusion of oxygen from air to water. They also prevent the growth of submerged vegetation and oxygen delivering vegetation. Low oxygen concentrations may give rise to stench and fish kills. In anoxic water pathogens may

survive longer. Oxygen deficiency leads to strong stimulation of P-emissions from the sediment to surface water. High water temperatures increase the possibility of oxygen deficiency of. Though plants produce oxygen, the decay of organic matter requires oxygen. The exchange of oxygen between air and water is essential to keep sufficient oxygen in the water. This is generally not a problem in dynamic systems, but can lead to harmful effects in stagnant systems.

Recommended: avoid stagnant water or dead-end ends.
Recommended: stimulate exchange of oxygen by designing a fountain or artificial cascade.

3.6.2.3 Maintenance principles

The design can prevent elementary problems with respect to water clarity, but water systems need maintenance. Most common methods are: dredging, and mowing bank vegetation. However, prevention can also be part of the maintenance package. Possible maintenance options are:

- to prevent organic input as much as possible (discourage bird feeding, fertilizer addition near the surface water, remove trees or try to prevent that leaves will end up in the surface water),
- to keep the fish stock below 100 kg/ha,
- dredging,
- mowing (and remove the mown material),
- remove dense vegetation of submerged aquatic plants to reduces large fluctuations in O_2,
- removing floating aquatic plants and duck weed increases diffusion of oxygen from air to water.

3.6.2.4 Isolated turbid fishponds

There is a large sports fishing community that prefers to fish carp and bream. These benthivorous species profit from turbid water and the even make it more turbid by ploughing the sediment. It can be a choice to create a number of isolated artificial ponds that are suitable for carp and bream fishing (and feeding). Swimming and other recreation should be prohibited in these ponds. They can be high in nutrients, and stagnant. However, severe problems can exist regarding toxic algae and oxygen shortage. The maintenance of these water should be focused on prevention of these problems, by some aeration (during critical periods) and by repressing toxic algae for example by adding hydrogen peroxide.

3.7 Impact of green infrastructure on social interaction and physical exercise

3.7.1 Promoting and accommodating social interaction

Green spaces can enhance social interaction. The height of the buildings, presence of a private garden and the presence of public green connected to buildings can influence social interaction.

Design principles to optimize green infrastructure for social interaction:
- Green spaces should accommodate a variety of attractive attributes (diverse landscape features) and a variety of facilities encourage higher levels of use (e.g. Giles-Corti et al., 2005).
- Green spaces should be close to places where people live and they need to be accessible, this also relates to affordable public transport links and good access

points away from busy roads (Giles-Corti et al., 2005; Kaczynski and Henderson, 2007; Neuvonen et al., 2007; Royal Commission on Environmental Pollution, 2007.

- Green spaces also should facilitate diverse uses since single-use spaces, such as sports fields, do not encourage undedicated use (Croucher et al., 2007).
- People taking ownership of green spaces will improve state and use of these spaces (Weldon et al., 2007).

3.7.2 Promoting and accommodating physical exercise

Green spaces increase physical activity of children and have especially positive effects on children of families with low social-economic status (Claesens et al., 2014). For example, the Body Mass Index of American children living in green areas is lower than children growing up in an area with limited green spaces due to increased physical activity outdoors (Bell, 2008). In the Netherlands a study in less poor neighborhoods showed that an increase in green spaces reduces ADHD-medication, like Ritalin (de Vries, 2015). There is also proof that green spaces stimulate physical exercise of adults.

Design principles to optimize green infrastructure for physical exercise
- Green spaces need to be available within a range of 2,5 km of the demand (houses, offices, etc.).
- The design of green infrastructure need to be based on the motives citizens have to visit green infrastructure. Examples of these motives are: amusement, having a break, nature dedication and physical challenges.

3.8 Urban waters and medical health

3.8.1 Impact of blue infrastructure on exposure to toxic chemicals, algal toxines and pathogens

Pollution negatively affects the water quality. The main water quality problems in the city due to drought and high temperature are:
- toxic effects of blue-green algae
- fish and bird kills by botulism, also potentially harmful to people
- bacteriological damage to organisms, including people (by pathogens)
- dermal effects, like swimmer's itch or athletes foot
- toxic effects of chemicals (including ammonia, and sulphides)

The first three issues are easily notable. You can smell or see the effects, although some investigation is often needed to identify the exact cause. The effect of toxic chemicals is less pronounced. In Western European urban areas acute toxic effects to humans caused by toxic chemicals are rare. The effects of bioaccumulation may appear after many years and only after long term exposure. Most relevant exposure pathway is the consumption of fish. No direct human effects may be expected if there is no fish consumption from urban waters.

Mechanisms and quantification
Substances that can cause toxic effects end up in surface waters as a result of drainage, runoff, sewer overflows, direct discharges, and wind. Once these substances enter the water, the fate and transport is very relevant. If harmful bacteria enter the surface water, they can die, survive or even grow and reproduce.

Chemicals often bind to suspended matter and sediments decreasing their bioavailability. However, storage in sediment can lead to problems after a long time. More than 95% of available P in the system is often present in the upper layer of the sediment. The concentration of nitrogen and phosphorus in pore water is often more than 10 times higher than in the water column. Rooting plants can act as a phosphorus pump, contributing to higher P concentrations in the surface water, which might lead to toxic algae blooms. People that ingest toxins can get sick, comparable to food poisoning, but depending on the type of toxin it might even lead to death. Every year, a number of dogs die in the Netherlands caused by algal toxins.

Organic chemicals can decay into other chemicals or finally to CO_2 and H_2O. Degradation products can cause problems as well. The most relevant risk for humans as a result of chemicals is the consumption of chemicals via fish. Organisms can absorb chemicals, leading to direct effects or to storage. Storage can lead to relatively high concentrations in storage organs, like lipid. Compounds like dioxins, but also mercury and cadmium are examples that can result in concentrations that exceed health standards.

Pathogens may originate from faecal bird droppings, runoff from paved surfaces (including e.g. dog faeces), growth of micro-organisms in water and in some cases discharges of combined sewer overflows (De Man, 2014). She studied water borne infectious diseases in case of direct exposure (splash parks, fountains, and flood water). She showed that the risk of infection per case of exposure was higher for exposure to floodwater and splash parks than for swimming good bathing water.

The production of the toxin botulin requires a temperature of at least 20 °C alongside a protein rich anaerobic environment. Once infected carcasses are present in the system, this may lead to severe outbreaks, because many other organisms consume such carcasses. Mostly, the toxin does not affect human health.

3.8.2 Design principles
Healthy swimming and playing focuses on direct effects of pathogens (including algal toxins), because chemicals in surface water will never lead to direct effects in Western Europe. Even limited fish consumption might not be a problem, but it is better to recommend people not to eat fish from urban waters that had not been screened on bioaccumulative chemicals.

The design principles can be summarised in the so-called 'Quality trio: keep clean, separate and purify'.

Keep clean
Prevent discharge of dirty water in the urban system, by:
- minimising sewer overflows
- minimising surface run off
- creating a flow direction from better to worse water quality

Separate
By creating deeper and broad stretches the flow rate is reduced, resulting in a sediment sink as suspended matter settles in such an area. If such a sink is created at a location where the sediment can be removed easily, it reduces maintenance costs. Also, obstructions in the water can decrease the flow rate, such as weirs as well as aquatic plants such as reed. A lot of suspended matter will not pass the obstructions.

Purify

The higher the temperature, the less oxygen the water can contain. Moreover, biological processes are faster at higher temperatures. That rule applies for degradation processes, but also enhances growth of pathogens. Keeping the temperature at a reasonable level is beneficial for the stability and health of the aquatic system. During the year, trees along the water have a positive effect by tempering temperature. However, maintenance is required to remove the additional input of nutrients by leaf fall in the fall. Floating plants can also diminish the increase of the water temperature. Deeper water layers lying under dense floating leaves- or duckweed cover can stay cooler on sunny days than in areas without plants. Avoid that floating plants proliferate; therefore aquatic plants like water lilies are preferable above duckweed.

The riparian zone has a wide variety of flora and fauna. Plants serve as food but also shelter for many animals, including fish, insects and birds. The ecological impact of the bank thus goes far beyond the boundary between land and water. The bank also provides good opportunities for migration of plants and animals and as such is ideal as ecological corridor. Blue infrastructure needs green infrastructure. If the phosphate load is less than 0.8 mg/m2/day a natural bank may contribute to an improvement of the chemical water quality. To realize the desired shore development the maximum concentration of phosphate will have to be approximately 0.15 mg/l (Vossen en Verhagen, 2009).

Opportunities for 'design solutions'

In most cases, design principles limit the possibilities for design, but in some cases design principles may stimulate creativity, resulting in a more interesting design. One of the opportunities is to use aquatic vegetation to purify eutrophic and/or contaminated water. The plants should be harvested regularly. Also the construction of natural banks may improve the design, but only possible in case the phosphate load is not too high.

3.8.2.1 Maintenance

The design can prevent elementary problems with respect to sources, but maintenances is important:

- Remove dead fishes and birds that are infected with botulism
- to prevent organic input as much as possible (discourage bird feeding, fertilizer addition near the surface water, remove trees or try to prevent that leaves will end up in the surface water),
- Avoid erosion of sediments by fish (especially carp and bream), wind, recreation and boats.
- The most common maintenance action in the Netherlands is regular dredging and removing organic matter (water plants, duck weed, dead animals). This prevents a continuous storage in the system. It also helps to keep enough depth.
- Regular flushing of the water system with **cleaner** water improves water quality, lower the nutrient content.

3.9 Impact of blue infrastructure on healthy living

3.9.1 Impact of blue infrastructure on stimulating healthy living

Blue infrastructure can stimulate healthy life in several ways:
- It enables sports: rowing, sailing, swimming, ice-skating
- It might create attractive lanes/corridors to cycle, walk, run, skate
- It might invite to move: water playgrounds, fountains

Comparable to other uses of water, healthy living activities require clear (and in case of swimming) clean water. Additionally to the design principles that have been described already, these activities need connectivity, particularly for rowing, boating, sailing and swimming. Connectivity also serves the possibilities to flush, and enhances the ecological structure.

Mechanisms and quantification
Engineering works, like weirs, pumping stations, and culverts are often applied. These engineering works are barriers in the connection between the different surface waters. Some barriers can be solved by smart design or by removing the barrier, but that is not always possible.

Culverts hamper water sports, but are not a problem for the functioning of a cylcle/walk-corridor. The same applies for fish passages, and pumpingstations. Sluices offer the possiblility for boats to pass, whereas weirs can be developed such that boats can pass (depending on water levels).

3.9.2 Design principles
It is advised to connect the watersystem to other systems in the city or to the rural area by cycle lanes and walking tracks along the different water systems. A vision on a city level should be developed on how boating (particularly rowing/canoeing/water bikes) can be encouraged by development of connected water ways.

3.10 The relationship between urban biodiversity and health

Biodiversity and human health relations are an emerging topic. In 2015 a report has been published by the WHO with the state of the knowledge, see WHO (2015). This report contains many references to the relationship between urban biodiversity and heath impact in various levels of 'scientific robustness'. Although the exact relationships between biodiversity and designing a healthy urban environment are not known to date, these issues may lead to new urban design principles in the future. One such notion on the importance of biodiversity for human health is copied here from the WHO report.

"*Reduced contact of people with the natural environment and biodiversity and biodiversity loss in the wider environment leads to reduced diversity in the human microbiota, which itself can lead to immune dysfunction and disease*. The immune system needs an input of microbial diversity from the natural environment in order to establish the mechanisms that regulate it. When this regulation fails there may be immune responses to forbidden targets such as our own tissues (autoimmune diseases; type 1 diabetes, multiple sclerosis), harmless allergens and foods (allergic disorders, eczema, asthma, hay fever) or gut contents (inflammatory bowel diseases, ulcerative colitis, Crohn's disease). Urbanization and loss of access to green spaces are increasingly discussed in relation to these NCDs. Half of the world's population already lives in urban areas and this number is projected to increase

markedly in the next half century, with the most rapid increase in low- and middle- income countries. Combined, these findings suggest an important opportunity for cross- over between health promotion and education on biodiversity." (WHO, 2015)

'Improve biodiversity' or 'provide more biodiversity' could intuitively be formulated as a first and simple design principle. However, further research is needed to elucidate some of the potential knowledge gaps on linkages between biodiversity and human health.

4 Benefits of Green Infrastructure

4.1 Introduction

The first chapters of this report described the functions and potential services that can be provided by green and blue infrastructure and translated these into design principles. This chapter will go one step further and analyse economic benefits that can be derived from these services by showing some important potential benefits in comparison with the present situation. The ecosystem services concept (see Chapter 1) has been used to distinguish services and define benefits. This analysis will help to better compare green infrastructure with alternative (grey) infrastructures in cities. This chapter is limited to green infrastructure. Benefits of blue infrastructure are not included at this stage.

Green infrastructure (GI) is frequently associated with several environmental and social benefits (particularly human health) that can be 'translated' into economic benefits. Since these benefits are multiple and usually not easy to monetize, it is a big challenge to collect reliable information to make well-informed decisions. This chapter aims at providing scientific evidence for the links between GI in cities and its economic benefits based on a literature review.

4.1.1 Short overview of literature on benefits of green infrastructure

The literature on benefits of GI is extensive. Prominent institutions in the United States with extensive experience in valuation of green-blue infrastructure are the US Environmental Protection Agency, Centre for neighbourhood technology and Centre for clean air policy (2010). Also in Europe experience in valuation of green-blue infrastructure is growing with the United Kingdom as biggest contributor with for example the BeST tool developed by Ciria (2015). In the Netherlands literature started to increase after the release of the 'Vitamine G' study in 2006, but there was still little focus on the economic rationale of green and blue infrastructure (Maas, 2008). Currently, there is an increasing demand from (local) governments for economic arguments to invest in GI. Therefore some societal cost benefit analyses are applied: a comparison of a project' benefits and costs for society. A good example is the cost benefit analysis of green roofs in the Rotterdam area (STOWA, 2014). Also the 'TEEB stad' tool[6] responds to this demand (Buck Consultants, 2013).

4.1.2 General overview of potential benefits of green and blue infrastructure

Green and blue infrastructures can deliver many potential services (see Chapter 3). Examples range from environmental services to social services: there are services related to climate adaptation such as reduction of storm water runoff and an enhanced urban microclimate; services related to climate mitigation, including reduction of CO_2 emission and energy use; and social services/public goods, such as increasing social cohesion. All these services can be linked to economic, social-cultural and biophysical benefits that in turn can be valuated with monetary, non-monetary and deliberative methods (Braat et al., 2015).

The present ACC project focuses on the economic value of the services by using the total economic value concept. In this concept economic values can be defined as the values assigned by people to benefits that contribute to physical wealth, welfare and/or well-being of

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[6] www.teebstad.nl

people[7]. We assume that social-cultural and biophysical benefits are included by designing urban infrastructure in a participatory way.

For the purpose of connecting societal economic valuation to business cases a distinction is made between the following types of economic benefits: (direct) financial benefits, indirect benefits for human health and the environment and other indirect benefits. If GI delivers services for which there is a clear and well-functioning market, a financial benefit will occur. Cost savings, reduction of energy costs and savings of pumping costs are examples of financial benefits of GI. The financial benefits can be directly fed into the business case. As people value good health and living environment, also human health and environmental benefits are distinguished. Typically, there is no clear and well-functioning market to identify the 'real' willingness to pay, but it is possible to include the value of these benefits by using other methods. Although the categories financial, human health and environment cover most benefits, there may be other (indirect) benefits such as feelings of safety. These are therefore also included.

Table 4.1 shows the type and extent of potential benefits related to the services of GI. The benefits will differ between different types of GI. Therefore, upon assessing potential benefits of GI, first it has to be identified if the green infrastructure has a certain effect or function. If the function is present, the table gives an indication of the potential benefit. Some benefits are highly certain (presented by a score 2), while others are less certain (presented by score 1) or not present at all (presented by score 0). The table suggests that there are many potential benefits. According to the large amount of scores 1 (compared with 0 and 2) in the table, most potential benefits are uncertain or dependent on the context.

For example, the benefits of green infrastructure may differ between locations due to e.g.:
- Type and design of green infrastructure (e.g. trees, shrubs, grass)
- Current condition of green infrastructure
- Current quality of the environment (e.g. extent of pollution)
- Number of people living in the area
- Current quality of human health

A good description of the reference (e.g. current) situation is essential to identify the effects and benefits of GI.

Besides indicating the benefits and values of green infrastructure, it is important to identify how costs and benefits are distributed between stakeholders to promote successful implementation of GI. ARUP (2014) showed that potentially all stakeholders in the city obtain some benefits from GI (see Figure 4.1), but authorities and city dwellers have the widest range of potential benefits.

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[7] This concept distinguishes direct use, indirect use, option values and non-use values.

Table 4.1   Indication of the certainty that green infrastructure delivers benefits. 0 = no potential benefit; 1 = a potential benefit with low certainty; and 2 = a potential benefit with high certainty. Direct financial benefits indicates avoided costs and damages. The list of green infrastructure services is based on CNT, 2010; Greenspace Schotland, 2008; Buck Consultants International, 2013; Kumar et al., 2012; ARUP, 2014. The qualification of the benefits is based on expert judgment in combination with a literature review based on the before mentioned sources and e.g. Ahern et al., 2005; Derkzen et al., 2015; EPA, 2008).

Services	Financial benefits	Human health benefits	Environmental benefits	Other
Climate Adaptation				
Reduction storm water runoff	2	1	1	1
Improved air quality	0	2	1	0
Enhanced urban microclimate	1	2	1	0
Better water quality	1	1	1	0
Enhanced groundwater recharge	1	0	1	1
Climate Mitigation				
Reduced energy use	2	0	1	0
Reduced CO_2 emission	1	0	2	0
Circular economy				
Longer life span infrastructure	2	0	1	0
Contribution closed water loop	1	1	2	0
Contribution closed energy loop	2	1	1	0
Contribution closed (other) commodity loop	1	1	2	0
Other services				
Increased recreational possibilities	1	1	0	0
Increased amenity value	0	1	0	1
Increased social cohesion	0	1	0	1
Increased physical activity	0	2	0	0
Reduced noise pollution	0	1	1	0
Improved habitat function and biodiversity	0	0	1	1
Increased food production	1	1	0	0
Reduced criminal behaviour	1	1	0	1
Reduced need for management and maintenance	2	0	1	1

TO₂ federatie
De samenwerkende organisaties
in toegepast onderzoek
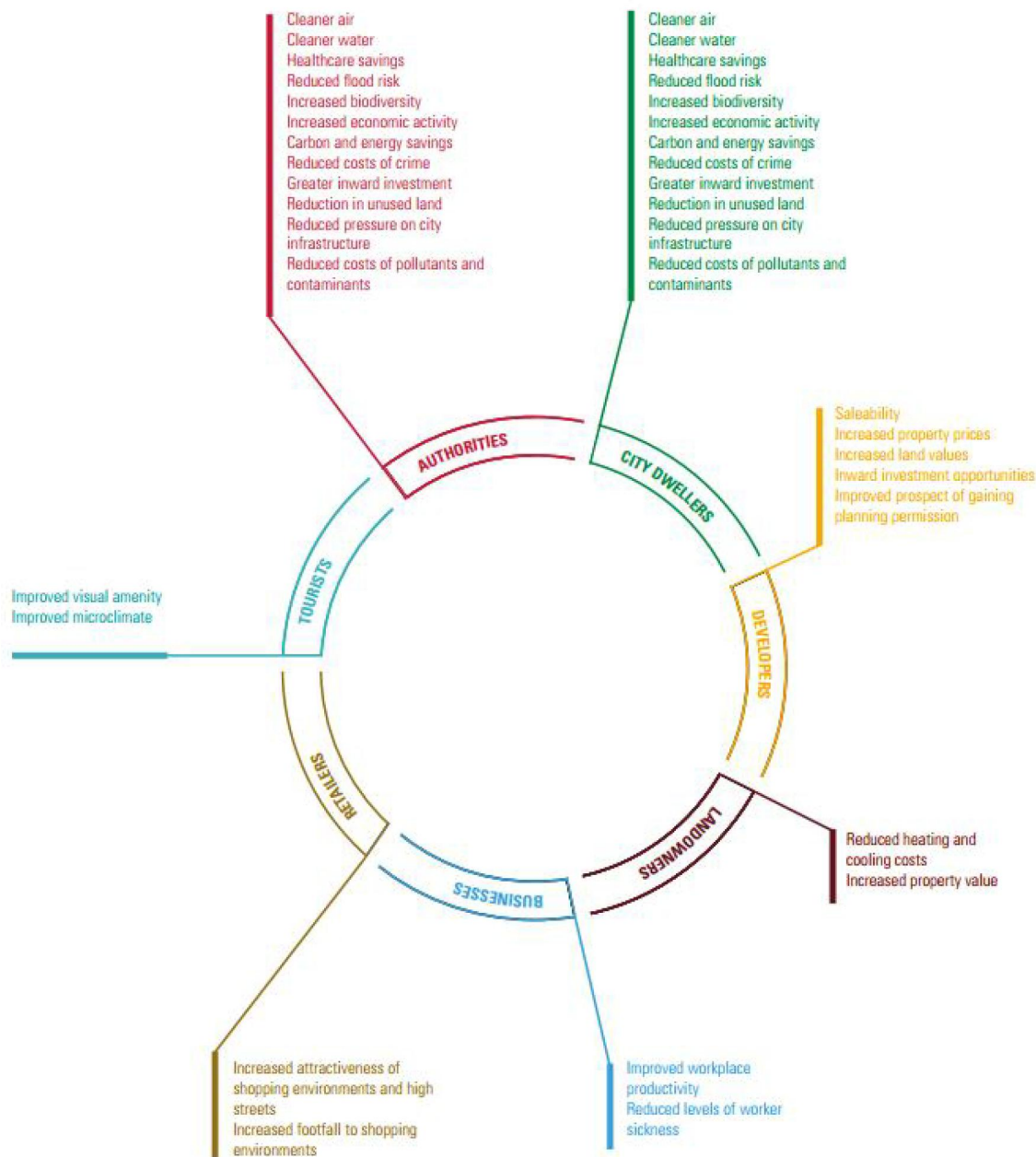
Figure 4.1   Potential benefits for different stakeholders (ARUP, 2014)

This general overview of the type of benefits of GI together with the results of Chapter 3 is the point of departure for the next part of the chapter. We will provide an overview of the GI functions and benefits (including valuation options) based on a literature review, for each of the following functions/services of GI:

- Air quality regulation
- Temperature regulation
- Water regulation
- Noise reduction

Since these functions and services are well-described in Chapter 3 and are all related to climate adaptation, we choose to extend this analysis with a description of the potential economic benefits. Additionally, we will indicate how these benefits can be translated into either monetary or non-monetary benefits. Consider that this does not give a complete overview of all the benefits of GI. For an overview of the most important potential benefits, we refer to Table 4.1. We recommend to use the freely available BeST tool (Ciria, 2015) for an indication and estimation of all potentially relevant benefits.

4.2 Air quality regulation

4.2.1 Service

The main service of GI is to remove pollutants from the atmosphere. However, GI can also deliver a disservice by increasing the exposure of city inhabitants to pollutants. This may occur when trees are planted in a busy, 'canyon'-like, road, obstructing the wind flow and removal of pollutants.

Average reduction of pollutants by urban green
The estimated effect of GI is on air quality from increased deposition is limited: not more than 1% (Nowak et al., 2006). The amount of captured pollutants depends on pollutant concentration, type of green, the season, condition of green and other local circumstances. Investments in GI should be viewed in combination with existing trend and policy. If the proposed European policy for climate and air is executed, this can decrease $PM_{2.5}$ levels with 5 µg/m^3 - the target level in the EU is 10 µg/m^3, while current levels range from 5-19 µg/m^3 in the Netherlands. This policy consists of stricter requirements for industry, transport sector and ecodesign of heaters; and reduced CO_2 emission and increased sustainable electricity production (Maas et al., 2015).

4.2.2 Benefits

Depending on the extent to which pollutants (CO, NO_x, O_3, PM_{10}, SO_2, $PM_{2.5}$) are removed from the atmosphere by urban green and the reduction of exposed humans, benefits for human health are gained in the form of increased *life quality* and increased *life quantity*. In the Netherlands the length of a human life decreases on average up to 9 months due to exposure to fine particles and approximately 4 months due to exposure to NO_2. Additionally, exposure to fine particles increases the number of sick leave days by approximately 4.5 million in comparison to a situation without air pollution (Maas et al., 2015). The reduction of pollutants will benefit human health, which can be translated into the following economic benefits: decreased health costs for hospital visits, higher work productivity and the economic value of (extending) a human life. Although these benefits can be present, the potential of GI to remove pollutants is quite uncertain and strongly dependent on various circumstances. In general, it is thought to be rather small (approximately 1% removal), which results in insignificant benefits.

The majority of literature focuses on valuing damage due to fine particles as this is the most damaging for health, and most effectively captured by vegetation (Derkzen et al., 2015; (Knol, 2005), and NO_x concentrations. The benefits of health risk reduction can be expressed in VSL, QALY or DALY (see textbox).

- **Health risk reduction**: measured in VSL (value of statistical life, also 'preventable fatality'): rather than the value of an individual's life, the VSL is the aggregate value of reducing the annual *probability* of death of a large population by a small amount. This is usually measured using a contingent valuation method - defining the willingness to pay using surveys (*stated preference*) Invalid source specified.: what people are prepared to pay for a change in the conditional probability of dying (*length of life*) **(Consulting, Willis, & Osman, 2005)**. As the effect of air pollution is only felt later in life, the WTP is generally much lower compared to WTP of exposure to substances that have an immediate effect. This reduces the value of the benefit substantially. Another way to determine the VSL is by using a hedonic pricing method (*revealed preference*). In this case the WTP is deduced actual costs or compensation people require to accept increased risk Invalid source specified..

- **Health-adjusted life years** (non-monetised): measured in QALY (quality-adjusted life years: one year of life in full health) or DALY's (disability adjusted life years: degree of life quality is included proportionally) – these concepts combine morbidity and mortality **(Hollander & Melse, 2004) (ASSC, 2008)**.

DALYs and QALYs are a consistent and transparent way to measure the effects of air quality improvements. A disadvantage of using health-adjusted life years is that the social distribution is not covered in the approach.

In summary the (health) benefits of the effects on air quality of urban green depend mainly on:
- Type of removed pollutants (e.g. $PM_{2.5}$ is expected to have a larger health effect than the coarser fraction within PM_{10})
- The reference situation in a city, for example the benefits of fine particle reduction are much larger in a city with extensive air pollution problems.
- The number of exposed people and vulnerable groups (elderly, chronically ill people, children).

In addition, the increased exposure of inhabitants to air pollution due to a canyon effect may result in a negative benefit of GI in cities. The negative benefit can be measured in a similar way as the potential positive effects of GI (e.g. with DALY's and QALY's).

Besides human health benefits, air quality improvement may have positive environmental benefits. For example, a reduction of nitrogen oxides may reduce eutrophication in lakes, which potentially reduces the amount of fish kills and loss of plant and animal diversity (Patrick et al., 2015). Although this effect can be present, we expect that this is most of the time not significant.

4.2.3   Valuation of benefits

Few studies relate a health cost or benefit directly to the amount of emitted or deposited pollution. Most studies focus on the health cost on a national scale. Hollander et al. (2005) arrive at the conclusion that the costs of air pollution are approximately ¼ to 1/3 of the total annual budget for health care (note: this is based on willingness to pay, not actual money). Singels et al. (2005) arrive at a health cost decrease of 100-800 M a year for a decrease of 1 $\mu g/m^3$ PM_{10} in the Netherlands.

Attempts have also been made to put a price on a DALY: 40,000-50,000 dollars is regarded by health economists as acceptable (Hollander & Melse, 2004). CE Delft estimates a decrease in DALY of 3% for every increase in $\mu g/m^3$ PM_{10}. VSL estimates from the US,

Canada and Australia are around 4 million dollar, but there is a large variation (ASSC, 2008). In the Netherlands the mostly used value of a VOSL is 2.8 million euro (Schroten et al., 2014, price level 2010).

To give a rough idea of the benefits related to urban green, some estimated frequently used values are included in Table 4.2. Consider that these values are based on kg of pollution captured and not on decreases in concentration. Basing benefits on kg of pollution captured consigns the actual effect of fine particles on human health to the background (Romeijn and Renes, 2011)

Table 4.2   Frequently used estimates of GI benefits for air quality regulation

Effect	Capture capacity	Benefits	Source
PM_{10} (Ruijgrok et al., 2006)	Not specified within urban area	70 E per kg	(Ruijgrok, 2006)
NO_2 Ruijgrok et al., 2006)	Coniferous trees: 205 kg/ha/year	12 E per kg NO_x	(Ruijgrok, 2006)
TEEB city: Pm_{10}	Trees: 0.1 kg/tree/year Grass: 1/ha/year Reed: 10 kg/ha/year Green roof: 0.005 kg/ m2/year	403 E/kg	(Buck Consultants International, 2013)
TEEB city: Not specified	Increased green 1% = 1.5% decrease health complaints (avg = 3.9 p/p)	28 E/ complaint	(Buck Consultants International, 2013)
PM10 (CPB/PBL 2015)	(not urban green): 12.5 kg/ ha trees	224 E/kg	CPB/PBL 2015)

4.2.4   Summary

Health problems resulting from air pollution in cities are generally regarded as one of the largest costs of living a city. To give a rough estimate: assuming half of the inhabitants of Amsterdam (800.000) suffer from air pollution which reduces their life by 9 months, and the price of a DALY €40.000 euro, costs of air pollution are in Amsterdam are €12 billion [8]. Although GI contributes slightly to the reduction of air pollutants in cities, a reduction of pollutants of 0.5% will result in considerable health gains (between €250.000 to €2 million a year). The actual services of green infrastructure highly depend on the design, type and condition of the green infrastructure. Potentially green infrastructure may even negatively affect human health due to the canyon effect. This has to be considered when taking air quality benefits of GI in consideration. Additionally, most indicators expressing benefits of GI in monetary terms directly translate captured kg into euros. However, the benefit of a reduction depends highly on the number of people exposed to the source of pollution and the initial concentration. It is recommendable to include this into the analysis. This can be done by translating the pollution reduction first to DALYs, which can then be valued. Table 4.3 gives an overview of the possible benefits. We propose to just use DALYs to better express the human health benefits and to avoid double counting.

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[8] *For the period of a human life (~80 years)*

Table 4.3   Overview of potential benefits of GI for air quality regulation

Type of benefits	Benefit	Potential value
Human health	• Possibly reduction of mortality and improvement of life quality • Less air quality related diseases	- Expressing in DALY - Expressing in DALY - Reducing number of sick leave days - Reducing hospital costs - Higher productivity (see table … for potential value numbers)
Environmental	Reduced eutrophication resulting in less fish kills and loss of plant and animal species	If significant potentially expressed in nature points

4.3   Temperature regulation

4.3.1   Service

As elaborated in Section 3.3, green infrastructure can regulate temperature by:
- Reducing the air temperature
- Reducing the radiant temperature[9]
- Reducing the physiological equivalent temperature (PET, perceived temperature)

The effect on air temperature is relatively small. If approximately 10% of the paved and built surface in cities is replaced by vegetation, the maximum temperature can be reduced by 0.4 to 0.6 degrees (Steeneveld et al., 2011; Heusinkveld et al., 2014; Van Hove et al., 2015). However, on summer days the temperature in parks can be reduced by approximately 3 degrees in comparison with the surroundings.

The radiant temperature is often reduced by vegetation with a large crown such as trees. 10% more tree crowns in a street result in a reduction of approximately 1 degree of radiant temperature (Klemm et al., 2013a; Klemm et al., 2014b).

A field study in Utrecht showed that people generally perceived urban green spaces as thermally comfortable. The respondents evaluated green environments as having a positive thermal comfort effect on warm summer days. For example, on average green spaces were characterized by PET values 1.9 degrees lower than the city centre and 5 degrees lower than the open grassland outside the city (Klemm et al., 2015).

4.3.2   Benefits and valuation

In preceding paragraphs, the effect of green on air temperature and comfort temperature has been explained. It would have been interesting if these results could be taken one step further

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[9] *The area weighted mean temperature of all the objects surrounding the human body.*

to show the effect of green on actual heat stress reduction, expressing e.g. the number of deaths, hospital admissions and productivity rates. This is, however, not known, because of various reasons; 1) the actual effect of (high) temperature on the physical functioning of the body is poorly known; 2) the impact of the urban heat island effect, in addition to increased regional outdoor temperatures, is very localised, as the factors discussed in Section 3.3.3 display a large variation in cities; and 3) the effect on heat stress very much depends on the local situation, e.g. the number of elderly actually benefiting of the green, and, therefore, requires very detailed local information.

The closest information available has been an attempt to estimate the economic consequences for the Netherlands of increased morbidity (illness), mortality (death) and decreased productivity during a period of extreme heat in various climate scenarios (Daanen et al., 2013; Stone et al., 2013). Based on the W+ KNMI'06 scenario (van den Hurk et al., 2006), the economic costs of climate change were estimated at approximately 100 million euros per year around 2050 (Table 4.4). The most important factor in the costs is decreased productivity as a result of heat. This is partially compensated by the lower costs of decreased mortality rates and hospital stays due to less cold winters. Since more people die of cold than heat in the Netherlands, each of the KNMI'06 scenarios leads to a decrease of the number of deaths per year. For the "warmer" scenarios, however, the number of heat-related deaths increases with higher average temperatures. The same correlation exists for temperature-related hospital stays: it decreases for the full year, but increases in summer (Stone et al., 2013).

Table 4.4   Economic consequences of heat stress in MEuro/jaar (Stone et al., 2013)

KNMI06 scenario	G	G+	W	W+
Mortality	-12	-16	-23	-25
of which in July and August	1.3	2.7	3.7	8.7
morbidity (hospital admissions)	-103	-137	-193	-249
of which in July and August	-5	-1	2	14
losses in occupational productivity	0	0	6	391

The main financial benefits (and environmental benefits) are related to the reduction of energy consumption. Research shows that electricity demand for cooling increases around 0.5 percent for every 1 degree of temperature increase (Hekkenberg et al., 2009). A reduction of the maximum temperature by 0.4 to 0.6 degrees will therefore reduce energy demand up to 0.25 percent (EPA, 2015). This low number is due to the relatively small (4-5%) share of cooling applications in the energy market in the Netherlands. In other countries this share is much larger, causing larger changes in electricity demand for every degree of temperature increase (Hekkenberg, et al., 2009). Potentially, effects of climate change will increase the number of cooling application in the Dutch energy market. A lower energy demand will also reduce CO_2 emission, which can be monetized by using the CO_2 emission price (mostly set at €20 to €50 per ton CO_2).

Another environmental benefit is linked to water quality. During heat waves the water temperature increases, which may reduce the water quality in cities (affecting human health and habitat for species). Reduction of the air temperature and shadow of trees may positively affect the water quality. However, GI may also have negative effects on water quality due to e.g. leave fall. There is no information on the degree of these potential environmental benefits. Potentially, these benefits can be illustrated with the nature points method (PBL, 2014). However, it is likely that these benefits are rather small.

The main human health benefit of temperature regulation by GI is the reduction of mortality. For example, a heat wave in France caused approximately 15.000 additional deaths. Studies showed that also in other European cities heat waves can cause up to 30% of additional mortality. The strongest health effects of a heat wave are observed in cities where heat episodes are rare events. Heat waves have the most effect on respiratory mortality (Ippoliti et al., 2010). Specific heat related illnesses include: heat cramps, heat rash, heat oedema, heat syncope, heat exhaustion and heatstroke (Public Health England, 2015).

GI in cities will reduce the air and radiant temperature, which may reduce mortality in cities. However, there is limited information on the degree of potential reduced mortality. This will highly depend on the context, for example the number of elderly living in a city, the building style of dwellings and the behaviour of sensitive groups. Additionally there is little information on the actual effect of (high) temperature on the physical functioning of the body. Generally spoken, the benefits of information campaigns, air conditioning and adjustments to homes are probably much larger than the benefits of green infrastructure.

Heat also potentially affects labour productivity. Australian researches calculated that lost productivity and absence of work due to heat waves costs the Australian economy at least 6.2 billion dollar a year. Approximately 70% of the working population had worked less efficiently and 7% missed a day of work due to high temperatures (Zander et al., 2015). Although this has not been directly related to temperatures or the reduction of temperatures (or PET) by green infrastructure, this study indicates that heat may have a substantial impact on work productivity. Other potential positive health effects are related to reduced exposure to UV radiation (due to shadow of green infrastructure), which may reduce the occurrence of skin cancer cases.

4.3.3 Summary

The difficulty to obtain quantitative information on the benefits of GI on temperature regulation (as mentioned above) makes it complex to value the benefits in economic terms. However, Table 4.5 summarizes the potential benefits and possible ways to monetize these benefits.

Table 4.5 Overview of benefits of GI for temperature regulation

Type of benefits	Benefit	Potential value
Financial	Energy reduction CO_2 reduction	Approximately 0.25% energy reduction in cities due to replacement of 10% of the paved surface by vegetation and CO_2 price.
Human health	Possibly reduced mortality Less heat related diseases Improved labour productivity	If possible expressed in DALY Less doctor visits or DALY
Environmental	Potential better ecosystem functioning due to possible positive effect on water quality	If significant expressing in nature points

4.4 Water regulation

4.4.1 Services

The main water regulating service of GI is prevention of pluvial flooding through the infiltration capacity of open soils underneath the vegetation and canopy interception. For example, a one in a 1000 year rainfall event (64 mm rainfall in one hour) will not generate runoff in an open loamy soil, while the runoff will be substantially in a sealed soil. Another important effect of green infrastructure is the reduction of the soil moisture content and possibly the groundwater levels. This can be seen as a disservice, but in cases of high groundwater level as a service (e.g. in preservation of wooden foundations).

4.4.2 Benefits

The benefits of the prevention of pluvial flooding are:
- **Reducing flood damage** (the most critical function of water regulation):
  o Physical damage on buildings, infrastructure, etc.
  o Acute health risks and risks of spreading diseases (especially in warmer countries) (Ahern et al., 2005)
- **Lower investment cost in water infrastructure (**e.g. drainage, sewers). This also holds for moderate rainfalls (Derkzen et al., 2015; EPA, 2007).
- **Reduced water treatment costs** by waste water treatment plants (WWTP): during storm events, sewers overflow leading to higher pollutant loads. Also, green infrastructure pre-treats surface water by filtering pollutants (Center for Watershed Protection, 2007).

4.4.3 Valuation

Although much is written on the economic damage of flooding in urban areas, research on the potential of vegetation and urban green in reducing this risk is still limited. For example, there are several studies on the potential of various green infrastructure measures on capturing runoff, but actual quantification of decreased demand for traditional water infrastructure or decreased flood risk is not often made.

Reducing flood damage
The benefits of decreased flood risk can be calculated based on the (change in) risk, i.e. the 'probability' times 'the expected damage' in case of flooding. Scientific studies analysing that data of damages due to pluvial flooding in the Netherlands are scarce - this hampers the development of prediction models for rainstorm damage. Most models focus on fluvial flooding or flooding from the sea. A promising source of damage estimates for pluvial floods are insurance databases – however, only a small part of water-related claims relate to public system failure during storm events, causing sewer flooding and depression filling. Claim sizes for sewer flooding are between 1150-3160 euro; this tends to occur when 7-8 mm rainfall/hour threshold is exceeded (Spekkers, 2015). Nelen en Schuurmans (2012) estimated average restoration cost of direct damage of 12.500 for 50 m^2 on the ground level; and 500 € indirect damage per day for every day before restoration has taken place. The latter varies strongly over various building types.

Besides direct damage to properties, floods can have a wider economic impact. Impacts may be losing hours of work in order to clean up, losing business income as well as impact on

human health and increased stress (human health effect). For example, the results of a survey held in Cook County, Illinois showed that 84% of the property owners experienced stress and 74% of the property owners lost hours of work to clean up, which resulted in approximately 3000 dollar of lost wages (CNT, 2014). Flooding may impact human health by floodwater spreading waterborne infectious diseases. A large study in the Netherlands showed that urban flood water contains various viruses and bacteria such as Giardia and noroviruses. This result in an increased risk of infection for children who were exposed to floodwater: 33% increased risk from water from combined sewers, 23% from water from storm sewers and 3.5% per event from rainfall generated runoff. For adults the increased risk of infection was respectively 3.9%, 0.58% and 0.039% (De Man-Van der Vliet, 2014).

Decreased investment in water infrastructure
Benefits of lower requirements for water infrastructure can be measured through the following mechanisms (Buck Consultants International, 2013). Reduction of peak flows lower the standards for the infrastructure, which will in turn decrease the costs of drainage infrastructure. The saved investments and lower maintenance and operation costs can be seen as benefit of the water regulation by vegetation.

Based on 17 case studies in the US, it was estimated that 15-80% of total capital costs in new storm water infrastructure can be saved by introducing green infrastructure – and this does not even include other benefits derived from using more sustainable measures. It is however hard to estimate the costs of these 'low impact design' techniques as this differs over various designs. These costs - for example plant material, increased project management and site preparation - may not always be cheaper than traditional infrastructure (EPA, 2007).

Reduced water treatment costs
The reduced water treatment costs can be measured from lower demand. In man-regulated water systems like in the Netherlands, the shift from water processing by the WWTP to processing by a pumping station (Buck Consultants International, 2013) is also a benefit as costs for the latter are much lower. Water that is infiltrated in the soil enters the regional groundwater system and in the end is processed by a pumping station. Water that enters the sewage system is processed by a WWTP, which is more expensive. The difference in processing costs after the redistribution of rain water is an economic benefit of water.

Buck consultants (2013) take the avoided costs for the WWTP as a benefit. In the western part of the Netherlands, all surface water not processed by the WWTP will be processed by a water pump: this is 0.72 euro/m^3 water cheaper than if the same water is processed by a WWTP (so if it ends up in the drainage system). It is important to note that this is not particularly polluted water – just storm water that ends up in the sewer system. The service of urban green assessed here is not its potential to purify water or increase water quality, but merely to shift the water from being processed by the WWTP to the 'natural' water system.

Valuation example
An example of a cost-benefit analysis of applying Sustainable Urban Drainage (SUDs) in the urban area in the UK was positive for permeable paving and rain barrels. Rainwater retention (e.g. open water) measures could yield a benefit of approximately 5 million pound yearly (Environment Agency, 2007). In the UK urban flooding caused by rainfall overwhelming drainage capacity is expected to occur more often in the future due to climate changes. In England and Wales, costs of urban flooding are expected to increase from 270 million a year (in 2010), to 1-10 billion/year in 2080 if no action is taken. In this light, a reduction of runoff of 20% could be a valuable amount (Forest Research, 2010).

> **Sustainable Urban Drainage vs. Green infrastructure**
> A term often used in in the context of using green infrastructure for water regulation is 'sustainable urban drainage systems' (SUDs): improving water drainage in the urban system through 'green' measures such as permeable paving, rainwater harvesting, increasing vegetation cover and green roofs. However, not all measures included in the SUDs-concept are actually 'green' in the strict sense (vegetation): some 'grey' measures like infiltration filter drains and swales are also part of it. Valuation studies on green infrastructure focus mostly on SUDs, not making a distinction between the effects of vegetation-related and other measures (Environment Agency, 2007; Zhou, 2014).

4.4.4 Summary

Local urban flood risk depends strongly on the local functioning and capacity of the urban drainage system and GI already in place. Therefore, valuation of the benefit is very context specific. However, green infrastructure measures can have a significant effect in reducing flood damages. The benefits show a different range of mainly financial benefits. However, it is important to watch out for double counting of benefits. For example, lower requirements of water infra possibly cancel out the reduction of flood damage. Table 4.6 summarizes the GI benefits for water regulation.

Table 4.6   Overview of GI benefits for water regulation

Type of benefits	Benefits	Potential value
Financial	Reduced flood damage	- Direct damages f.e. claim sizes sewer flooding 1150-3160 euro (7-8 mm rainfall/hour), ~ 12.500 euro per 50 m2. - Loss of working hours - Loss of business income
	Lower requirements water infra	- Potentially between 15% and 80% saved investments for new infrastructure - Saved investments existing infrastructure and operation and maintenance costs
	Reduced water treatment costs	- Processed water by water pump is 0.72 euro/m3 water cheaper
Human health	Less infections of children and adults Less stress due to flooding	- Fewer risks expressed in DALY or less doctor visits.

4.5 Noise reduction

4.5.1 Services

Vegetation buffers with a (dense) combination of trees and shrubs can reduce up to 3-8 dB of noise, if placed within 50 m of the road. Depending on the intensity of the road and initial noise, this can be up to 50% of the noise (dB are measured in logarithmic scale) (Alliance for Community Trees, 2011; Derkzen et al., 2015).

4.5.2 Benefits

Noise pollution is stated to be one of the four major pollution problems worldwide (Dzhambov and Dimitrova, 2014). Statistic research has even pointed out that noise pollution is one of the primary disutilities from living in urban areas as opposed to rural areas (Weinhold, 2008). In the European Union about 250 million residents suffer from noise exposure higher than 55 decibel, of which 80 million are exposed to noise levels higher than 65 decibels. This level is considered unacceptable (European Commission, 1996). Costs related to hindrance from noise are twofold:

1. Noise can seriously increase the risk of major health problems like loss of hearing and cardiovascular diseases (Bolund and Hunhammar, 1999; Ising and Kruppa, 2004).
2. Noise has a damaging effect on the working environment and liveability of an area. Even when there are no direct psychological or medical symptoms, noise can significantly affect the quality of life (Dzhambov and Dimitrova, 2014).

The extent of benefits that can be derived from noise reduction depends on:

- Location and type of vegetation;
- Type of the source;
- Frequency of the produced noise;
- Local climatic circumstances (wind speed, - direction, temperature, humidity);
- Number of affected people.

There is a reasonable extent of literature on the costs of noise pollution, as its valuation is mandatory in most developed countries, mainly in transport project appraisal studies on airports, highways and roads (Odgaard et al., 2006). The background of most of these studies is on relatively large scale projects, and not necessarily specified for the urban area, nor on the potential mitigating effect of vegetation.

4.5.3 Valuation

The costs of noise pollution can be categorized in three types: annoyance costs, health costs and productivity loss (IGCB, 2010). The following four major techniques are mostly used for measuring the economic costs or benefits of noise reduction (Becker and Lavee, 2003):

- Cost of Abatement: the most straightforward method, but not necessarily related to the benefits of noise reduction- these are harder to estimate and not necessarily directly related to the benefits of the abatement
- Cost of Illness: health expenditures are used as a proxy – e.g. comparing the health costs related to hearing capacity of a population subjected to noise, and a population unaffected by noise. Also possible to use DALYs.
- Contingent valuation method: using surveys to ask people what their willingness to pay is for noise reduction. This method can be used to value less tangible aspects of noise, like 'nuisance' and psychological impacts. However, this method is frequently subject to biases.
- Hedonic pricing method: e.g. using real estate prices as proxy for the WTP for a less noisy apartment.

Especially measuring the costs of socio-psychological health effects as annoyance, sleep disturbance and disturbance of performance is difficult, as these effects can be very subjective (Weinhold, 2008), and there is no certainty on the longer term health effects (often used for monetary valuation) (IGCB, 2010).

Contingent valuation and hedonic pricing methods are the most commonly used to estimate the WTP for noise reduction, relating mostly to annoyance costs (IGCB, 2010; Nijland, Van Kempen, Van Wee, and Jabben, 2003), followed by health costs. To address the full scope of noise pollution, in large-scale studies a combination of methods is used to address annoyance costs, health costs and productivity loss (Igcb/Defra, 2008)

For example, the UK estimated the costs of noise pollution on at least 7 billion pounds/year: 3-5 billion pounds annoyance costs, 2-3 billion health costs and 2 billion productivity loss (IGCB, 2010). Swinburn et al. (2015) estimate that a reduction of 5 dB could decrease the two main noise-related diseases - hypertension and coronary heart disease – in the US with respectively 1.4 and 1.8%. The annual benefit for the US would be approximately 3.9 billion dollars.

Table 4.7   *Shadow price per dB/person/year for increase/decrease in dB. Source: (Delft, 2014), price level 2010.*

dB (A)	Road			Railway		
	Hinder	Health	Total	Hinder	Health	Total
63	166	0	166	102	0	102
64	179	0	179	115	0	115
65	192	0	192	128	0	128
66	205	0	205	141	0	141
67	217	0	217	153	0	153
68	230	0	230	166	0	166
69	243	0	243	179	0	179
70	256	0	256	192	0	192
71	268	72	340	205	72	277
72	281	80	361	217	80	297
73	294	89	383	230	89	319
74	307	98	405	243	97	340
75	320	106	426	256	106	362
76	332	115	447	268	115	383
77	345	124	469	281	124	405
78	358	132	490	294	132	426
79	371	141	512	307	141	448
80	383	149	532	320	149	469
>81	396	158	554	332	158	490

Using a hedonic pricing method, Rodrigue et al. (2013) find a value for a decrease in property value of 8-10 $ per dB increase. Weinhold (2008) finds a value of 146 euro/month per household for relatively severe[10] noise pollution in general. Other sources, mostly based on contingent valuation studies, relate noise costs directly to dB. As this is a logarithmic scale, the benefits of reducing a relatively high noise level are higher than reducing a lower noise

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[10] *Weinhold (2008) does not include a clear definition of what noise level in dB is defined as 'relatively noisy'. This study is based on contingent valuation – respondents themselves determined wheter or not they felt they were living in a 'relatively severe noise pollution'. This is, of course, strongly subject to bias.*

level (Table 4.7[11]) (Delft, 2014). A literature study on WTP for noise reduction shows that WTP typically lies between 4-24 €/year/dB/household, averaging around 20 €. However, WTP estimation often overestimates the actual value. Most valuation studies focus on the benefits of decreasing noise of a minimum level of approximately 55-65 dB (Defra, 2011).

4.5.4 Summary

If urban green is applied effectively in the urban system, local noise levels can be reduced with 3-8 dB. The expected noise reduction value can be multiplied with the economic value – ideally based on annoyance and health costs - for those noise levels and the amount of households/ persons suffering from that noise level. For example, if a quarter of the population of Amsterdam would benefit from green measures reducing noise nuisance by 4 dB, this could yield benefits of 8 million € (4 dB*20 €/dB/hh*100.000 hh). However, the current level of noise pollution needs to be taken into account. Table 4.8 summarizes the benefits.

Table 4.8   Overview of GI benefits for noise reduction

Type of benefits	Benefits	Potential value
Human health	Less physical health problems

Less annoyance

Less productivity loss | Most studies do not make a distinction between valuations of the different health effects. For example, studies showed a 8-10 dollar decrease in property value per db, 146 euro/month/household per month noise pollution or up to 554 euro per dB/person/year noise reduction (Table 4.8). Otherwise use DALY, loss of working hours etc. |

4.6   Overview of the services and benefits

This chapter showed the benefits of some of the functions and services of GI. The results indicate that there are many potential benefits, but all of them tend to be small. The final benefits depend on the final services that green infrastructures deliver and the exposure (of humans) to these services. If humans are not exposed to services of GI or the services are very small, the benefits are probably not significant (and can be excluded).

From the four analysed services, the water regulation function of GI is potentially the largest followed by temperature regulation, noise regulation and air quality regulation. The type of benefits of the services differ, e.g. water regulation has potentially the most financial benefits, while temperature regulation probably has most human health benefits. For human health, DALYs are potentially a good instrument to value morbidity and mortality. Additionally, the analysis showed that there are not always reliable indices available to estimate the potential benefits in monetary terms. Besides the services and benefits included in the analysis, GI potentially delivers much more services and benefits. Table 4.9 provides an overview of the most important potential benefits. We recommend to use the free available BeST tool (Ciria, 2015) for an indication and potentially an estimation of the relevant benefits.

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[11] *A shadow price is the 'social price' of a good or service that does not have a place in actual markets. If you see environmental quality – and in this case, silence – as a service, the shadow price are the costs for not having these services. In this case, the shadow prices include both nuisance and health costs.*

Table 4.9   Summary of potential benefits of GI

Type of service	Financial		Human Health		Environmental	
	Benefit	Valuation	Benefit	Valuation	Benefit	Valuation
Air quality regulation			Possibly reduction of mortality and improvement of life quality	*Expressing in DALY*	Less eutrophication, haze and less effects on wildlife (also aquatic wildlife)	*If significant expressing in nature points*
			Less air quality related diseases	*. Expressing in DALY . Reducing number of sick leave days . Reducing hospital costs*		
Temperature regulation	Energy reduction	*Approximately 0.25% energy reduction in cities due to replacement of 10% of the paved surface by vegetation*	Possibly reduced mortality	*If possible expressed in DALY*	Potential better ecosystem functioning due to possible positive effect on water quality	*If significant expressing in nature points*
			Less heat related diseases	*Less doctor visits or DALY*	CO2 reduction	*CO2 price (~€ 20 and € 50 per ton)*
			Improved labour productivity	*Value increased productivity*		
Water regulation	Reduced flood damage	*. Reduced direct damages f.e. claim sizes sewer flooding 1150-3160 euro (7-8 mm rainfall/hour), ~ 12.500 euro per 50 m2. . Fewer losses of working hours . Fewer losses of business income*	Less infections of children and adults	*Fewer risks expressed in DALY or less doctor visits.*	Better water quality	*See financial benefit and potentially epxressing in nature points*
	Lower requirements water infra (new infra)	*- Potentially between 15% and 80% of the costs saved*				
	Reduced water treatment costs	*Processed water by water pump is 0.72 euro/m3 water cheaper*				
Noise reduction			Less physical health problems	*Value of total health effect up to 554 euro per dB/person/year noise reduction. Or DALY, loss of working hours etc.*	Less disturbance of animals	*In cities probably not significant*
			Less annoyance Less productivity loss			

The analysis showed the potential benefits of GI, but not *who* benefit from GI. This is relevant information for developing business cases. Table 4.10 shows a first attempt to indicate the beneficiaries that receive the benefits listed in Table 4.9. Remarkable is that city inhabitants, insurance companies and employers are frequently indicated as beneficiaries, while especially insurance companies and employers are not the most frequently involved stakeholders in urban planning. This intuitive analysis suggests that these stakeholders should preferably be involved in the design of GI.

Table 4.10 Intuitive identification of the beneficiaries of the benefits listed in Table 4.9

Services	Potential beneficiaries
Air quality regulation	City inhabitants (mainly vulnerable health groups), health insurance companies, employers, nature organisations, regional water authorities.
Temperature regulation	City inhabitants (and visitors), health insurance companies, employers, nature organisations, regional water authority
Water regulation	Municipality, home owners, insurance companies, drinking water companies, regional water authorities, insurance companies
Noise reduction	City inhabitants, health insurance companies, employers.

5 From design principles to design: 1. application of design principles to design of green areas in Utrecht

5.1 Aim of the pilot in Utrecht

The aim of the pilot study was to test the usefulness of the design principles developed in the previous chapters in a district in the city of Utrecht (see Section 1.4). The design principles are based on the understanding of the functions of green infrastructure for the delivery of a variety of ecosystem services (temperature regulation, air quality regulation, flood prevention, noise reduction, recreation, etc.) relevant for the municipality. We explored how the formulated design principles could best support planning and design of green spaces, in this way enhancing the effectiveness of green infrastructure for ecosystem services that contribute to healthy urban living and climate adaptation

In order to test the applicability of the principles, a design workshop was organized for civil servants of the municipality Utrecht involved in planning and design of green infrastructure and relevant fields of expertise. We discussed and explored the effectiveness of green spaces for selected ecosystem services in the Utrecht district Kanaleneiland/Jaarbeurs/Central Station (see Figure 5.1). After the workshop, participants evaluated the workshop and the applied design tools.
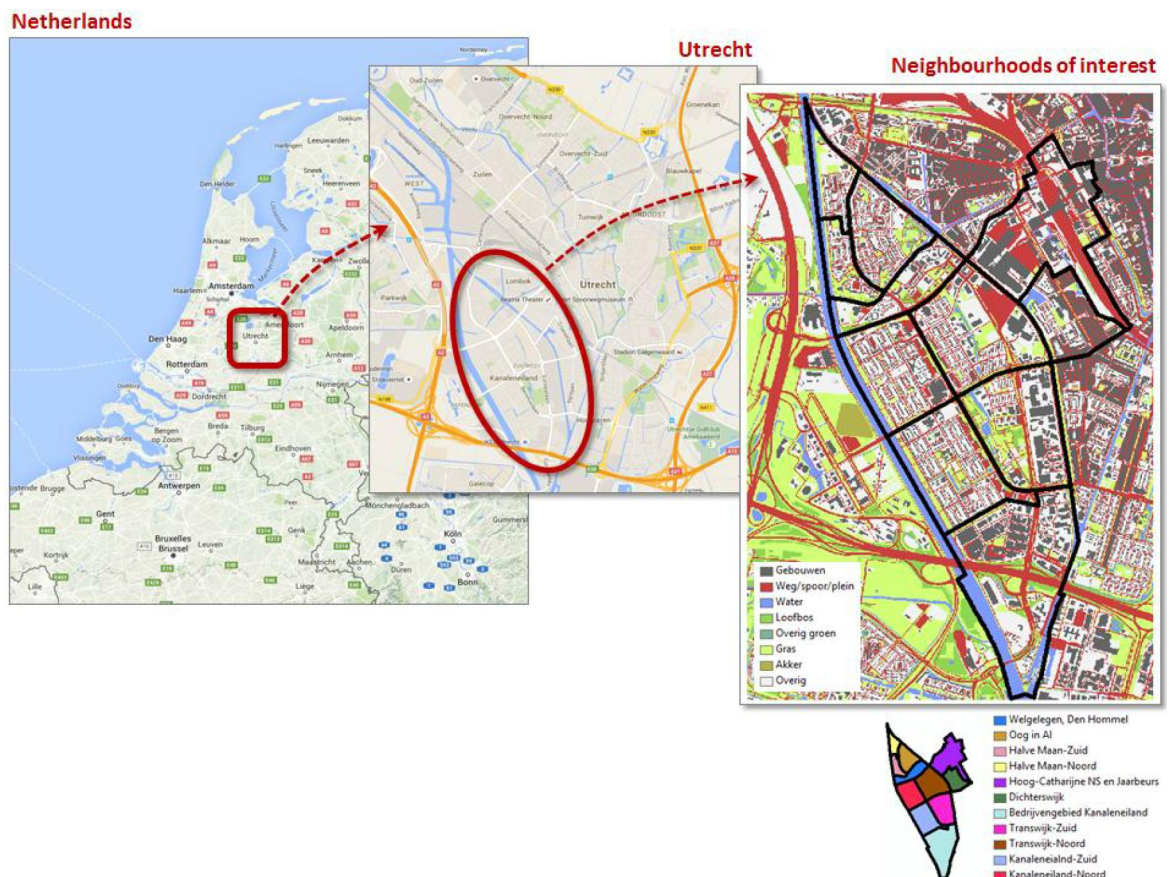
Figure 5.1   Location of the city of Utrecht in the centre of the Netherlands, and the pilot study area, the Kanaleneiland/Jaarbeurs/Central Station district.

5.2 Approach: design workshop

5.2.1 Set-up and activities

The workshop took place on 31st October 2015, in the town hall of Utrecht. During the workshop, participants were informed about the general effectiveness of different types of green spaces for the selected ecosystem services based on the scientific evidence presented in the previous chapters. Participants responded to the infographics presented in Section 2.1.

The participants and the scientists explored the demand for ecosystem services in Utrecht during an interactive session using their own knowledge and maps of the city. The services explored were of a physical nature (heat stress mitigation, air quality regulation, water quantity regulation, noise reduction) and cultural (stress reduction and promoting physical activity/recreation and social interaction). In two parallel sessions, the Adaptation Support Tool and QUICKScan tool were used to explore the effect of changes in green infrastructure in Utrecht at city level (macro) and street level (micro).

For the design workshop, three spatial levels were considered: city level, district level and street level. For the district level, the area around the Central Station and the Jaarbeurs fair was chosen because this area will be renovated in the near future. It is currently also one of the least green areas of the city. In order to include a residential area, the adjacent district called Kanaleneiland was considered as well.

Annex A contains a list of participants. Participants were asked to evaluate the workshop at the end of the meeting and by answering a questionnaire.

5.3 Design tools

Three design tools have been used in the pilot to design public green spaces in the Kaneleneiland/Jaarbeurs/Cental Station district: the Infographics, the Adaptation Support Tool and the QUICKScan tool.

5.3.1 Infographic multifunctional green infrastructure

The infographic is explained in Section 2.1. During the workshop, a draft version was presented to the stakeholders.

5.3.2 Adaptation Support Tool

The Adaptation Support Tool (AST) is part of the Adaptation Support Toolbox, a planning toolbox for a climate resilient and ecologically sustainable urban environment (http://bgd.org.uk/tools-models). The method supports selection of climate change adaptation measures that are suitable for the specific local topography, climate and urban layout. The toolbox also enables the development of an urban adaptation plan that meets stakeholders' needs.

The AST is an interactive software tool that can be used on a map table, a touch screen or a regular computer. Based on local conditions, the AST provides a list of feasible measures for climate change adaptation. Users can draw measures on a geo-referenced background image (aerial photo or map), for example areas where green roofs might be applied. AST calculates the effectiveness of the measure for water quantity regulation (reduction of runoff) and reduction of heat stress (see Figure 5.2). The effect of an intervention on the occurrence time of a flooding event is estimated based on the storage capacity, a simple hydrological multi-reservoir model and meteorological data. The effect of an intervention on heat stress is

determined by the local cooling effect and area of an intervention (based on literature) and the surface area.

The AST has been developed in the context of the Climate KIC project Blue Green Dream, by Deltares and Alterra, in collaboration with Bosch Slabbers, TU Berlin and Arcadis.

Figure 5.2   AST calculates the effectiveness of the measure for water quantity regulation (reduction of runoff) and reduction of heat stress (http://bgd.org.uk/tools-models/).

5.3.3   QUICKScan

QUICKScan is a tool to facilitate the decision process in participatory settings (http://www.QUICKScan.pro/; Figure 5.3). By including stakeholder knowledge and preferences and the ability to calculate impacts in-situ, QUICKScan supports the discussion and the convergence of perceived values. QUICKScan enables the creation of alternative storylines for questions defined by stakeholders, and translates these in-situ into a model by combining tacit expert knowledge with available spatially-explicit monitoring and statistical data. QUICKScan builds on concepts from Participatory Modelling and Participatory GIS and uses visualisation and interpretation tools to support the exploration of options allowing and facilitating discussion of alternatives, analysing their consequences, and determining trade-offs and synergies. The QUICKScan tool is designed to run quickly and can, therefore, perform multiple iterations of a modelling exercise during a workshop. The results of each iteration feed into the discussion among stakeholders and policy-makers creating input for the next iteration. - QUICKScan has no system dynamics or feedback loops and is limited to spatially-explicit issues (Verweij et al., submitted).

Figure 5.3   QUICKScan builds on concepts from Participatory Modelling and Participatory GIS and uses visualisation and interpretation tools to support the exploration of options allowing and facilitating discussion of alternatives, analysing their consequences, and determining trade-offs and synergies.

5.4   Results from the workshop

5.4.1   Utrecht municipality needs for ecosystem services

Heat stress is most prevalent at the Jaarbeurs site and at business parks. The health impacts of heat stress seem to be limited since not many people live at these sites but participants also indicate that there is a lack of knowledge on the impacts of heat. In the future, more houses are planned in the hotspot areas for heat stress. It is recommended to take future predictions for heat stress into account. Besides, the negative impact of higher temperatures on air quality should be considered.

Air pollution is mainly a problem close to the source of emissions, which is mainly traffic. Both particulate matter and nitrogen oxides are problematic.

Sources of noise that is perceived as a problem are neighbors, traffic (especially the highway south of Kanaleneiland), the railway and the railway station (including the intercom) and industry. It is important to consider both actual noise levels and perception of noise.

Flooding problems are mainly concentrated in two neighborhoods: Wittevrouwen and Tuindorp, and to a lesser extent at the Jaarbeurs site. Causes are depressions and soil

sealing. Also <u>drought</u> is a local issue. Activities such as aquifer thermal energy storage and soil sealing can induce drought. As a result of drought, irrigation of vegetation is required.

Low <u>availability of green spaces</u> is mainly identified in northwest Utrecht and at the Jaarbeurs site. Lack of space results in general limits the quality of green spaces (quality is not specified during the discussion).

5.4.2 Feedback on the Infographics

Participants asked for more insight in the background of figures, e.g. if the figures for effectiveness of green spaces are based on measurements, models or expert judgment.

Besides some detailed suggestions for graphical improvements, it was suggested to make an additional infographic in which green elements are the starting point instead of the functions, e.g. provide information about the functions of trees, lawns etc.

5.4.3 Results AST session

For an effective exploration of interventions a representative case area of Kanaleneiland was chosen (Figure 5.4). Two steps have been undertaken in the session. In a first step locations have been identified where exposure to heat stress and flooding is highest. As indicator of heat stress, maps of the simulated relative temperatures have been used (Figure 5.4 *right*). As indicator for flood exposure, water levels predicted with a hydraulic model (3Di) have been used. Heat stress in general is highest in paved areas at the sun facing side of buildings in absence tall shadow providing vegetation like trees. In the pilot area these areas are found in some roads and parking lots and in some of the common gardens that have been paved.
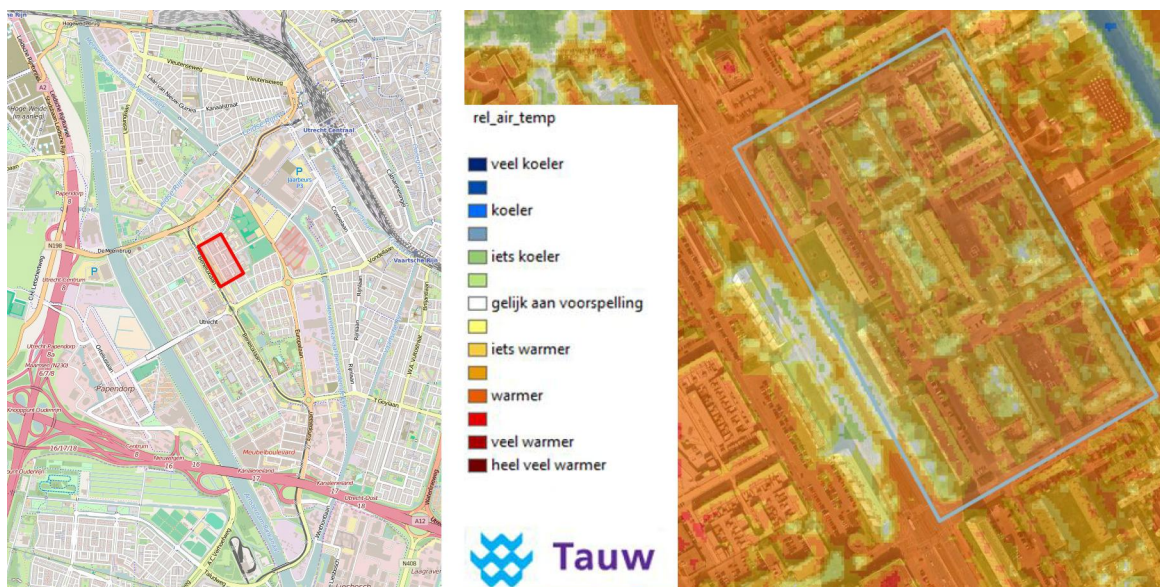
Figure 5.4   The case study area for the AST-session (left) and a calculated heat stress map (right)

During the session the following interventions were planned in the pilot area targeted at reducing the air temperature at the warmest places and reducing runoff (Figure 5.5):

- Urban Agriculture: the practice of cultivating, processing, and distributing food in or around a village, town, or city. Next to food production it also contributes to social interaction and awareness for healthy food.
- Adding green elements (trees) in the streetscape; reduces the air air-temperature by evaporative cooling and providing shade. It reduces runoff through interception and infiltration underneath the tree
- Adding grass/herbs, was implemented to provide a playground. It reduces the air-temperature by evaporative cooling and reduces runoff through interception and infiltration into the soil
- Intensive green roofs, with a thickness between 15 and 50 cm, can support a wide variety of plants. Underneath the growth medium is a waterproofing membrane. Water can be stored within growth medium of the green roofs. Annually the runoff reduction equals the evapotranspiration rate. During extreme events the peak flow is reduced by temporal storage of stormwater. Due to evaporative cooling intensive green roofs have a cooling effect, however not at street level.
- A water square, is a (public) square that can temporarily store water and is often combined with improvement of the quality of urban public space. The water square can be understood as a twofold strategy. It makes money invested in water storage facilities visible and enjoyable. It also generates opportunities to create environmental quality and identity to central spaces in neighbourhoods. Water squares can reduce air temperature by green elements they contain and by evaporation of stored water.
- Porous pavements or permeable pavements include a range of pavement systems that allow the movement of stormwater runoff through the surface. In addition to reducing runoff, these systems can trap suspended solids and filter pollutants from the water. Effect on air temperature is negligible.

The effectiveness of the interventions is shown in Table 5.1. The air temperature reduction as a result of the individual interventions and of the total is provided as average values over the whole case area. At the location of the interventions the air temperature reduction is higher. The created water storage to reduce runoff is 2.138 m^3. This equals a storage capacity of 21 mm over the whole area. This is enough to store a once in two year rainfall event in and is in general more than what can be stored within a sewer system. The return time of a runoff event that occurred once in 2 years now occurs once in 22 years.

Concluding remarks
The case area is not planned to be renovated any time soon. Therefore it is unlikely the results will end up in an actual design. One of the takeaways for the municipal representative of the department of green infrastructure is that in normal practice the multiple benefits of green infra are not taken into account in the design. The session and using the tool created additional awareness of the co-benefits. This is useful, as it provides an argument for experts from the health and green departments to be consulted earlier in the process of design and planning as they can provide solutions to multiple relevant decisions on other issues (heat stress reduction, pluvial flooding). In addition, it helps them to optimize their design to be more effective in for instance reducing heat.
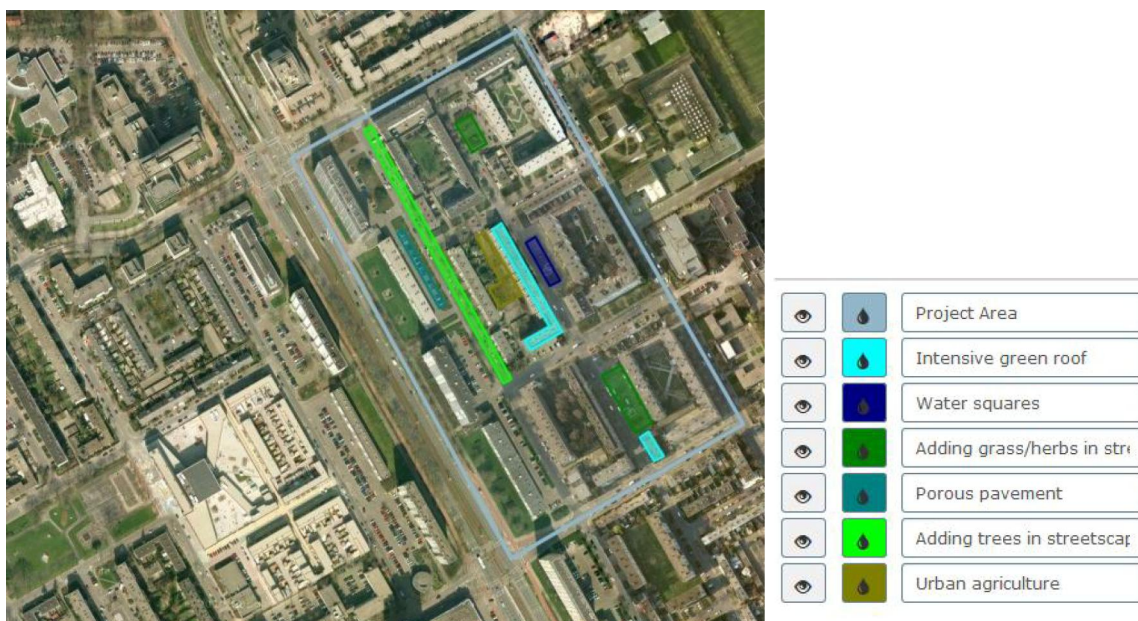
Figure 5.5   Implemented interventions in case area.

Table 5.1   Effect of interventions on case area.

Intervention	Storage capacity (m³)	Return time off runoff event(y)	Heat reduction (°C)
Adding trees in streetscape	926	3.8	-0.09
Porous pavement	50	3.0	0.00
Water squares	246	6.8	-0.09
Adding grass/herbs in streetscape	330	14.0	0.00
Intensive green roof	302	2.0	-0.04
Urban agriculture	284	2.9	-0.02
Total	2138	22.4	-0.25

5.4.4   Results QUICKScan session

The session was prepared in advance based on: the project's objective, three workshops with the scientific experts, and on interviews with experts and officials from the municipality of Utrecht. The preparation provided the following data and information:

- the study area (Kanaleneiland/Jaarbeurs/Central Station Area);
- spatial resolution (5x5 km²)
- gathering of relevant spatial and statistical data (land use, location of individual trees, tree species, tree age and size, green index, temperature, noise levels, air pollution and topography).

During the two-hour participatory QUICKScan session, the impact of the greening scenarios was explored with eight municipal experts on green, soil, energy, health, air quality and the research team (scientists and civil engineers). Together we identified five indicators (air quality, cooling capacity, aesthetic value and recreation, noise reduction and stress reduction) linked to the functions of green infrastructure. Based on the participants' knowledge we jointly mapped these indicators for the present situation and for in-situ devised scenarios, such as

green roofs, tree growth, tree plantation and removal, and planting of bamboo along roads (as noise reduction).

Results were presented as hot-spot maps, bar diagrams and spider diagrams (as trade-off analyses) for the different districts. Annex A shows several examples of the maps developed for several functions of green developed with the QUICKScan during the session. The developed scenarios impacted districts differently and it was concluded that the exercise helped to identify targeted measures for each district. At the end of the meeting the municipal planners indicated that the assessment could be further improved by considering the integration of the green functions (synergisms and trade-offs) and including a cost-benefit analysis.

5.5 Evaluation

The feedback provided during the wrap up of the workshop, the evaluation questionnaire and the answers of all respondents are provided in Annex A.

The results of the evaluation can be summarized as follows:
- Most participants value the information provided in the workshop and the results of the AST and QUICKScan applications as useful. A useful aspect of the AST and QUICKScan tools is the assessment of the effects of measures. Participants want to use this analysis to explore the added value of green measures in the context of green projects and policy making. Also the interactive capabilities of the tools is appreciated. In order to use the tools, it should be clear how the municipality can apply the tools, e,g, how to obtain the required equipment and operational support.
- In response to the application of the tools and presentation of the infographics, some participants wanted to know more about the background of the information, especially when it comes to quantification of the effectiveness of green infrastructure. Participants stated that they want to know if the figures are based on measurements, expert judgement or model calculations (and see the formulas) before they can rely on the figures and know how to use them.
- The usefulness of the presented draft infographics is rated as hardly useful to very useful. Suggestions for improvements involved detailed changes in the pictures or the figures. These suggestions have been used to further improve the infographics in the final version. One participant stated that the infographics provide a lot of graphics but limited information, the oral explanation made the story come to live.

A participant proposed to start an infographic from the measures (instead of the functions), e.g. show what the effects are of a green roof, park, tree, grass lane etc. One participant suggested to perform a benchmark study to compare the quality of the living environment in different neighborhoods. Another suggestion is to distinguish between the effects of private and public green elements. It was also suggested to provide insight in the cumulative effects of green spaces for multiple functions.

6 From design principles to design: 2. combining design principles with a conceptual visualization of a healthy city

6.1 Aim and approach

Dutch design bureau for spatial strategies POSAD has developed a Toolbox Healthy Urban Living (http://posad.nl/en/projects/gezonde-verstedelijking/), a schematic design of a city district containing recommendations for urban planners and designers to take into account when designing a healthy city. The powerful visualization of this Toolbox forms a very interesting combination with the science based design principles for green infrastructure and healthy urban water systems as developed in the present ACC-project, as this combination potentially produces a more specific deepening of the Toolbox on designing blue and green infrastructure to support healthy urban living.

Therefore a workshop was held on 30 November 2015, in which the added value of linking the Toolbox and the ACC-design principles was discussed by representatives of Deltares, POSAD, Municipality Utrecht, Rijkswaterstaat and RIVM. As a result, the schematic visualization of a healthy city from the Toolbox has been combined with the BGI design principles developed in the present ACC project.

This chapter includes highlights of the discussion during the workshop. The adapted visualization of a healthy city is provided in Section **Error! Reference source not found.**.

6.2 Integration of ACC design principles with the Toolbox for healthy urban living

The toolbox includes four generic principles with which the urban environment may contribute to human health:
1. Healthy movement through the city
2. Designing public space for exercise, recreation, meeting and sports
3. Synergy between public and private space (work, school, care provision)
4. Healthy basic services (drinking water, health care, information, nutrition)

The toolbox consists of a schematic visualization of healthy urban living in a city district.

Development of the toolbox was supported by Rijkswaterstaat and it is currently used by the city of Utrecht in the design of the Central Station / Jaarbeurs area. According to the Municipality of Utrecht, the Toolbox is being used frequently. For example, a civil servant responsible for public health uses the images to support cooperation with designers.

City representatives explain that it is nowadays not possible or desirable for the government to instruct or dictate citizens on how they should live their lives. Instead, they focus on developing a healthy urban environment and designing the public space in such a way that it accommodates and encourages healthy behavior. Blue and green infrastructure can play an important role in this respect. For the municipality, small and even uncertain benefits of green infrastructure are important as part of the bigger picture. In the context of the role of both private and public, we refer to the report by De Jong (2015) that provides the results of an assessment in the districts Tuindorp and Overvecht in Utrecht; the assessment involves quantification of ecosystem services provision by private and public green spaces.

The infographics from the current ACC-project, including the background knowledge on effectiveness of blue and green measures and design principles for green spaces (Chapters 2 and 3) are considered as 'scientific' and they may be less useful for the practical support of designers of the municipality. However, one participant states that she can very well use the information when talking to colleagues involved in health measures. Representatives of the municipality disagree about the importance of the effectiveness of 'green' measures and how to determine this. Some state that knowing the theoretical positive impact on health and moral support for the measures is most important, others consider it important to quantify the effectiveness.

The combination of the more abstract and perceived 'scientific' design principles from the present ACC-project (and the background knowledge compiled in Chapter 3) and the visualization as presented in the POSAD Toolbox together form therefore a more complete picture and support tool for designing BGI for a healthy urban environment.

The design principles, tools and the background information provided in this report on the effectiveness of green measures on health can contribute to completion and deepening of the toolbox.

The role of the different elements in healthy urban design is demonstrated in Figure 6.1. At present, the key factors for healthy urban water are still under development. The Toolbox has therefore been adapted for green infrastructure only. In 2016, design principles for BI will be formulated and the Toolbox can then be adjusted to further specify the role of water in healthy urban living. Figure 6.2 through Figure 6.5 show the results of combining the Toolbox visuals with the ACC design principles.

Figure 6.1   *Available design principles and tools from the Toolbox (TB) for healthy urban living and the present ACC-report.*

1. Healthy movement

SHORTCUTS
Short, save and illuminated routes along schools and parks.

WIDE SIDEWALKS
Wide comfortable sidewalks on the sunny side makes it more attractive to walk.

POCKET PARKS
Green spaces accessible along sportroutes and connected with (healthy) facilities.

RIVER BANKS
Nature friendly riverbanks with enough space for animals and plants.

BIKE HIGHWAY
The bikehighway crosses as much as possible trough green corridors. Fresh air and parks are the base of this fast route.

BUS STOP
Bus stop nearby bike and footpath routes, preferably in the sun.

WATER QUANTITY REGULATION
Disconnect rainwater from roofs and streets. Guide towards infiltration streets to reduce overflow in sewage systems.

Figure 6.2   Green infrastructure can stimulate cycling and walking by providing an attractive urban landscape. Green elements can reduce nuisances from motorized traffic such as noise and air pollution. Trees provide shade during summer and all vegetation can contribute to reducing urban air temperature.

2. Designing public space

NOISE 'REDUCTION'
Green as sound buffer;
psychological effect reduces the
perception of sound.

SHADOW SIDEWALK
2 meter walking space and parking.
The other side is 4 meters wide and
sunny without parking.

CYCLE STREET
A cycle street is a street that is
designed as a bike route, cars are
allowed but seen as guests.

PHYSICAL ACTIVITY
Recognizable routes to practice
different sports. Set goals to track
how many kilometers you sport.

OUTDOOR WORKPLACES
Outside work, lunch or meetings
allows workers to take fresh air and
intake of vitamin D.

ACCESSIBLE WATER
Acceptable quality of water in
canals and lakes so it can be used
for swimming.

PAVILION
Multifunctional pavilion for sports,
relaxing, interaction and shelter
from the rain.

SOCIAL INTERACTION
Public space is a space for culture
and interaction. Create enough
meeting places outside and in green
public space.

Figure 6.3   Green spaces close to people's homes or working place can provide an attractive urban landscape for physical exercise and social interaction. Green elements can reduce nuisances from motorized traffic such as noise and air pollution. Trees provide shade during summer and all vegetation can contribute to reducing urban air temperature.

3. Synergy between public and private space

SIDEWALKS
Wide accessible sidewalks with possibilities to rest and enjoy the sun.

PUBLIC SPACE
Connect offices with public space.

OUTDOOR CLASSROOM
Giving classes outside provides more fresh air and intake of vitamin D.

ROOF GARDEN
Learn to eat/grow your food makes you aware of a healthy diet and provides educational activities.

CLIMBING TREES
Objects which are challenging for children to play with.

INFILTRATION FIELDS
Infiltration fields where it is spatially possible.

WIDE SIDEWALKS
4 meter wide sidewalks on the sunny side, connected with bike and footpaths.

CONNECT SCHOOL FACILITIES TO PUBLIC SPACE
Healthy school squares are green, challenging and linked to other play streets and places.

Figure 6.4 Connecting private and public green spaces can enhance possibilities for physical exercise in an attractive and healthy environment close to people's homes or working place (e.g. lunch walk). Public space and business areas in general are more suitable for large trees than private gardens, while reducing the amount of impermeable pavement in private can contribute significantly to storm water runoff mitigation (De Jong, 2015).
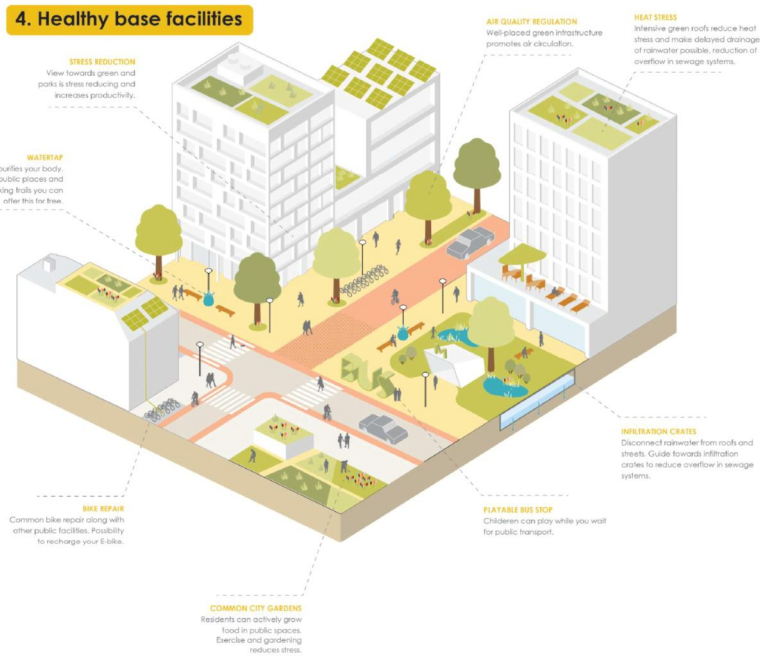
Figure 6.5 Green infrastructure as part of the base facilities of a healthy city. Smart green design contributes to a healthy environment that accommodates a healthy lifestyle. Especially for children and other people who are less mobile, green spaces closes to home are important. Even looking at green elements has a positive effect on mental and physical health.

7 Conclusions and recommendations

7.1 Conclusions on the effectiveness of green and blue infrastructure

This report provides concepts and design principles for blue and green infrastructure that not only support climate resilience but also contribute to a healthy and attractive urban environment. A healthy and attractive urban environment contributes to the strengthening of the socio-economic climate in cities.

The objective of the project was to assess how the functional use of urban blue and green infrastructure can potentially contribute to a liveable and healthy city. The effectiveness of blue and green infrastructure was assessed on the basis of available literature and experience from the city of Utrecht, and design principles were formulated for the design of blue and green infrastructure in the urban landscape.

Effectiveness of green infrastructure
The infographics for green infrastructure as presented in Chapter 2 and substantiated in Chapter 3, are a visual compilation of design principles for multifunctional green infrastructure and also provide information on the effectiveness of green spaces to deliver ecosystem services. The design principles focus on a variety of ecosystem services that contribute to healthy and attractive cities such as temperature regulation, air quality regulation, flood prevention, noise reduction and recreation.

Air temperature regulation: urban vegetation can reduce heat stress in the built environment by providing shade and evaporative cooling. In addition, green elements have a significant positive influence on the human perception of temperature. In general, measurements in the Netherlands indicate that, when 10% of the paved and built surface is replaced by vegetation, the maximum value of the UHI can be reduced by approximately 0.4-0.6°C. Local effects in green areas can be higher. On summer days the temperature in parks can be reduced by approximately 3 degrees in comparison with the surroundings.

Air quality improvement: in principal there are three mechanisms by which air quality is influenced by green infrastructure. These are increase in deposition of pollutants, altering the wind flow, and emitting biogenic volatile compounds and pollen. The use of green infrastructure may improve air quality on a city scale; it is estimated that the effect will not be higher than 1%. On the local scale however, air quality may deteriorate due to a decrease in ventilation due to obstructing vegetation. Hence, it is important to ensure that in the area where people live and recreate green elements are positioned in such a way that air circulation is promoted. The use and design of green infrastructure should therefore always take into account the typical characteristics of such an area.

Water regulation: the function of green infrastructure for water regulation that is considered in this report is reduction of storm water runoff. The effectiveness of green infrastructure for water regulation depends on rainfall intensity and frequency, vegetation and soil characteristics. In the temperate climate of the Netherlands rainfall events are not intense, which can make green infrastructure very effective for water regulation. The main contribution of green infrastructure for reducing stormwater runoff and preventing pluvial flooding is through the infiltration of stormwater into open soils underneath vegetation. Often applied tree pit sand consists mainly of loamy sand that has an average infiltration capacity of about 250

mm/h and can range between 150 and 500 mm/h depending on exact composition and degree of compaction.

Noise reduction: green infrastructure can reduce traffic noise by serving as a natural sound barrier. Direct functions imply the attenuation of noise due to adsorption and dispersal and scattering of sound waves. Indirect functions imply the adsorption capacity of open soil and the noise reducing effect of decreasing wind speed. Vegetation buffers with a (dense) combination of trees and shrubs can reduce up to 3-8 dB of noise, if placed within 50 m of the road. Besides the direct and indirect physical noise reduction mechanisms, vegetation also provides noise reduction services via psychological effects. Just visually screening the noise source by providing a view on a green barrier makes that noise is perceived as less annoying.

Mental health: research results indicate positive relations between nature or green elements and health. Seeing green elements already has a positive relation with stress reduction. Positive relations between health and green spaces are sometimes corrected for other factors influencing health, but in general there is limited proof for cause-effect relations.

Social interaction and physical activity: green spaces can enhance social interaction. The height of the buildings, presence of a private garden and the presence of public green connected to buildings can influence social interaction. Green spaces increase physical activity of children and have especially positive effects on children of families with low social-economic status.

Effectiveness of blue infrastructure
A well-functioning blue infrastructure requires an integrated approach to create a network that prevents floods and droughts, and has a good water quality. This is essential because water is a dynamic substance which flows, evaporates, runs off the surface and leaches. Urban water quality may vary depending on the functional use. Particularly a recreational boating network requires a plan on city or regional scale, but possibilities for urban waters to flow may contribute to a better water quality.

We distinguish three categories of health aspects of water and ecosystem services that support human health: 1. direct exposure to water contributing to medical health; 2. encouraging healthy living by creating possibilities to exercise, and 3. aesthetical aspects of water contributing to mental health. Services 2 and 3 are closely connected to green infrastructure.

Medical health: in case of direct contact, the chemical and biological quality of water should be good. People should be able to swim or play in urban waters without any substantial risks of toxic algae, pathogens and other nuisance organism, or toxic chemicals.

Healthy living: In order to create attractive surface water that contributes to an urban environment that promotes physical exercise and mental health, it is preferred that urban waters are clear with some visible life (vegetation, fish, birds). In case of boating water should be connected as much as possible.

Mental health: People enjoy the water, just to sit along the banks or on a terrace to drink a beer. Stench and noise can hamper the pleasure, as well as visible contamination like litter and floating layers of algae or duckweed.

Potential benefits of green and blue infrastructure
In this study the benefits were shown for some of the ecosystem services of GI. The results indicate that there are many potential benefits, but all of them tend to be individually small. The total value depends on the sum of benefits related to services that green infrastructure delivers and the number of people that benefit from the services.

From the analysed services, the monetary value of water regulation is potentially the largest, followed by temperature regulation, noise regulation and air quality regulation. The type of benefits of the services differ, e.g. water regulation has potentially the highest financial benefits, while temperature regulation probably has most human health benefits. For human health, DALYs are potentially a good instrument to value morbidity and mortality. Additionally, the analysis showed that there are not always reliable indices available to estimate the potential benefits in monetary terms. Besides the services and benefits included in the analysis, GI potentially delivers more services and benefits.

7.2   Recommended design principles

Green infrastructure
In order to optimize water regulation, maximize water uptake, both by the canopy and by the root system, by choosing coniferous trees over deciduous trees. Increase the vegetation density by allowing for multiple vegetation layers. Maximize infiltration rates by increasing the surface area of open soil, by increasing the infiltration capacity of the soil with coarse grained materials and by temporarily storing water to allow it to infiltrate during a longer period. Similarly for green roofs, choose vegetation types with a high interception capacity and growth layers with maximum allowable thickness.

In order to regulate air temperature optimally, maintain or increase the percentage of green in the city, especially at the windward side during hot conditions. Add trees with large crowns in streets, parks or squares. Take vegetation maintenance into account from the start. Allow infiltration to ensure sufficient soil moisture content for vegetation.

To improve air quality, the design of green infrastructure in a city should be carefully considered, as air quality can also deteriorate as a result of misplaced green elements. The design should consider residence time of air, the type of green infrastructure and maintenance. For street canyons it is advised to place trees only sparsely, so that the polluted air at street level is mixed with cleaner air atop. Another solution for street canyons is using green walls. For green roofs it is advised to use intensive green in multiple layers to ensure mixing of air and removal of dust. For horizontal surfaces it is advised to use coarse green structure which can potentially remove dust instead of flat smooth surfaces. In order to minimize the emissions of harmful compounds and to maximize capture of different pollutants, a variety of species should be used including coniferous and deciduous species. Maintenance is important to manage the amount of pollen emitted and because the overall health of vegetation influences the capacity to remove pollutants.

For effective noise reduction, locate vegetation close to the noise source while providing an appropriate setback for accidents. Evergreen species will offer year-around noise control. Create a dense buffer with trees and shrubs to prevent gaps. Plant the vegetation in a crossings arrangement to optimize the reduction of low frequency noise. Crossing arrangements were determined to be more effective in the level of noise attenuation over an abreast design.

As for improving mental health, maximize visual contact with green elements and connect the design process to the various recreational motives that people may have for visiting green spaces. To promote social interaction and physical exercise, organize green spaces close and accessible to where people live and facilitate peoples' diverse motives such as sports, amusement, etc.

Blue infrastructure
Clear water is important for contributing to an attractive urban environment for physical exercise and mental health effects of the presence of surface water. For chemically and biologically clean water some additional factors play a role: sources of contaminants and pathogens (waste, stormwater, sewer overflows).

To create clean water 1) limit algae growth and prevent floating layers by reducing of nutrients, decreasing the residence time, 2) limit resuspension by removing or capping fluffy organic top layers, limit the fish stock below 100 kg/ha, and creating vegetation, and 3) avoid oxygen shortage by reducing the organic load and a minimum water depth of 1 meter, and avoid dead ends.

To improve blue infrastructure for leisure and use, it might be necessary to create places to enter (and to leave) the water, and to build some infrastructure to facilitate playing, paddling, etc.. To connect various waters, bridges are needed instead of culverts and dams.

If citizens are directly exposed by surface water by swimming, playing, irrigation of gardens, etc. additional measures are needed to avoid pathogens, biological toxins, and chemical. The latter is generally a minor issue in developed countries, but pathogens are often related to sewage overflows, and waste water treatments plants. Reducing the (effects of) sewage is the most important measure.

Except design principles, a well-functioning blue infrastructure also requires maintenance. If maintenance is neglected, the quality will definitely decline. Some suggestions for maintenance are presented in this report. For example, maintenance is required to remove the additional input of nutrients by leaves in the fall.

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ANNEX A: Results of questionnaires on design workshop

.1 Workshop participants

Eight civil servants from the municipality and a representation of the scientific project team participated in the workshop. The list below provides information about their field of expertise.

Table A.1   List of municipality participants and representation of the scientific project team during the workshop.

Expertise	Affiliation participants
Ecology	Municipality Utrecht
Subsurface, subsurface energy	Municipality Utrecht
Public health	Municipality Utrecht
Air quality	Municipality Utrecht
Soil and green spaces	Municipality Utrecht
Maintenance public space	Municipality Utrecht
Designer	Municipality Utrecht
Noise	Municipality Utrecht
Water management	Municipality Utrecht
Hydrology	Deltares
Air quality	ECN
Land use change, QUICKScan	Alterra Wageningen University and Research centre
QUICKScan tool	Alterra Wageningen University and Research centre
Urban climate, QUICKScan	TNO
Environmental economy	Deltares
Climate adaptation in urban areas, AST	Deltares
Hydrology, AST	Deltares
Ecosystem services	Deltares

.2 QUICKScan results

This annex provides information on the data specifically incorporated into the QUICKScan software tool for the workshop in order to map several functions of green spaces as they are now, and under alternative greening scenarios All data were preprocessed to the same spatial resolution of 5x5 km^2, the same spatial extent (roughly 3x4 km^2) and the same spatial projection. The figure number indicates the figure where the data have been used for developing the map.

Incorporated data:
- Interpretation of Remote Sensing satellite imagery
  - Land cover (Figure 5.1)
  - Green index
  - Temperature (reflection, July 2015)
- From Utrecht Municipality
  - Management of green (Figure A.1)
  - Owner of green (private/municipality
  - Tree density (municipality managed trees)
- National and provincial

- o Neighbourhoods of interest
- o Measured noise
- o Main roads
- o Particles PM10
- o Location of schools
- o Exceedance of health standards (GES)
- National tree registration (private and public trees)
  - Tree height
  - Tree species
  - Tree width
  - Tree growing curves (under various scenarios)

Examples of the mapped functions of green:
- PM10 particle reduction: Figure A.2, Figure A.3, Figure A.4, Figure A.5;
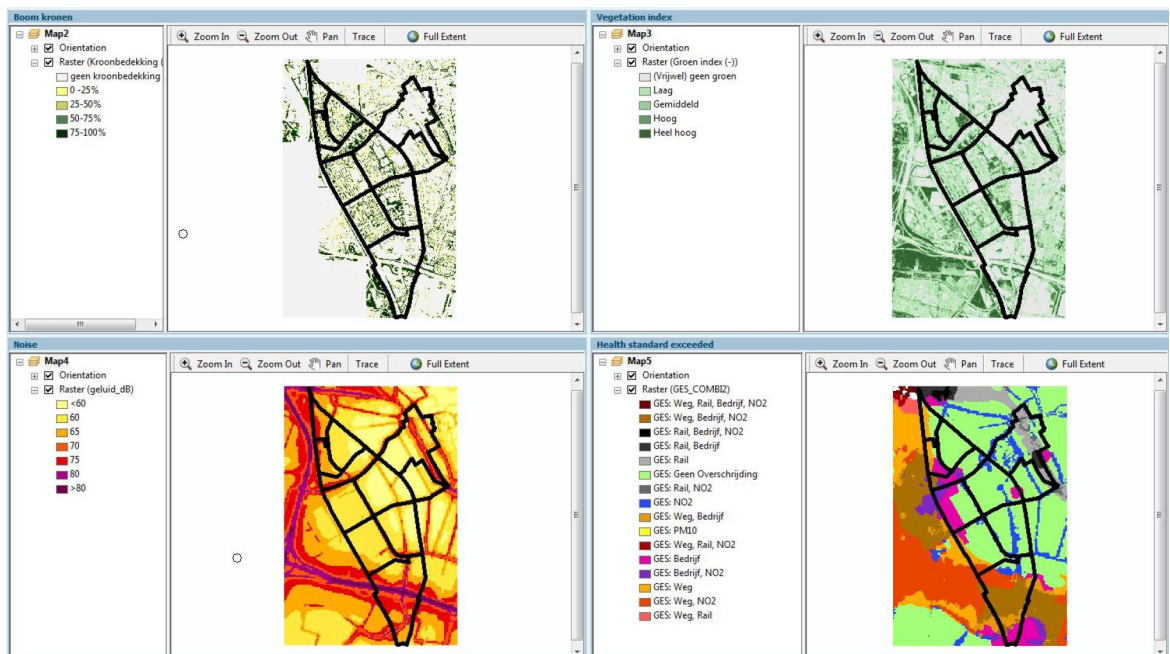- cooling effect: Figure A.6 and Figure A.7;
- stress by noise: Figure A.8.

Figure A.1   Examples of input data: tree sizes, vegetation index, noise and municipal management
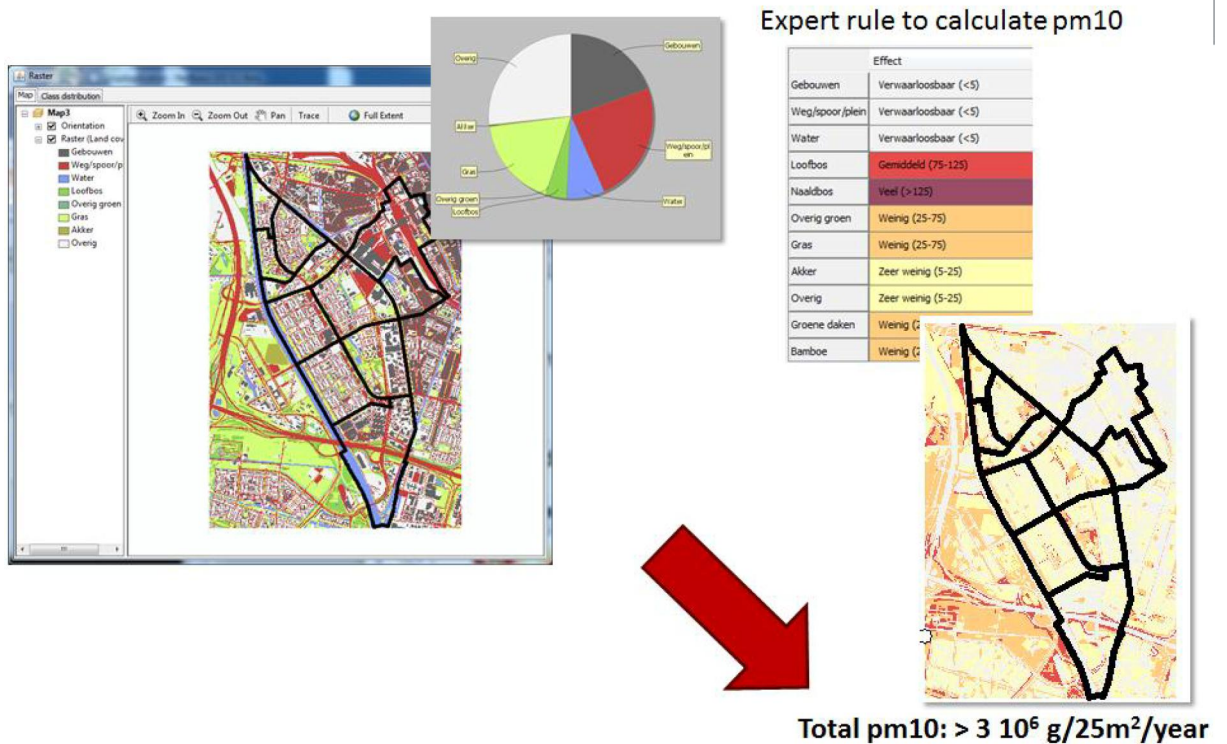
*Figure A.2 Expert rule to calculate PM10 particle reduction based on green land cover of the present situation.
Present PM10 reduction is more than 3 10^6 g/25m^2/year for the total study area*

*Figure A.3 Defining a 'greening' scenario: create green close to busy roads (within 100m), add green roofs on
buildings and replace all present green with coniferous forest. The maps on the top left show the distance
from busy roads; the map on the bottom left the current shows land cover; and the map on the bottom right*

represents the scenario based on changing the land cover. The matrix formed on the top right shows the expert rule for creating the future land cover map.
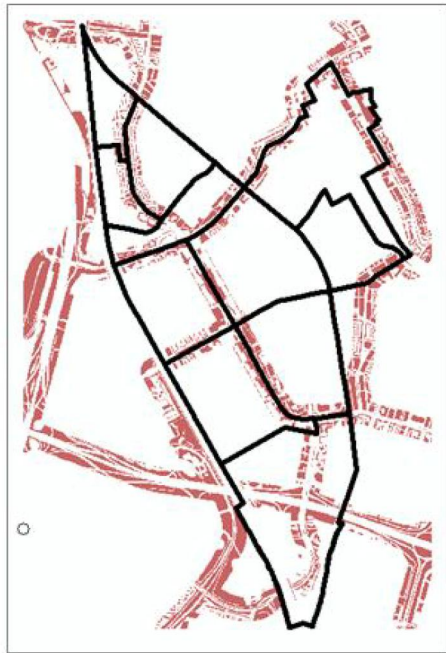
Notice areal losses in some land use classes (deciduous, grass, artificial surfaces) and increases in others (coniferous, green roofs)
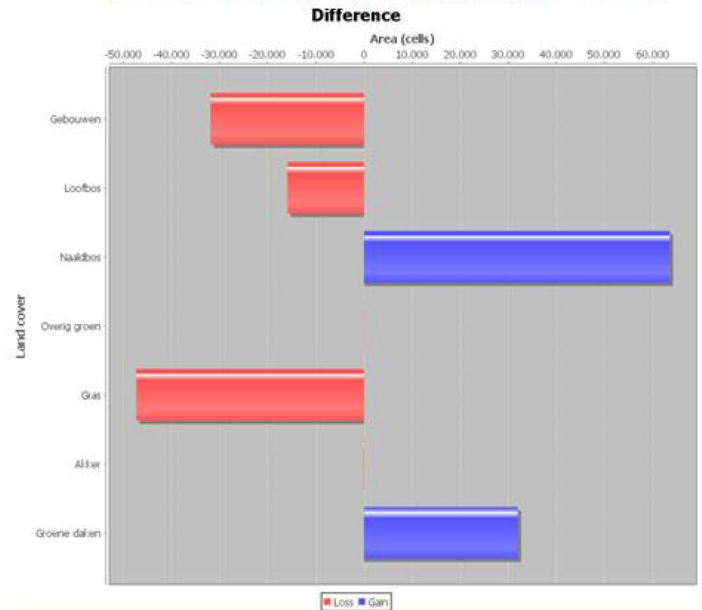
Figure A.4   Land cover difference map, presents current land cover vs. greening scenario based on changing the current land cover
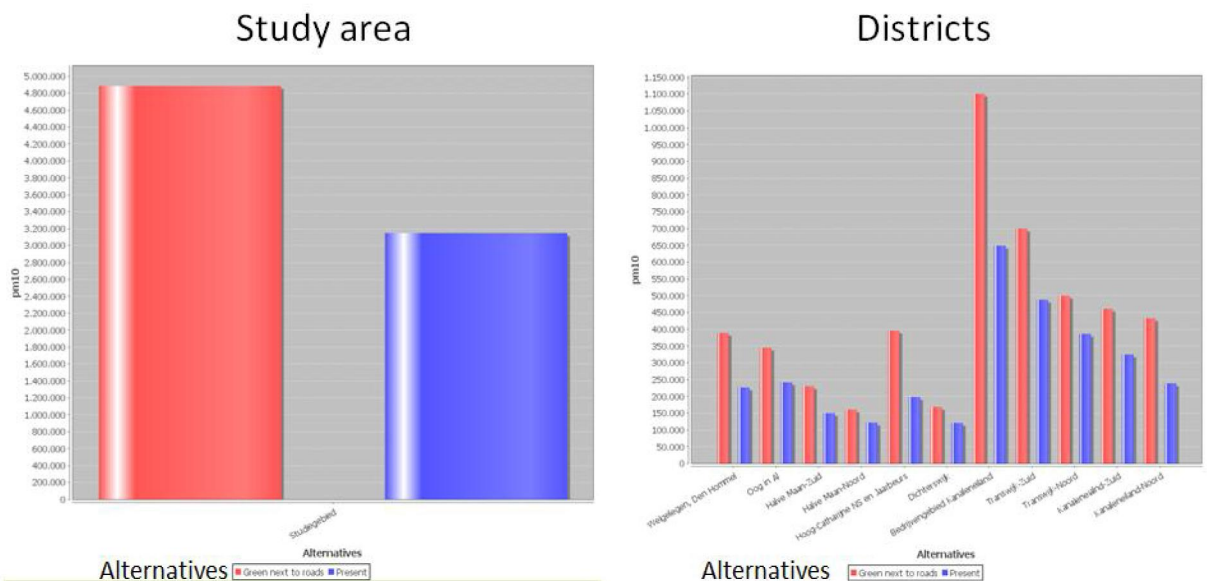
Figure A.5   Comparing the present situation (blue bars) with the greening scenario's (red bars) PM10 reduction capacity in g/25m² /year. The left bar chart summarizes the pm10 reduction for all of the study area. The right bar chart summarizes the pm10 reduction per neighbourhood. Note the high impact of the greening scenario on the pilot study district 'Bedrijvengebied kanaleneiland'

Figure A.6   Cooling effect of tree crown density under the scenario that current standing trees will grow optimally until 2050

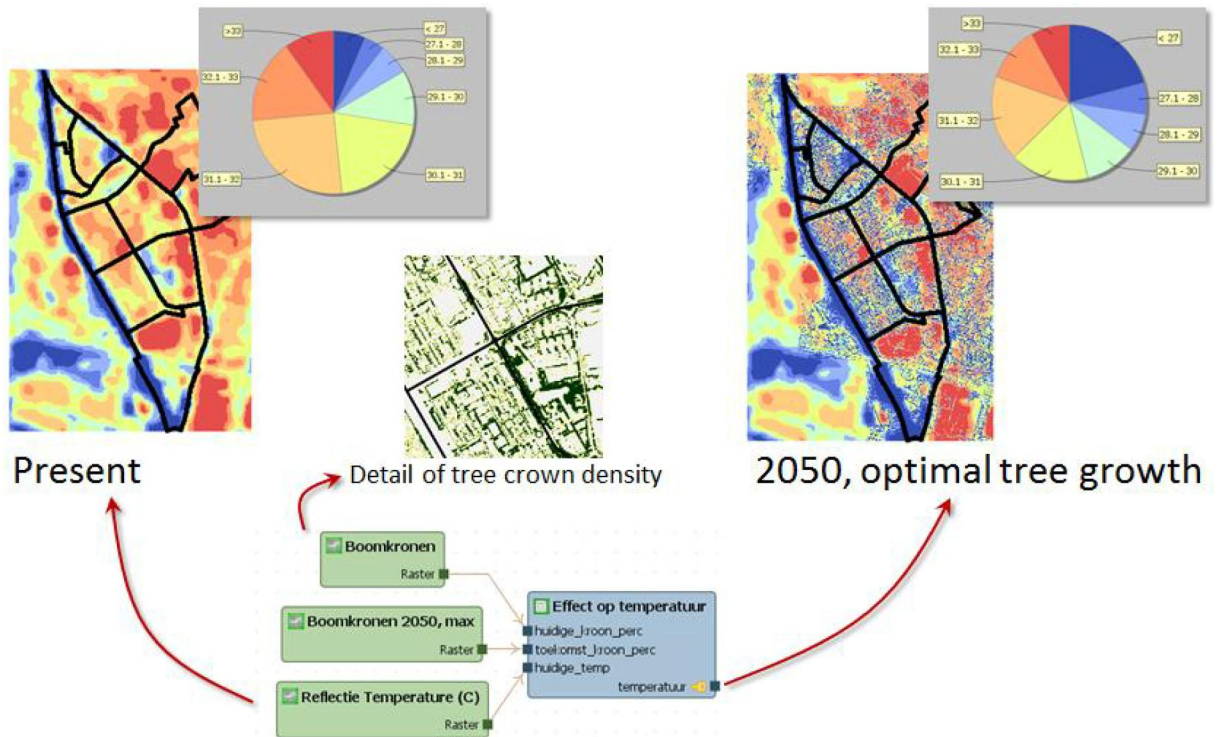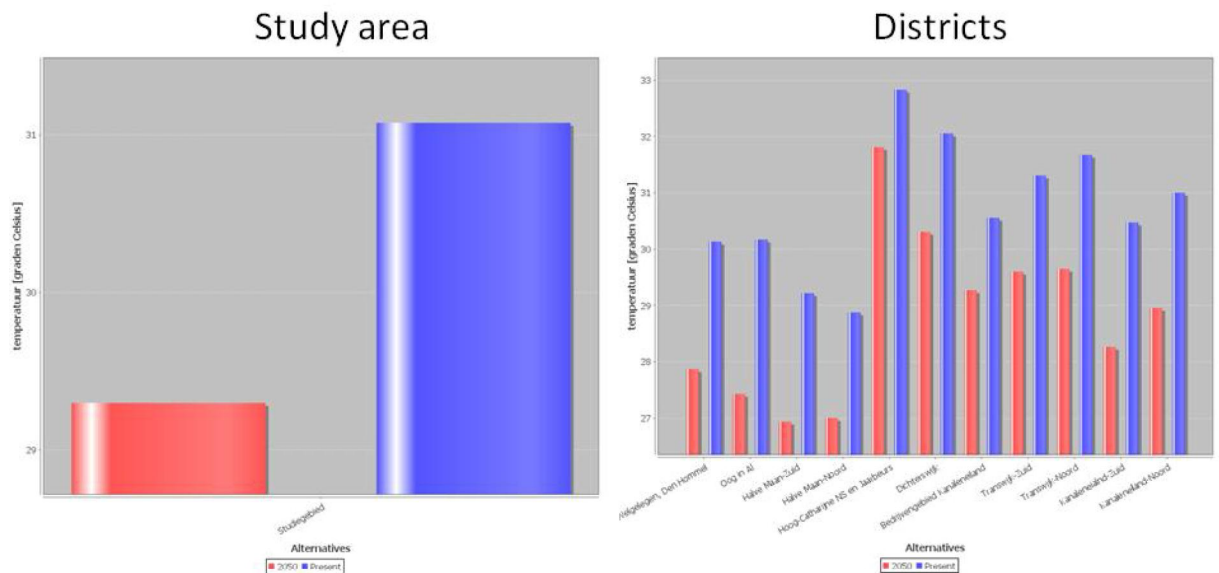*Figure A.7   Mean temperature on hot day in July: comparing the present situation (blue bars) with the greening scenario's (red bars). The left bar chart shows the mean temperature for the city of Utrecht. The right bar chart shows the results disaggregated per neighbourhood.*

geluid_dB \ Land cover : Stress

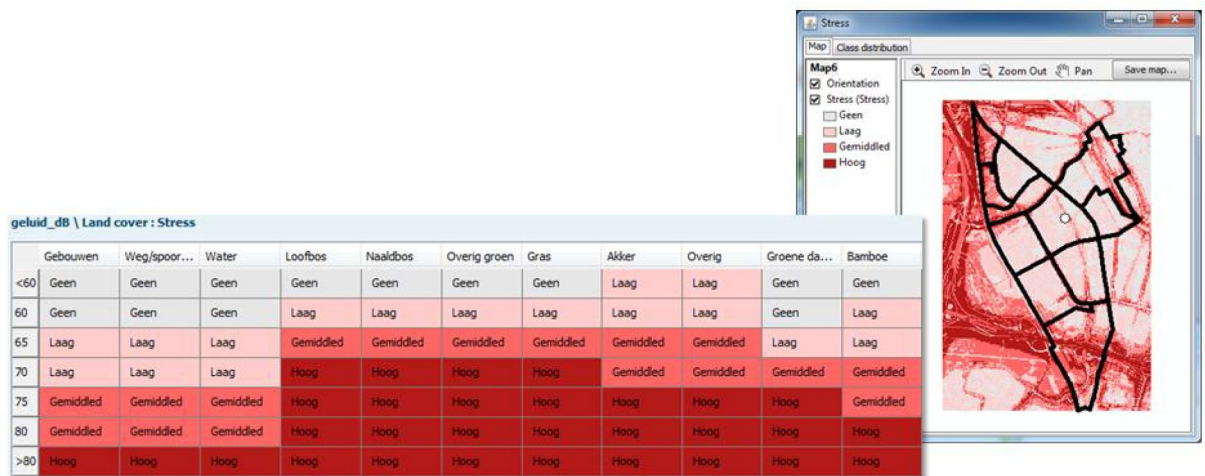|	Gebouwen	Weg/spoor...	Water	Loofbos	Naaldbos	Overig groen	Gras	Akker	Overig	Groene da...	Bamboe
<60	Geen	Geen	Geen	Geen	Geen	Geen	Geen	Laag	Laag	Geen	Geen
60	Geen	Geen	Geen	Laag	Laag	Laag	Laag	Laag	Laag	Geen	Laag
65	Laag	Laag	Laag	Gemiddled	Gemiddled	Gemiddled	Gemiddled	Gemiddled	Gemiddled	Laag	Laag
70	Laag	Laag	Laag	Hoog	Hoog	Hoog	Hoog	Gemiddled	Gemiddled	Gemiddled	Gemiddled
75	Gemiddled	Gemiddled	Gemiddled	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog	Gemiddled
80	Gemiddled	Gemiddled	Gemiddled	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog
>80	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog	Hoog

Figure A.8 'Stress by noise' rule, assigning qualitative values to noise (DB) depending on the surrounding land cover, as example of rules created by participants during the workshop.

.3 Evaluation of the workshop

General conclusions during workshop wrap up

- It was a useful experience to experiment in an area to see what the effect of a measure is in the area. Find out what the added value can be of green in areas where budget is available to do something. I am not sure if this makes sense for a new development site. But definitely useful.
- I was very critical, but I think that these are very useful instruments to use when policy decisions need to be made. However, I want to see the formulas of calculations before I trust the outcomes; it will enable me to estimate the sensitivities. That is something we can communicate. I am open to discuss with colleagues dealing with air quality.
- When I think about trees, I see more effects of trees than the ones we considered. I gained a broader view. It was a surprise to me that green roofs have little impact on heat stress. It is interesting to know what it really provides.
- It is all very global, while I normally deal with a very small piece. It is nice to have a quick insight in effects; it was very interesting.
- I like it that the tools are very interactive. It is interesting to see that it is possible to use figures in discussions. At a small spatial scale it is very uncertain.
- Suggestion: benchmark for different neighborhoods (e.g. for air quality). What are good examples?

Evaluation results from the questionnaires

Questions	Number of responses				
	Not usefull at all	Hardly useful	Medium	Useful	Very useful
How useful is the information that has been presented during the workshop?	0	0	1	6*	0
How useful is the information in the infographic on the effectiveness of green infrastructure?	0	1*	0	6	0
How useful is the information in the infographic on the design principles?	0	1**	3	1	1
The purpose of the infographic is to summarize all information that will also be included in the report. How would you prefer the infographic to be delivered? (multiple answers possible)	Digital (online)	Digital (as PDF)	Poster	A4-flyer	Other
	4	5	0	0	0
In which workshop did you participate?	AST	Quickscan	None		
	2	5	0	0	0
How useful is the information that has been provided in the AST-workshop?	not usefull at all	hardly useful	medium	useful	very useful
	0	0	0	3***	0
How useful are the results of the AST tool for spatial planning in the municipality Utrecht?	Well useful for quickly gaining a view on the consequences of the diversity of measures.				
	Only useful if we can use it at the moment that plans are developeed for a specific area.				
Do you have suggestions for improvement of the AST-tool?	(no answers)				
How useful is the information that has been provided in the Quickscan-workshop?	not usefull at all	hardly useful	medium	useful	very useful
	0	1	0	5	1
How useful are the results of the Quickscan tool for spatial planning in the municipality Utrecht?	For air quality in relation to green and heat stress usefulness is limited at this moment. Mainly because wind effects are not taken into account and scale effects unclear or not included in the model calculations. Howeveer, also willing to discuss and/or to receive clarification.				
	Difficult to say, depends on the information of the area that is being used as input and if we can discuss with other disciplines (urban development, plan economist, mobility expert etc).				
	Interactivity is useful in discussions.				
	Good to roughly show effects; support tool to show importance of types of green; fast application.				
	It is crucial that somebody knows the system and good input and data.				
Do you have suggestions for improvement of the Quickscan-tool?	It would be nice if the (for the audience not relevant) intermediate actions could be condensed.				
How can you and will you use the information from this workshop?	In project Defensieterrein, effect of large trees on reduction heat stress (if they can become e.g. 100 years old).				
	If possible, distinguish private/public space (demonstrate contribution of civiliaans to e.g. reducing heat stress).				
	As background information possibly useful to inform the municipality council.				
	Maybe use it in a project.				
	In my opinion, every litlle bit helps and 'a good 1 + a good 1 = 3'. So also if it is 0.01% that something can contribute to vitality of the city/ less air pollution we should still do it, especially because a green function provides an additional contribution to reduction of other nuisances and contributes to well being. i did not see much about that sum, I would like to see more about it.				
	The infographics: use them once they are ready as arguments pro green although some effects require further elaboration, for example based on the PHENOTYPE research project. AST: I don't know how we as municipality can use this. Do we rent the equipment and someone who can apply it?				
Other remarks:	*Comment related to workshop and Infographic: In general, may 'graphics' and limited 'info'. The pictures do not provide much directions for to approach of the problem. Due to the good oral explanation,it came to live.				
	**Comment to infographic, design principles: harldy useful for my discipline				
	*** (Person responds to the short presentation about AST) Concrete compared to Quickscan for smaller areas.				

Note: some participants of the AST workshop also shortly visited the Quickscan workshop and a short plenary presentation about the AST tool. As a result the number of responses can be higher than the number of participants. One respondent skipped question 2.