Technische Universiteit Delft

Towards climate resilient green-blue roofs

Defining the strengths and weaknesses of green-blue roofs regarding temperature management and water storage

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Thursday January 28, 2021 at 12:00h.

Student number:	4379306	
Project duration:	April 20, 2020 – January 28, 2021	
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Cover image: green-blue roof at the faculty of Civil Engineering of TU Delft.

Preface

Dear reader,

We live in a rapidly changing world in which one crisis follows another and new challenges ask for creative solutions. Climate change requires an adaptive attitude and a solution-oriented approach, but it is not always easy to take the necessary steps. At the same time, the year 2020, which was dominated by the Covid-19 crisis, taught the world that acting and adapting quickly is certainly one of our qualities. Only the will to change is required to accomplish the impossible.

With this study into the climate resistance of green-blue roofs, I will finish my master's degree in Water Management. I enjoyed the process, taking care of the green-blue roof at our faculty and the collaboration and discussions with my committee members. I have good memories of the days when Olivier and I, during lock-down, were one of the few who had access to the faculty to install measuring equipment and sensors on the roof. Thanks to the enthusiasm and hands-on attitude of Olivier, I even learned a lot about how to install an infrared camera. Furthermore, I would like to express my gratitude Marjolein and Susan for their constructive feedback and critical questions during the meetings we had.

Starting in lock-down, and ending in lock-down, I am now putting the finishing touches to this report. A result that I am proud of. I have learned the importance of being flexible and keep adapting to new circumstances, both in this research as in real life. But, I could not have performed this research without some support from my family and friends. I would like to thank my roommates Wietske, Sita and Vita for their support during my research. Together we made it fun to work from home while the university was closed. Also a great thanks to Maarten for his believe in me and for taking the time to read my report. Finally, I would like to thank my father for his input and the refreshing discussions that we had.

I hope you will enjoy reading this report. And remember: It's not only about green-blue roofs. It's about a green-blue living!

A. van Hamel
Delft, January 2021

Summary

To provoke the benefits of both green and blue roofs, green-blue roofs have been designed. A green-blue roof consists of a water storage layer with on top a substrate layer covered with vegetation. Due to the presence of the water storage layer, a green-blue roof is better capable of retaining heavy rain events. A movable valve makes it possible to manage the amount of water on the roof and the timing of drainage from the roof to the sewer system. In addition, the stored amount of water is made available to the vegetation layer via a passive capillary irrigation system. This could potentially result in a higher evapotranspiration rate and therewith a reduction of the sensible heat flux compared to green roofs.

Because of its qualities, green-blue roofs have been added to the list of measures that contribute to mitigation of the Urban Heat Island (UHI) effect and pluvial flooding. However, during dry summers a third climate related challenge arises namely drought. The question arises whether it is sustainable to increase the amount of vegetation in cities, as this increases the water demand during droughts. During long dry spells it can be challenging to store enough water for vegetation and cooling while keeping sufficient empty storage available at the same time. A conflict in water-related functionalities of the roof is the result. It was the aim of this thesis to investigate how implementation of green-blue roofs can be made climate resilient by defining its strengths and weaknesses regarding temperature management and water consumption and come up with possible ways to improve the roof system.

To investigate if the presence of a water storage layer enhances the cooling effect of a green-blue roof on the indoor and outdoor environment, a measurement campaign was conducted in the summer of 2020. Thermal fluxes at a green-blue roof and a conventional black roof were analysed, showing a clear cooling effect of green-blue roofs over black roofs. The contribution of the water storage layer of a green-blue roof to cooling was studied by comparing two situations with either an empty or full water storage layer. Measurements showed that for a full water storage, due to the increased heat capacity of water, the indoor environment was slightly less sensitive to sudden changes in the outdoor temperature and a delay in response was observed. On the outdoor environment an additional cooling effect of approximately two degrees close to the roof surface was observed as result of unlimited water availability. However, as the additional outdoor cooling effect remains mainly sensible close to the roof surface, the enhanced cooling effect at pedestrian/street level is expected to be minor. At the same time, any reduction of the air temperature just above the roof surface could be beneficial for the installment of solar panels or air intake for the indoor climate system in summer, but this should be investigated more.

To study the climate resilience of green-blue roofs, a bucket model was used in combination with climate data that was obtained from the KNMI. Based on the modelling results it was found that climate induced changes in precipitation and temperature will indeed lead to larger challenges regarding rainfall retention, heat mitigation and vegetation survival of green-blue roofs, especially in summer. Based on these findings, it is concluded that additional adaptation measures are required to make sure green-blue roofs can still contribute to a better and more resilient urban area towards the future.

Several measures are available to improve the performance on water retention and drought resistance, like valve management, enlargement of the storage capacity on the roof or on ground level and irrigation. Closing the water cycle locally is important to make green-blue roofs self-sustainable in water consumption, which reduces the risk on conflicts on water use during droughts. Only regarding UHI mitigation, other measures like creating shade could be more efficient as the enhanced cooling of the urban area due to unlimited water availability is small, unless large-scale application of green-blue roofs.

In the end its all about integration. A green-blue roof does not stand on its own: it's part of a building. Adaptation measures should not only make roofs climate-proof. By investigating possible interactions between the water storage and water- or energy related functions within a building, green-blue roofs could not only contribute to a climate resilient urban environment, but also to future-proof buildings.

Contents

1

Introduction

1.1. Current situation and challenges

Roofs, which represent sometimes up to 50% of the urban area [23], have received increased attention in the past decades and do no longer only serve to protect a building against rain and wind. They have become multi-functional and different roof systems have been designed such as green roofs (roofs with vegetation), cool roofs (white coloured roofs with a high albedo) and blue roofs (roofs with a water storage) [33]. Green roofs serve several purposes such as absorbing rainwater, providing insulation and reducing air temperatures [1, 8, 20, 23]. By replacing the existing impervious black cover with a substrate layer and vegetation, green roofs even contribute to the urban ecosystem as a natural habitat for insects and birds. Blue roofs, on the other side, are specifically designed to retain water on the roof surface and therewith decrease and delay the amount of runoff to the sewer system [20]. To provoke the benefits of both green and blue roofs, green-blue roof systems have been designed recently. A green-blue roof system is a combination of a green roof system (vegetated top layer) and a blue roof system (water storage layer below).

Since climate change and urbanization cause challenges in the urban environment, such as the Urban Heat Island effect (UHI) [33] and pluvial flooding [9], the application of green-blue roofs is one of the suggested mitigation techniques. The investment costs for the construction of green-blue roofs is higher than for green or blue roofs and more maintenance is needed [40]. But, by combining the benefits of green roofs and blue roofs, a green-blue roof system is better capable of retaining intense and heavy rainfall events. Due to the presence of both vegetation and water, a higher potential evapotranspiration rate could possibly cause a reduction of the sensible heat flux and therewith cooling of the micro-climate in urban areas [7, 8].

However, during dry summers a third climate related challenge arises which is still underexposed, namely (urban) drought. In periods of extreme temperatures, when the cooling effect via evapotranspiration is important, water stress can put restrictions on water consumption. The vegetation has to be kept alive when precipitation remains zero during long dry spells. Wilted and dried out vegetation looses part of its cooling effect as well as its aesthetic value and contribution to the urban ecosystem [41]. In some situations additional irrigation is required to protect the vegetation from dying, but this means that water has to be provided from elsewhere. The question arises whether it is sustainable to increase the amount of vegetation in cities, as this increases the water demand during droughts. In addition to the water demand during summer needed for vegetation and to provide cooling, sufficient storage capacity should be available to be able to capture sudden extreme rainfall events. As these also mainly occur during the summer months, a conflict in water functions arises. During long dry spells it will be impossible to store enough water for the vegetation and cooling and keep sufficient empty storage available at the same time. To guarantee sustainable water use, a fine balance is needed. A sustainable green-blue roof system should be able to manage water in such a way that as little water as possible is wasted, and preferable no external water sources are used. Understanding of the different elements, uncertainties and interactions within the roof system is crucial to increase the sustainability and climate resistance of green-blue roofs.

From the above it becomes clear that several questions regarding cost efficiency and future-proof implementation of green-blue roofs remain unanswered. Although a lot of research has been performed on the effects of green roofs on their environment, less is known about the performance of green-blue roofs on cooling. Especially the interaction between the green and blue layer is underexposed. In addition, it is unknown how climate change will effect the future performance of green-blue roofs and what challenges should be expected to arise. How future-proof are green-blue roofs and will they still manage to retain extreme rainfall and provide cooling towards 2050? This lack of knowledge makes it more difficult for decision-makers, like roof owners and municipalities, to support (large scale) implementation of green-blue roofs. Scientific substantiation is needed to demonstrate the qualities of green-blue roofs on managing the temperature of the indoor and outdoor roof environment, as well as the effects on the local water cycle and water use. Now and towards the future.

1.2. Research objective

It is the aim of this thesis to provide a better understanding of the cooling effect and water consumption of green-blue roofs. Understanding how green-blue roofs interact with and respond to heat waves, extreme rainfall and drought, also towards the future, is important to be able to define the strengths and weaknesses of green-blue roofs. When future challenges have been identified, it will be possible to come up with solutions that might contribute to a more climate resilient roof system. The final objective of this research is to provide knowledge that supports climate resilient and worthwhile implementation of green-blue roofs. To summarize the objective in one sentence, the main objective is: *to investigate how implementation of green-blue roofs can be made climate resilient by defining its strengths and weaknesses regarding temperature management and water consumption and come up with possible ways to improve the system*.

In the attempt to achieve this objective, three main questions have been defined that focus on (1) the effect on temperature, (2) future water storage and water consumption and (3) ways to make the roof system more resilient to climate change towards 2050. The main research questions are defined as follows:

1. What is the contribution of the water storage layer to the cooling effect of a green-blue roof?
2. Which elements and uncertainties play an important role in making green-blue roofs, with a water storage capacity of 60 mm, more climate resilient and sustainable with respect to water consumption?
3. What are suggested improvements to make implementation of green-blue roofs more resilient to climate change towards 2050?

The first part of this research will investigate the cooling effect of the green-blue roof of the Faculty of Civil Engineering at Delft University of Technology on its indoor and outdoor environment. The major focus will be on the possible contribution of the water storage layer to the cooling effect. The cooling effect is defined as the temperature difference between the green-blue roof and the conventional roof for both the indoor as the outdoor roof environment.

The second part of this research focuses on the water consumption and storing capacity of green-blue roofs. The maximum storage capacity of the roof depends on the thickness of the water storage layer, which is set on 60 mm within this study. By taking into account climate predictions and the different functions of the roof system, the climate resistance and future performance of green-blue roofs is studied. This will result in essential knowledge that can be used to optimize the implementation of green-blue roofs.

The last part of this research will combine the findings regarding the cooling effect and water consumption to define the strengths and weaknesses of the green-blue roof system towards the future. Based on the obtained insights, improvements of the roof system are suggested to make the roof more climate resilient.

1.3. Research scope

This research will be executed in the Netherlands, under the conditions of a Dutch climate. Part of the research data will be collected via a measurement campaign on an existing green-blue roof which is located at the faculty of Civil Engineering at Delft University of Technology. The measurement campaign took place during the summer months of 2020 and the main focus during this research is therefore restricted to summer conditions. Additional data is provided by the KNMI, which is the Dutch national weather service. Due to the high variation in climate globally, this research will be most representative for other regions with a comparable climate to the Netherlands.

1.4. Reader guide

To start with, Chapter 2 will give an introduction to different roof types and their qualities within an urban environment. In specific the functions and different components of green-blue roof systems are explained, as well as definitions like the UHI effect and pluvial flooding.

The following three chapters will all focus on one of the three research questions. Chapter 3 discusses the impact of green-blue roofs on temperature, with a main focus on the contribution of the water storage layer. This chapter is build up in a logical order, starting with the relevance of the topic followed by the methodology that is used to come up with an answer. A roof experiment is conducted by making use of two roofs, a green-blue roof and a conventional black roof. After presenting the most important results, it becomes clear how water can play a role in enhancing the cooling effect of green-blue roofs, compared to black and green roofs. The results are followed by a discussion.

Chapter 4 is built up in the same way as Chapter 3 but gives an answer to the second research question. The effect of climate change on the roof performance is investigated by making use of a designed bucket model (hydrological model) that can simulate a green-blue roof. The results show how the response of the roof is expected to vary for different climate scenarios and what challenges can be expected to arise.

Chapter 5 discusses possible improvements that can contribute to making green-blue roofs more climate resilient and future-proof. Several measures can contributed to improving the water-related functions of a green-blue roof. By taking into account findings from Chapter 3 and Chapter 4, a discussion is started about which measures might be more efficient then others.

In Chapter 6 all the findings are wrapped up and conclusions have been drawn. The main take away is to approach green-blue roofs not as a separate measure to solve current challenges in the urban environment, but to see them as being part of something bigger: part of a building, a neighbourhood, a city, etc. By integrating several functions within the building with functions outside the building, different measures might become the most efficient. The report concludes with a number of recommendations.

2

Green, blue and white roofs

This chapter will give an introduction to different roof types and their qualities within the urban environment. After a short introduction to the most common roof types, we will focus in specific on the qualities of green-blue roofs. Also definitions like the Urban Heat Island (UHI) effect and pluvial flooding get explained and how roofs can interact with these urban challenges.

2.1. Multi-functionality of different roof systems

Conventional roofs, with their impervious black cover, partly contribute to urban challenges such as the Urban Heat Island (UHI) effect and pluvial flooding, but they also provide room for solutions. As a large percentage of the urban area, up to 50%, consists of roof surfaces [23], roofs have a great potential to mitigate these challenges. Suggested mitigation techniques include different roof systems, such as green roofs, white roofs and blue roofs (see Figure 2.1).

Green roof systems consist of a substrate layer with vegetation and underneath a thin drainage layer to drain water away. The type of green roofs are very divers, depending on the type of vegetation, the soil media and its depth. The most common green roofs are *extensive roofs* which have a substrate layer between 5 and 20 cm depth and allow for mosses, sedum, grasses and other drought resistant vegetation types to grow. The small soil depth keeps the additional load from the green roof minimized. *Intensive roofs* form the other end of the spectrum. With a thick layer of soil (>1m) shrubs and trees are able to grow on this type of roofs, which makes them also attractive for a roof terrace. Although the aesthetic value of a roof garden might be higher, a thicker substrate layer also results in higher loads and construction costs. Therefore extensive roofs are more often selected for implementation, especially on existing buildings that initially were not designed to carry high loads.

Blue roofs are designed to retain water on the roof surface and thereby they decrease and delay the amount of runoff to the sewer system [20]. The amount of storage depends on the constructional design of the roof. Blue roofs can be classified as *active* or *passive* depending on the control system that is used to regulate drainage. Active systems make use of a mechanical valve that is controlled by an automated system. This control system manages the amount of water that is stored on the roof and the timing of drainage. Passive systems do not intervene in the drainage other than by lengthening the path the water must take in order to reach the outlet drain. By using modular trays or slow-releasing roof dams, the water is forced to pond on the roof. Water remains stored on the roof until it either gets evaporated or passive/active released to the drainage system. Unlike green roofs, blue roofs have no aesthetic value and they operate often without the building users being aware of the system.

White roofs are conventional black roofs that are painted such that they get a high albedo and reflect incoming solar radiation. In contrast to blue and green roofs, white roofs do not necessarily need to be flat. Since white roofs are mainly designed to mitigate heat, they are also referred to as *cool roofs*.

Earlier studies have resulted in a better understanding of the different roof type systems and their contribution to insulation, water retention and the effect on the urban microclimate, which are seen as their main functions. These effects are explained in the sections below.

Figure 2.1: From left to right: a white roof with a high albedo value [37], a blue roof with water storage capacity [16] and an intensive green roof with a large diversity of vegetation types [21]

2.1.1. Insulation by green roofs

Green roofs provide insulation due to the presence of the vegetation layer. Based on the thickness of the substrate layer, green roofs have a higher insulation potential which reduces the energy consumption for buildings [8]. During summer, insulation can keep the indoor temperature more comfortable, as Gaffin et al. [13] reported an indoor temperature which was on average 2 degrees cooler below a green roof in Pennsylvania than below a reference roof without green coverage. During winter, vegetation is used to increase the thermal insulation and protect the inside for the cold climate. Green roofs are therefore very common in for example the Nordic countries [44]. A better insulation of the roof protects the indoor environment from extreme temperatures and fluctuations, both warm and cold. This protection is provided by a number of thermal phenomena, such as solar shading by the vegetation, evapotranspiration, high plant albedo and the thermal resistance of the substrate layer. Dynamic energy simulations have suggested that a reduced heating consumption of 5% and a reduced cooling consumption of 16% could be achieved by implementing green roofs in city blocks in Greece [23]. The reduced amount of energy needed results in direct benefits, whereas the comfort of the indoor environment is also improved.

2.1.2. Water retention by blue and green roofs

Blue roofs are specifically designed to retain water on the roof surface and therewith decrease and delay the amount of runoff to the sewer system [20]. Depending on the type of drainage system (active/passive) that is used, the amount of stored water and the moment of draining can be controlled. When a mechanical valve is used, the water could be stored on the roof until the rain event has passed, which reduces the pressure on the existing sewer system during peak flows.

Besides blue roofs, also green roofs are able to retain and delay rainfall. The rainfall retention of green roofs depends on the type and thickness of the substrate, and can be 45% [23] or up to 50% [44] of the total precipitation. This means that half of the annual rainfall is not directly drained away to the sewer system, but retained in the substrate and evaporated. In a way, green roofs are passive blue roofs that lengthen the drainage path of the water, since water first needs to percolate through the substrate layer before it can drain away. Some of the water will be used by the vegetation, results in a higher moisture content of the substrate or evaporates.

The prior moisture content is strongly related to the effectiveness of storm water retention and can be used as a good predictor for water retention [39] of green roofs. When the substrate is almost saturated prior to a rain event, the retention capacity is much less than for a dry substrate. When comparing the water retention performance of green roofs in different climates, the drying rate of the substrate and the soil moisture content prior to a new rain event are stronger related to the level of water retention, rather than the differences in precipitation distribution. However, this is not the case for active blue roofs and green-blue roofs, as the storage capacity of these roof systems depends on the depth of the water storage layer and the water level prior to the rain event, instead of the soil moisture content.

2.1.3. Cooling of the urban microclimate by green and white roofs

The urban microclimate is defined as the local climate in an urban area, influenced by moisture, temperature, wind speed and direction near the ground. Since some roof systems reduce the air temperature around the roof, they affect the urban microclimate [1, 8, 20, 23]. Due to the presence of vegetation, heat can be released via evapotranspiration. The cooling effect of green roofs is largely affected by wind speed, solar radiation and climate conditions [1], but also water availability plays a decisive role in the actual rate of evapotranspiration. Gaffin et al. [13] measured a surface temperature difference between a black roof and a green roof of 40 degrees in Pennsylvania State at a summer mid-day, while on average the green roof surface was 19 degrees cooler during day and 8 degrees warmer at night. The presence of vegetation on green roofs makes the conditions on a roof less harsh and this even results in better circumstances for urban ecosystems that provide natural habitats for insects and birds. Additional irrigation of a green roof increases the actual evapotranspiration and therewith reduces the sensible heat flux and external roof surface temperature [7, 8]. As shown by Kaiser et al. [22], irrigation of extensive green roofs could reduce the temperature by up to 10 degrees at the roof surface and up to 4 degrees on average at the water proof membrane, in comparison with non-irrigated roofs.

At the same time, the cooling effect of a white roof should also not be underestimated. Solcerova et al. [41] found that the cooling effect at night time was less strong than the daytime warming for a sedum-covered green roof relative to a white gravel roof. This resulted in a net warming effect of the green roof on the surrounding environment over the whole 24h period, relative to the white gravel roof. Also Costanzo et al. [8] showed that cool roofs with an albedo >0.65 are more effective in reducing the sensible heat flux and external roof surface temperature than green roofs. However, compared to conventional roofs, the cooling effect of green roofs is still visible and Solcerova et al. [41] points out that water availability in the substrate seems to play an important role in the cooling effect of the vegetation on air. Whereas white roofs cool the air above it, they do not generate other beneficial properties as can be found for green roofs, such as an increased insulation capacity, a higher aesthetic value and the contribution to the urban ecosystem by providing a habitat for insects and birds.

2.2. Green-blue roofs

While extensive research has been done on the performance of green roofs, less is known about the performance of green-blue roofs. A green-blue roof system is a combination of a green roof system (vegetated top layer consisting of substrate and planting) and a blue roof system (water retention buffer below), see figure 2.2. A green-blue roof system combines the benefits of green roofs with a higher water retention capacity of a blue roof, and therefore a green-blue roof system is better capable of retaining intense and heavy rainfall events. Via a capillary irrigation system, stored water is kept available for the vegetation layer on top until the water is evaporated or actively drained away. A movable valve makes it possible to manage the retention or drainage of the water.

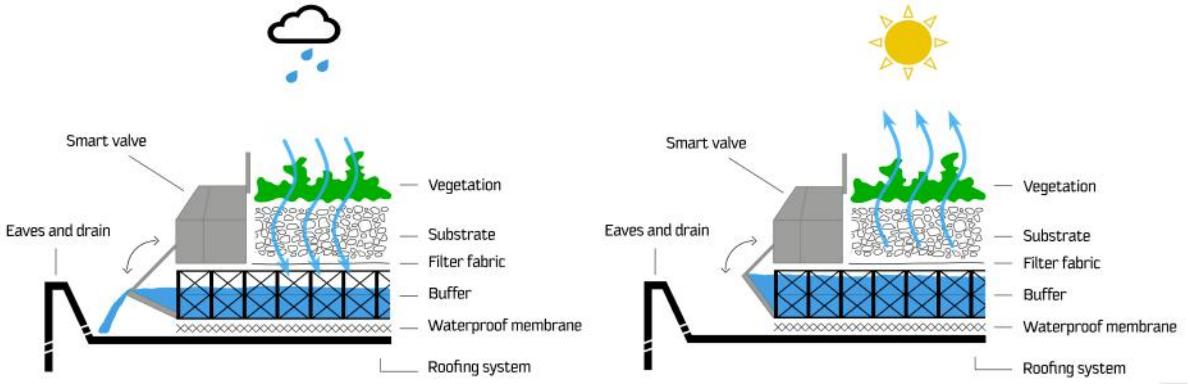

Figure 2.2: A green-blue roof system contains of a green top layer with substrate and planting and a blue layer where water can be stored. When the valve is closed, water is stored in the blue storage layer and kept available for the vegetation layer via a capillary irrigation system so it can be used for evapotranspiration (left). Rain infiltrates through the substrate and ends up in the storage layer. When the valve is open, the water is drained away (right).

During hot and dry periods, in contrast to green roofs, the additional stored water delays the evapotranspiration reduction and decrease of latent heat flux [7]. This is important since there is the risk of wilting and drying out of vegetation during dry spells. To meet the potential evaporation and reach the most optimal cooling effect, sufficient water must be stored. The size of the required water storage depends on the evaporation rate of the vegetation and local climate conditions, but a larger storage results in larger loads which the building must be able to carry. How the water storage and consumption is affected by climate change is studied in more detail in chapter 4. Currently, green-blue roofs are suggested as a suitable mitigation technique for the Urban Heat Island effect and to prevent pluvial flooding. How green-blue roofs can play a role in the mitigation, is explained in the sections below.

2.2.1. Urban heat island effect

The Urban Heat Island (UHI) effect is a phenomenon that affects cities and people all over the world. Urban areas experience a significant higher temperature compared to the surrounding rural areas, which has negative consequences for the health and well-being of people living in cities. The UHI can be illustrated by drawing a curve from one side of a city to the other, mapping the temperature change from the rural to the urban environment and back to the rural environment. The 'island' would be represented by a large peak above the urban areas, while the rural surrounding experiences less high temperatures. The increased use of man-made materials with a low albedo and high solar absorption together with the increased anthropogenic heat production are the main causes of the UHI [33]. Also the geometry of urban areas plays a role, as heat is captured between high buildings and the scarcity of air circulation hinders the release of heat. Since the global temperature is rising due to climate change and urbanisation moves the worlds population to cities, the challenge to mitigate the UHI effect is becoming even more relevant.

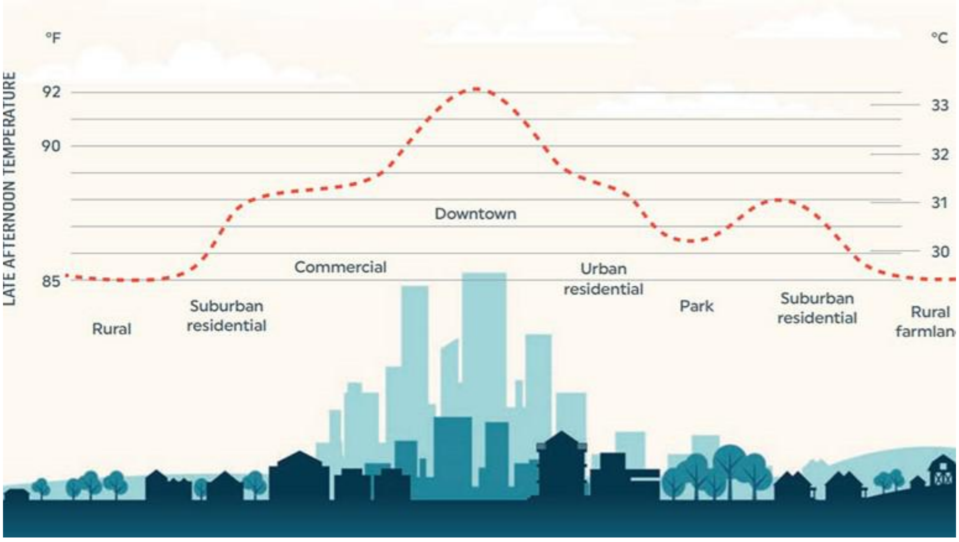

Figure 2.3: The urban heat island profile. The 'island' would be represented by a large peak in air temperature above the urban areas, while the rural surrounding experiences less high temperatures. [45]

The UHI effect has a great impact on the livability of urban areas. High temperatures can result in discomfort and health problems such as a significantly increased level and risk of illness and even mortality [43]. Other consequences of UHI are the increase in water consumption and the increase in electricity demand for cooling. Air conditioners do not only use energy, but by cooling the air indoors additional heat is released to the already warm outdoor urban environment. High temperatures also have a strong impact on urban ecosystems and results in a degradation of the living environment. The UHI effect on the air temperature is the highest during night, while during the day also the high physiological equivalent temperature (PET) can cause much discomfort.

Measures to mitigate the UHI effect have been well studied and well documented [33]. Key measures to reduce the air temperature focus on the cooling effect of wind and water. In a Dutch climate an increase of 10% in green and blue areas results in 0.5 degrees cooling [25]. By making the surfaces more permeable, porous and water retentive, cooling can be enhanced and also the implementation of cool surfaces by increasing the albedo is a suggested mitigation technique. Although a multifaceted approach is desired, several studies emphasize the potential of green-blue roofs [1, 8, 33].

2.2.2. Pluvial flooding

As a consequence of climate change, annual precipitation in the Netherlands is rising as well as the intensity and occurrence of extreme rainfall. On average the precipitation extremes in the Netherlands have increased in the past 50 to 100 years. The annual precipitation in the Netherlands rose by approximately 26% between 1910 and 2013. In addition, observations suggest that the hourly intensity of extreme rainfall events will increase with approximately 12% for each degree of global warming [30].

Urban areas are particular vulnerable to extreme rainfall due to the large percentage of impermeable surfaces, such as roads, roofs and pavements that generate increased surface runoff. In addition, the existing drainage systems are not designed for such a climate-change-induced increase of intensity and frequency of rainfall events. As a consequence, pluvial flooding has become an increased risk for urban areas. When runoff exceeds the capacity of the drainage system, water nuisance is the result. In case of a combined sewer system, where rainwater and sewerage are drained together, serious water pollution due to sewer overflow form a risk for the urban environment. Pluvial urban flooding may lead to large-scale economic damage and hindrance. Not only buildings and interiors are affected, but also traffic congestion, malfunctioning of the public transport, data and telecom cuts could be consequences. Pluvial flooding may also induce irregularities in the provision of electricity [5, 9].

As a reaction on the changing conditions, Dutch municipalities have decided to focus more on climate adaptability. The city of Amsterdam, for instance, started the project *Amsterdam Rainproof* with the objective to be fully rainproof by 2025 [2], and also Rotterdam and Utrecht want to prevent pluvial flooding towards the future [14, 15]. From the different adaptation plans it becomes clear that the dutch approach will focus more on the capturing and storing of rain water, instead of immediately discharging the abundance of water. Since technical solutions like increasing the sewer systems capacity are very costly, new green-blue measures are introduced such as water storage on streets, on roofs, in gardens and in parks by installing wadi's, green-blue roofs, water squares, etc. Because the above mentioned measures often affect private property, it is important for municipalities to cooperate with residents and property owners. It can be concluded that the relevance of research on green-blue roofs is clearly presented in the current Dutch water management approach.

3

Impact of green-blue roofs on temperature

3.1. Introduction

Due to the presence of vegetation and water, green-blue roofs allow for higher potential evapotranspiration which could have a cooling effect on its environment. Within this report, the cooling effect is defined as the air temperature difference between a green-blue roof and a conventional black roof for the indoor or outdoor environment. The cooling effect is high when the air temperature around a green-blue roof is several degrees lower than for a conventional black roof. However, the extent to which the cooling effect is noticeable by people, and whether this is sufficient to make implementation of green-blue roofs cost-effective, is subjective and differs for every situation. In general, the investment cost for the construction of green-blue roofs is higher than for green or blue roofs and more maintenance is needed [27]. This could be an obstacle for roof owners and municipalities to support (large scale) implementation of green-blue roofs. Scientific substantiation is therefore important to demonstrate possible qualities of green-blue roofs on managing a cooler indoor and outdoor temperature at the building on which it is applied.

Research objective and questions

Although several research projects have been performed to study the cooling effect of green roofs on its environment, less is known about the performance of green-blue roofs. Especially the interaction between the green and blue layer is underexposed. To fill this knowledge gap, we will investigate the cooling effect of green-blue roofs within this chapter, with the major focus on the possible contribution of the water storage layer to the cooling effect. The main objective is captured in the following research question:

What is the contribution of the water storage layer on the cooling effect of a green-blue roof?

To support the main research question, four sub-questions have been formulated:

1. What is the cooling effect of a green-blue roof system compared to a conventional black roof on the indoor and outdoor roof environment?
2. How does the temperature vary within different layers of a green-blue roof system for a full and an empty water storage layer?
    (a) What is the cooling effect on the outdoor air temperature at different elevations above the roof surface?

   (b) What is the cooling effect on the indoor air temperature?
   (c) What is the cooling effect on the temperature of the roof surface, the substrate layer and the water layer?

3. Is there a relation between the cooling effect of green-blue roofs and the presence of water in the water storage layer?

Within this chapter it is the aim to formulate an answer to the questions above. To be able to answer these questions, first the methodology is described in section 3.2 leading to a comprehensive data set. In section 3.3 a general comparison is made between the cooling effect of a green-blue roof and a conventional black roof based on the obtained data. In section 3.4 the data is analysed for two specific periods in time for which the water storage layer was full or empty. This gives more insight in the effect of the water storage layer on the cooling effect of the indoor and outdoor environment of a green-blue roof. The results are discussed in section 3.5.

3.2. Temperature measurements at a green-blue roof

In this section the applied methodology is described. This study makes use of a real case where the thermal behaviour of two identical roofs, a green-blue roof and a conventional roof, are compared (section 3.2.1). A roof experiment is conducted to collect information about the relevant fluxes, for which on-site measurement devices have been installed (section 3.2.2).

3.2.1. Case study: green-blue roof and reference roof

This research makes use of two identical roofs that are located on top of the faculty of Civil Engineering at Delft University of Technology, the Netherlands (51.999° latitude 4.376° longitude). Both roofs are oriented in the southwestern direction, have a surface of 530 m^2 and are located at an elevation of ca. 9 m (Figure 3.1a). The reference roof is located on top of lecture hall A and B and consists of a black surface layer with direct run-off to the sewer system. A green-blue roof system is constructed on top of lecture hall C and D. Both roofs face shade from the adjacent building during the morning, but around noon the sun is able to reach both roofs at the same time.

(a) View from the top of the green-blue roof

(b) Topview of faculty building

Figure 3.1: (a) The reference roof (in orange), which is located 50 meter towards the north, has equal size and orientation as the green-blue roof (in green) from where this picture was taken. (b) Topview of the faculty building with the location and orientation of both roofs.

The green-blue roof system consists of a substrate layer with vegetation, a water retention layer and a controllable outflow valve (see Figure 2.2, Section 2.2). The water storage layer gives room to 60 mm of water, which is equivalent to about 32.000 litres of water that can be stored on top of this particular roof.

(a) Diverse vegetation types

(b) Sedum vegetation

Figure 3.2: (a) The vegetation layer is covered by various types of vegetation like different herbs, grasses and small vegetables have been planted. (b) Sedum vegetation on the green-blue roof

By lowering the valve, the water storage depth can be reduced, but during this study it was decided to keep the valve closed. On top of the plastic crates, of which the water storage layer consists, a filter fabric prevents the substrate of being flushed into the water storage layer. The substrate layer has a thickness of 10 cm and gives room for vegetation to grow. By adding mineral wool at multiple places to the plastic crate structure, the water from the storage layer is also made available to the substrate layer and the vegetation via passive capillary irrigation.

The green-blue roof is covered with various vegetation types like sedum, herbs, grasses and even small crops. The diversity in vegetation is visible at Figure 3.2a, showing a plant mixture with e.g. chives, lavender, garlic, pods, radish, strawberries and thyme. See Appendix C for more details and impressions of the large variety of vegetation types that can be found on the green-blue roof. The outer band of the roof surface is mainly covered by several sedum types as is shown at Figure 3.2b.

3.2.2. Roof experiment with on-site measurements

During a multi-week measurement campaign the behaviour of both the green-blue roof as the reference roof are studied under different conditions to investigate the cooling effect. It is expected that net radiation, wind speed, air temperature and humidity will vary over time, while the water availability for evapotranspiration remains unconstrained during a period with a full water storage. However, when the water storage becomes empty (water depth equals 0mm), the empty water storage layer will be like a stagnant air layer which is expected to function as an insulation layer within the roof system. Additionally, the soil moisture is expected to decrease as a result of evapotranspiration and vegetation will start to face water stress. First the measured fluxes are explained and summed up shortly. Afterwards, the roof experiment is explained in more detail. The results of the roof experiment and the effect of (un)limited water availability on temperature is analysed and studies in the next sections.

On-site measurements

The measurement campaign lasted from June 16th til August 24th in the summer of 2020. Despite some complications during the data collection, the final data set was comprehensive and covered varying weather conditions. By installing on-site measurement devices, the following fluxes have been monitored during the measurement campaign. Specifications about the used measurement devices can be found in Appendix D.

Air, water and substrate temperature

To study the thermal interaction of the roof with its surrounding, the air temperature is measured every five minutes by temperature sensors on, in and below the roof system. To measure the effect of the roof system on the outdoor air temperature, eight TMCx-HD temperature probes were installed, four on each roof, at respectively 20, 40, 80 and 160 cm above the roof surface. At the reference roof the temperature sensors at 40 and 80cm elevation have not been functioning well, providing us only with temperature fluctuations at 20 and 160cm above the roof surface. There were no problems observed at the air temperature sensors at the green-blue roof. The indoor room temperature is captured by a total of twelve temperature sensors (HOBO TidbiT MX2204 temperature loggers), three in each lecture hall, that were located just underneath the roof. Due to the Covid-19 epidemic the lecture halls were not in use and for the entire duration of the experiment the indoor climate system was switched off. This resulted in limited air circulations and the indoor temperature was measured without disturbances from inside. This was beneficial to be able to compare the conditions below both roofs. However, it should be realised that under normal conditions the climate system refreshes the indoor air and the presence of people causes turbulence of the air and warming. Lastly, the temperature is also measured at different layers within the green-blue roof by installing one TMCx-HD temperature sensor in the substrate layer and one in the water storage layer.

Infrared radiation from the roof surface

In addition to the measured temperature at different elevations above both roofs surface, the temperature of the roof surface itself is monitored as well. Two infrared cameras (FLIR A310 IR temperature sensor) were used for this. Emitted infrared radiation from the green-blue roof and the reference roof was captured every three minutes by two infra red cameras which were secured at the outside of the adjacent building on an elevation of approximately 15 m above the roof surfaces. This elevation provided a clear view on a significant part of both roofs. In combination with the emissivity of the surface, the amount of infrared radiation emitted by the roof surface is translated to the surface's temperature. Unfortunately, the cameras faced several technical problems during the roof experiment, which resulted in an incomplete data set. However, during the heat wave (the beginning of August) the cameras worked properly again, providing us with maximum roof surface temperatures during this extremely warm period.

Precipitation

Precipitation is measured by a total of eight tipping buckets (HOBO Rain Gauge Data Loggers) which are located on the green-blue roof and the reference roof. The tipping buckets have a resolution of 0.2mm. Tipping bucket 2, 3 and 8 stopped working very rapidly, whereas tipping bucket 6 and 7 continued working until the 6th of July. Only tipping bucket 1, 4 and 5 kept measuring until the 23th of July. The mutual differences in measured rainfall intensities showed to be negligible, as the tipping buckets were all located within two hundred meters from each other.

Evapotranspiration

Evapotranspiration is defined as the sum of transpiration, soil evaporation and evaporation from canopy interception, expressed in mm per unit time. Evapotranspiration strongly depends on water availability and net radiation. Evapotranspiration results in a decrease of water depth in the water storage layer and/or a decrease of soil moisture in the substrate layer. To measure the actual evapotranspiration at the green-blue roof a simple lysimeter was constructed, which had to be read out manually on a daily basis. This was done for a period of 5 weeks resulting in 20 measurements of daily evapotranspiration. The measured values of actual evapotranspiration have been compared with the daily reference evapotranspiration collected by the KNMI at Rotterdam Airport (at ca. 7 km distance). Additional details about the construction of the lysimeter and the lysimeter measurements can be found at Appendix A.

Water storage and outflow

On the green-blue roof, the water depth of the water storage layer was measured by an ultrasonic water depth measurement device. The water depth was controlled by an adjustable valve and can vary between 0 mm (open valve) and 63 mm (closed valve). With a closed valve the water depth can decline due to water loss by evapotranspiration. When the valve is opened, the remaining water flows of via drainage pipes to the sewer system. It is noticed that, even for a completely open valve, ponding on the roof occurs up to a water depth of 25 mm. This is a result of a not perfectly horizontal aligned roof surface and in addition the open valve still forms a small threshold for the water to run off. At the reference roof the water depth can not be controlled and rainwater will directly run off by gravitation to the sewer system. Some water will remain ponding and partly evaporate. The outflow discharge from the green-blue roof and the reference roof to the sewer system was measured by an OPTIFLUX 2050 C/W Electromagnetic flowmeter with a resolution of 5 liters.

Wind speed, humidity and radiation
At a small weather station on top of the green-blue roof wind speed and humidity were measured at 60 cm elevation above the roof surface, although not at the reference roof. The wind speed was expected to be the same for the reference roof as for the green-blue roof, as both roofs have the same orientation and are shielded from the wind in a similar way by the adjacent building. The humidity might have been divergent for the green-blue roof compared to the reference roof, since the green-blue roof is able to loose energy via evapotranspiration. However, it is assumed that this will already be captured by the surface temperature differences between the two roofs. Solar radiation is not measured at the roof location but this data is obtained from the Rotterdam Airport weather station of the KNMI at 7km distance. It can be assumed that the differences in daily solar radiation between both locations are small since they have the same orientation and are located next to each other.

Soil moisture
If the water storage layer is empty, this does not directly imply that there is no water available for evapotranspiration, since the substrate and vegetation will still contain water. To measure these variations, three soil moisture sensors of the type EC5 Soil Moisture Smart Sensor S-SMC-M005 were installed in the substrate. Soil moisture was only measured at the green-blue roof.

The roof experiment
From the 16th of June until the 24th of August of the year 2020, a multi-week roof experiment was conducted at the green-blue roof and the reference roof to collect sufficient data for this research. Since the roofs are located in open air, the weather had a great influence on the roof experiment and made it important to anticipate on the weather forecast during the experiment. To be able to answer the research question it was desired to study the behaviour of both roofs under different conditions and also compare periods for which the water storage layer at the green-blue roof was either empty or full of water.

Prior to the start of the roof experiment the water storage was completely filled up. But already after two days it was decided on the 17th of June to empty the water storage and make use of the predicted dry and warm weather to create a dry-out event. By opening the valve, the water level in the storage layer dropped rapidly and the water was discharged to the sewer system. However, the last 25mm of water remained on the roof due to ponding, although the valve was kept open. During the dry-out event, the water storage layer slowly dried up at a rate of approximately 3-4 mm/day, which was also expected based on experiments by Cirkel et al. [7]. From the 18th of June onward, the water storage layer and the substrate layer began to dry-out. The roof was completely free from water from the 26th of June until the 30th of June when another rain event occurred. To also be able to study the roof while the water storage layer is full of water, on the 6th of July it was decided to close the valve again and manually refill the water storage layer to its maximum capacity. For the remainder of the summer period, the water level has been maintained at more than 30 mm naturally by rain events or artificially by refill.

Measurements were collected until the end of August and therewith the heat wave which occurred in the middle of August was also captured in the data. This heat wave started on the 5th of August and persisted for thirteen days with temperatures above 25 degrees Celsius, which was a new record in Dutch meteorological history. For nine days in a row the maximum daily temperatures were even above 30 degrees. During the whole experiment the situation at the reference roof is kept unchanged and the temperatures at the outdoor and indoor roof environment were measured.

3.3. Temperature variations green-blue roof vs. reference roof

Based on the data set that was obtained after the roof experiment, some general observations can be made with respect to temperature differences between the green-blue roof and the reference roof:

- The *indoor air temperature* remained up to 2.5 degrees cooler below the green-blue roof than below the reference roof. For almost the entire duration of the experiment the indoor air temperature below the green-blue roof was cooler than below the reference roof. The only exception were the three days right after the heat wave when the indoor temperature below the green-blue roof was slightly warmer than the indoor temperature below the reference roof.

- The *temperature at the roof surface* was up to 17 degrees cooler at the green-blue roof than at the reference roof. The largest difference in roof surface temperature was observed during the heat wave in August, at noon. But at night, the roof surface at the green-blue roof could sometimes be warmer than at the reference roof, showing a maximum warming difference compared to the reference roof of 5 degrees.

- The *outdoor air temperature* at 160cm above the roof surface can be up to 6 degrees cooler above the green-blue roof than above the reference roof, during summer daytime. Again, the largest difference was measured during the heat wave of August.

In general these results suggest a significant cooling effect on both the indoor and outdoor environment of the green-blue roof compared to the reference roof. As it might be difficult to grasp what a few degrees cooling can do in terms of energy consumption and costs, the effect of 6 degrees reduction of the outdoor air temperature is explained in the box below.

However, the main research question is about the contribution of the water storage layer on the cooling effect. It was suggested that by varying the amount of water in the water storage layer, the cooling effect could be enhanced. To test this hypothesis, the following section will focus on the thermal behaviour of green-blue roofs and the effect of water on cooling under two different conditions: with an empty and a full water storage layer.

***Back of the envelope calculation* - Outdoor air temperature reduction of 6 degrees: what does that mean?**
The air intake for an indoor climate or ventilation system is often located on the roof of a building, which is also the case for the reference roof and the green-blue roof. Imagine the desired indoor temperature is 18 degrees and the indoor climate system refreshes the complete indoor air volume three times a day with fresh air from outside. However, in summertime the outside air temperature is too high and the air has to be cooled to keep the indoor temperature at 18 degrees. When the air intake is located at 40-80 cm above the roof surface and the air above the green-blue roof is 6 degrees cooler than above the reference roof, less energy is needed to cool the air till the desired temperature for the situation with a green-blue roof. A quick calculation shows how this can result in a reduction of energy costs:

Specific heat capacity of air = 1.006 J/kg/°C Density of air (20°C) = 1.2041 kg/m^3
Volume lecture hall = 2000 m^3 Cooling with 6°C and price per kWh = €0.22
Energy needed to cool with 6°C = 1.006 * 1.2041 * 2000 * 6 = 14.535 MJ = 4.04 kWh

When the entire volume of air is refreshed in 4 lecture halls 3x per day the total cost reduction is €10,66 per day

3.4. Contribution of the water storage layer on the cooling effect of a green-blue roof

To study the effect of a water storage layer on the cooling efficiency of green-blue roofs, two comparable periods of 7 days from the recorded summer of 2020 are selected for further analysis. The main difference between the two periods is the amount of water that is stored in the water storage layer (Figure 3.3):

1. **Empty water storage (24-30th of June):** The water storage depth was only 10 mm on the 24th of June and dropped to zero on the 26th. The empty water storage limits evapotranspiration, although evapotranspiration was still possible from the substrate and vegetation layer. On the 24, 25 and 26th of June the weather was sunny and warm with temperatures exceeding 30 degrees and high incoming solar radiation.
2. **Full water storage (7-13th of August):** The water storage depth was between 35-60 mm, which means that there was always sufficient water available for evaporation. As daily temperatures reached 35 degrees for five days in a row, this period was officially defined as a heat wave in the Netherlands. The sunny weather resulted in daily solar radiation larger than average.

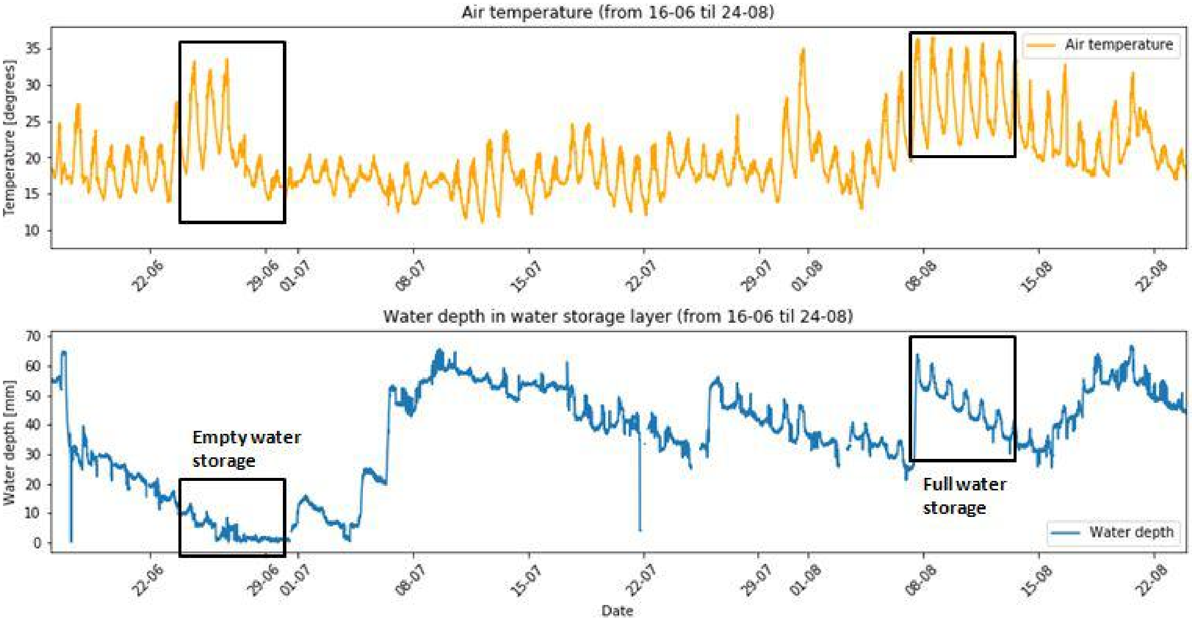

Figure 3.3: The temperature variation over time for the summer of 2020 (top) and the water depth at the water storage layer over time (bottom). Two periods of 7 days are selected for comparison: 24-30 June with an empty water storage and 7-13 August with a full water storage.

Even though the selected periods took place in different moments in time that do not compare perfectly, they do show important similarities with respect to maximum daily temperatures. Especially when comparing the first three days of the empty storage period with the full storage period, differences in temperature, wind velocity and incoming solar radiation were small. To study daily fluctuations, the 26th of June is the best day to use, since the water storage is completely empty and the solar radiation is comparable to the week in August (Figure 3.3).

In the following sections, the effect of the water storage layer on different elements is studied in more detail. First the average evaporation rate from the water storage is determined, which suggests a higher contribution to latent heat production for periods with water available compared with days without water (section 3.4.1). Secondly, the temperature fluctuations at the substrate layer and the water layer are studied (section 3.4.2), showing a clear difference in the behaviour of water and stagnant air. Thirdly, the cooling effect on the indoor room environment seems to remain unclear. However, it is observed that the presence of water increases the heat capacity of the building. This is not always beneficial for the indoor temperature (section 3.4.3). Lastly, the effect on the air temperature is measured at different levels above the roof to see if the cooling effect is sensible at several elevations (section 3.4.4).

3.4.1. Evaporation and latent heat production

Based on the water depth measurements at the water storage layer the average evaporation rate can be determined for the summer period (Figure 3.4). Sudden rises of the water depth are caused by rain events or by irrigation, while during sunny and dry days the water depth in general decreases at an almost constant rate. Small daily variations are visible, but these are caused by a measurement error. Nevertheless, the average trend is clear and it is realistic to assume an indirect average evaporation of 3 mm/day from the water storage layer, via evapotranspiration from the soil and vegetation, when sufficient water is available in the storage layer.

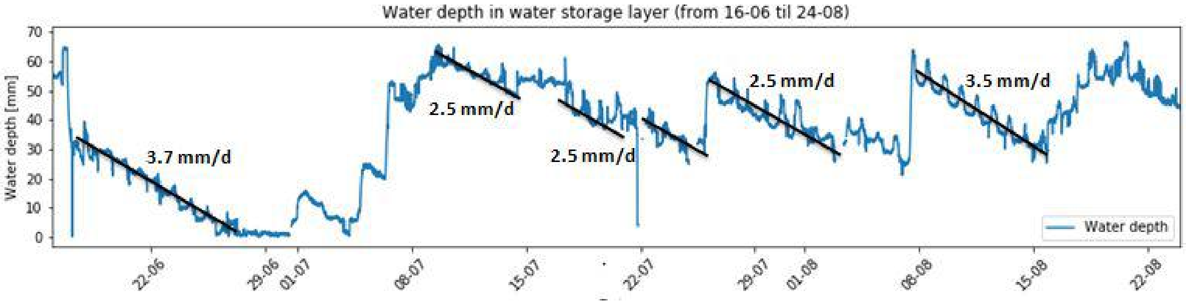

Figure 3.4: The average decline in water depth in the water storage layer equals approximately 3 mm/day during the summer period of the year 2020.

From the energy balance, it is known that energy from incoming radiation results in an increase of sensible heat, latent heat (by vaporization of water) and the ground heat flux. In the case of a roof system, the ground heat flux can affect the soil layer as well as the roof structure below it. By adding a water storage layer to the roof system, both the roof body that is able to store and release heat, and the amount of water that is available for evapotranspiration, are increased.

The average daily incoming solar radiation for the measured period equals 1900 J/cm^2. A rough calculation shows how much of the total solar energy is used for the evaporation of 3mm/day:

Latent heat for evaporation of water = 2.45*10^6 J/kg
Density of water = 997 kg/m^3
Evaporated water = 3 mm/day = 2.991 *10^{-4} kg/day
Needed energy = 747.75 J/cm^2

For evaporation of 3 mm of water per day approximately 750 J/cm^2 is needed. With average daily incoming solar radiation of 1900 J/cm^2, evaporation represents about 40% of the daily incoming solar radiation. This means that 40% of the radiation is used for the production of latent heat instead of sensible heat as long as sufficient water is available for evaporation. This reduction in sensible heat production is expected to become visible in or around the roof system when we compare the empty water storage period with the full water storage period.

3.4.2. Temperature of the substrate layer and water layer

At the green-blue roof, the temperature of the water layer and the substrate layer are measured for the entire duration of the roof experiment. In general it can be observed that the substrate reaches higher temperatures during the day than the water, while temperatures become almost similar at night. For days with less radiation or strong winds the temperature difference between the substrate and the water is less pronounced.

When studying the substrate and water temperature at the green-blue roof during the full water storage (7-13th of August), the following observations can be made. See also Figure 3.5 (right):

- The substrate warms up with almost 13 degrees during the day while the maximum air temperature reaches even higher.
- The temperature of the water layer increases only half as much, with approximate 6 degrees.

However, when the temperature fluctuations for an empty water storage layer are observed, a slightly different behaviour is visible, see also Figure 3.5 (left). Especially the first days (24-26th of June) have shown comparable weather conditions as the period with a full water storage, which makes these interesting for comparison. The following observations can be made:

- The substrate warms up with almost 18 degrees during the day and reaches values even higher than the maximum air temperature.
- The temperature of the empty water storage layer increases on average with 13 degrees and shows high fluctuations.

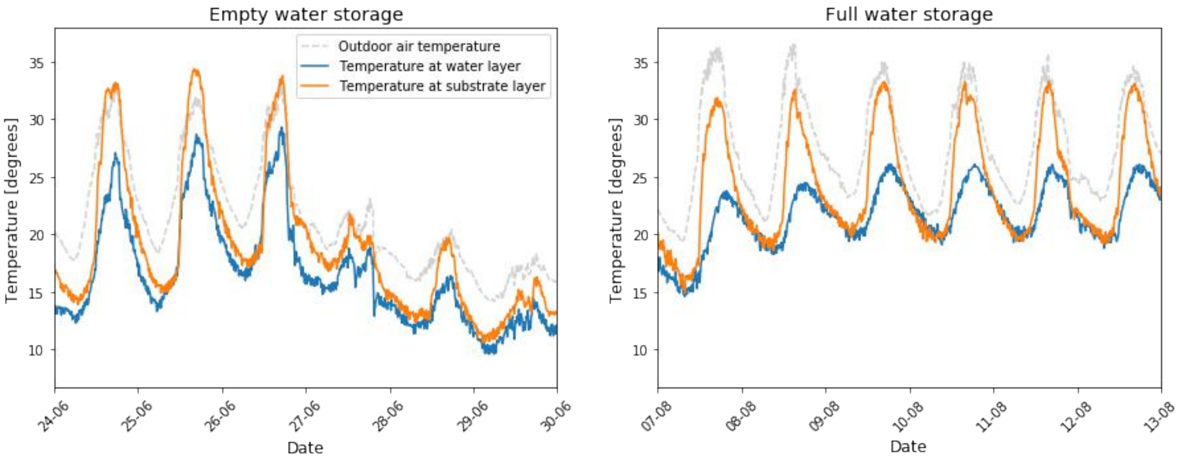

Figure 3.5: The temperatures of the water layer and substrate layer over time for an empty water storage (left) and a full water storage (right). Especially the first three days of the period with an empty water storage layer compare well with the period with a full water storage. In grey, the outdoor air temperature is given as reference.

The above observations imply that the substrate temperature will remain lower than the air temperature as long as water is available. This assumption appears to be substantiated by Figure 3.5, however this is not the case when we look at a longer projection of the substrate temperature against the air temperature. The substrate temperature can not only be predicted based on the air temperature and water availability. Also other factors like wind speed and radiation play a role.

When looking at the temperature that was measured by the sensor in the water storage layer, it seems that when the water storage layer becomes empty, the daily fluctuations in the temperature become larger and more similar to the temperature of the substrate. This can be explained by the fact that when the roof runs dry, the empty water storage layer acts like a stagnant air layer. The temperature sensor is no longer measuring the water temperature as all the water has been evaporated. The heat capacity of air is lower than for water, thus the same amount of added energy results in a larger rise in temperature for the stagnant air layer than for the water layer.

Independent of the water availability, the stagnant air layer as well as the water layer are able to release their heat towards the evening and reach night temperatures that are comparable to the substrate temperature. Both periods show a delay in the warming and cooling of the water layer compared to the substrate, although this delay is slightly more visible for the case with a full water storage.

3.4.3. The indoor room temperature and the effect of increased heat capacity

Based on the observed differences in temperature at the water layer when water is available or not, it can be wondered whether this affects the indoor room temperature below the roof. Figure 3.6 shows the indoor air temperature at the green-blue roof (green line) and the indoor air temperature at the reference roof (brown line) for the periods with an empty or full water storage.

When the water storage layer is empty, Figure 3.6 (left), the indoor air temperature below the green-blue roof increases step wise with approximately 1 degree every day as long as the maximum outdoor air temperature remains high. At the reference roof a comparable but more gradual increase of the indoor air temperature can be observed. The temperature difference between both roofs becomes smaller when the warm weather persists for multiple days. When the outdoor air temperature gets cooler again, the indoor air temperature at both roofs start decreasing slowly as well.

When the water storage layer is full, Figure 3.6 (right), the indoor warming below the green-blue roof is slightly more gradual during the first warm days. But remarkably, from the 10th of August onward the indoor air temperature at the green-blue roof starts to show a daily fluctuation. This daily warming and cooling of the indoor air temperature is comparable to the air temperature fluctuation which can be observed for the reference roof, implying that the roof is also able to release its heat partly. This is also in line with the earlier observed temperature fluctuations at the water storage layer, showing a daytime warming and cooling down in the evening. However, since the cooling is less than the warming, an overall warming of the indoor room environment is the result after several days with high temperatures. It cannot be explained by the measurements why the air temperature increase at the green-blue roof during warm days varies between being step wise, gradual of fluctuating.

Although it was expected to find a cooling effect of the indoor environment when the water storage layer was full, the temperature patterns in Figure 3.6 are not convincing. For both situations the indoor air temperature below the green-blue roof increases during warm days, independently from the presence of water in the water storage layer.

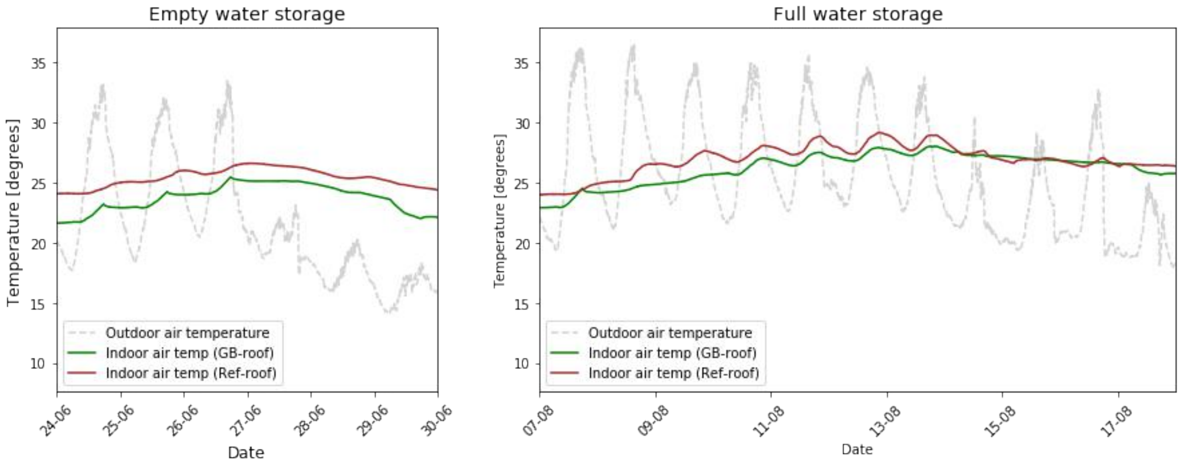

Figure 3.6: The indoor air temperatures below the green-blue roof (in green) and below the reference roof (in brown) for an empty water storage (left) and a full water storage (right). To visualise the process of cooling down after the heat wave, the time frame for the situation with a full water storage is extended on purpose from 13 to 18 August. In gray, the outdoor air temperature is given as reference.

By extending the time frame for the full water storage scenario, also the cooling down after the heat wave can be studied. During the warming period, the indoor air temperature differences between the green-blue roof and the reference roof decreased til 0.5 degrees on the 13th of August. When the outdoor air temperature starts decreasing on the 14th of August, the indoor air temperature at the reference roof responds more quickly and for almost three days in a row the temperatures below the green-blue roof and reference roof are approximately equal. These are the only days during the entire roof experiment that the indoor air temperature below the green-blue roof was higher than below the reference roof. However, after a few days the indoor air temperature at the green-blue roof has adapted to the outdoor air temperature and the air temperature below the green-blue roof is the coolest again.

The slower cooling down of the green-blue roof when the water storage is full is caused by the increased heat capacity of the roof system. It will take longer to warm up the water layer, but it will also take more time to release heat after a warm period. This could be positive quality when outdoor air temperature extremes only last for a short time, since the increased heat capacity delays and dampens the response of the indoor temperature. However, when a long period of heat takes, the slower cooling ability might not be desirable.

3.4.4. The outdoor air temperature

The outdoor air temperature has been measured at 20, 40, 80 and 160cm above the roof surface. To understand the daily fluctuations in air temperature at the different elevations, two specific days were selected for further analysis:

- **26th of June:** empty water storage, warm and very sunny weather (>30 °C), see Figure 3.7.
- **7th of August:** full water storage, heat wave, warm and sunny weather (>35 °C), see Figure 3.8.

Both days compare well, since they faced high maximum temperatures of more than 30 degrees, sunny weather resulted in high incoming solar radiation and the wind speed was negligible. Figure 3.7 and 3.8 show the temperature variations at and above the green-blue roof on the 26th of June (empty water storage) and on the 7th of August (full water storage) for a period of 24 hours.

From Figure 3.7 and 3.8 it becomes visible that the warming and cooling of the air is strongly affected by presence or absence of solar radiation. During the morning the roofs are still in the shade of the adjacent building, but around noon the sun hits the roof surface and this results in a rapid warming of the substrate layer. This is clearly visible at Figure 3.7 for the situation with an empty water storage. The cooling of the night continues til approximately 6 a.m., but when the sun comes up gradual warming of the air temperature above the roof is measured. There is no large variation between the temperature measurements at different elevations above the roof surface yet, and the substrate layer (orange dashed line) is not yet affected by the slow rise in air temperature. This changes rapidly when direct sunlight hits the roof and the temperature of the substrate rises quickly. As the substrate absorbs solar radiation, sensible heat is emitted to the air layers directly above the roof. This results in strong heating of the air at 20 cm above the roof and a diminishing heating effect at higher elevations above the roof. Simultaneously the temperature of the empty water storage increases, but the temperature of the stagnant air layer remains cooler than the substrate. After 6 p.m. the roof ends up in the shade again, which results in a rapid decrease of both the substrate and air temperatures. The small box at the right in Figure 3.7 shows the clear difference in temperature at 20 and 160cm above the roof, with higher temperatures at an elevation of 20cm. The maximum temperature of the substrate layer is now almost similar to the air temperature above it. When the roof ends up in the shade again, the temperature drops rapidly for the different air layers, the substrate and the empty water storage layer.

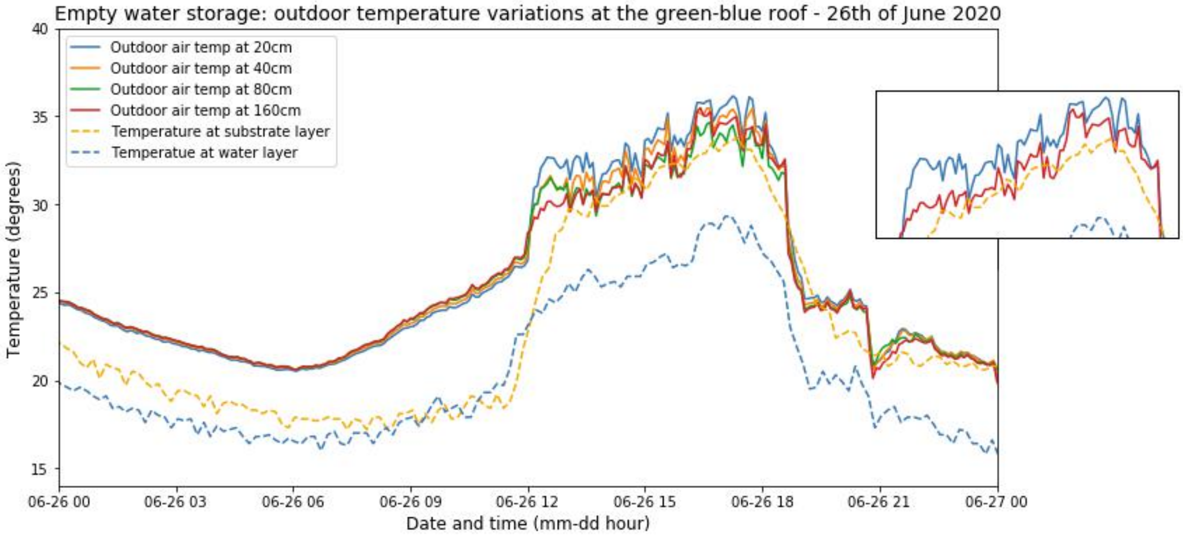

Figure 3.7: Temperature variations over a period of 24 hours on the 26th of June when the water storage layer was empty. The air temperature was measured at four elevations (20, 40, 80 and 160cm) above the roof surface. In the small box to the right, the temperature variations at 20 and 160cm are given again to show that the clear temperature difference between these elevations.

When looking at the situation with a full water storage, Figure 3.8, the observed behaviour is slightly different. Around noon, the substrate and air temperature warm up rapidly, comparable to what was

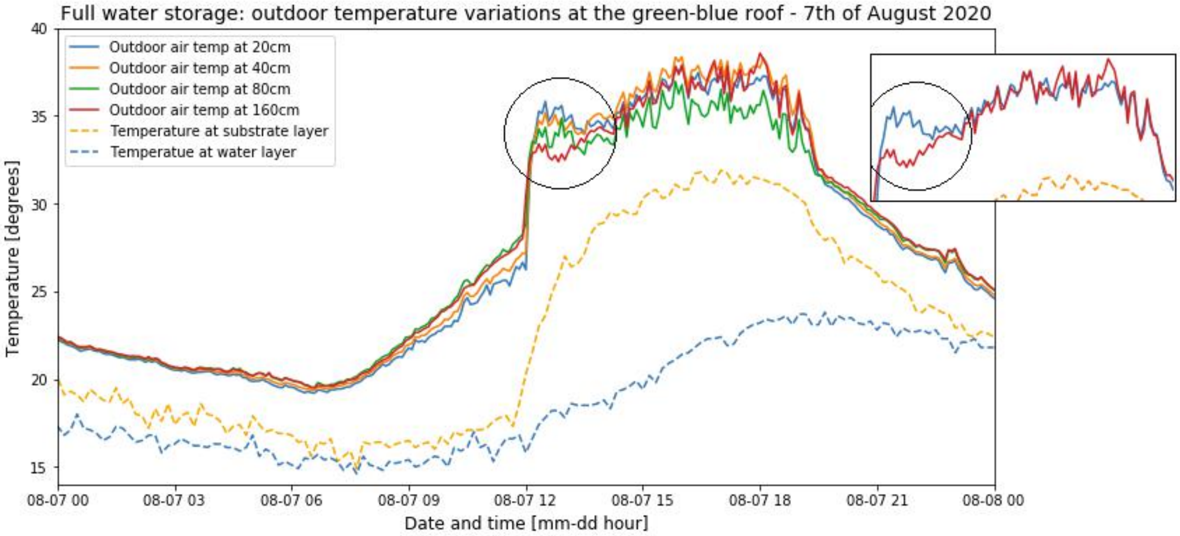

Figure 3.8: Temperature variations over a period of 24 hours on the 7th of August when the water storage layer was full with water. The air temperature was measured at four elevations (20, 40, 80 and 160cm) above the roof surface. In the small box to the right, the temperature variations at 20 and 160cm are given. It becomes clear that the temperature at 20cm starts high, but shows a decrease after one hour, ending up to be similar to the temperature at 160cm elevation.

observed on the 26th of June although the substrate remains almost 5 degrees cooler than the air above. Similar to the situation with an empty water storage, the air layers just above the roof warm up the most and this warming effect gets less strong higher above the roof. However, after approximately one hour, this phenomena weakens and the air temperature at 20, 40 and 80 cm show a drop (see the circle in Figure 3.8). During the following hours the air temperature at 20 cm above the roof is similar to the temperature at 160 cm above the roof, as can be seen in the small box to the right. The air temperature at 80 cm elevation (green line) remains the lowest. This shift in temperature distribution implies a cooling effect of the outdoor air of approximately 2 degrees up to at least 80 cm above the roof surface.

This cooling phenomena was not visible for the situation with an empty water layer, which suggests that the presence of a full water storage enhances the cooling effect by evaporation. When water gets evaporated, less energy is available for sensible heat production. However, when we study the soil moisture data it becomes clear that in both situations approximately 3 mm of water is evaporated. For the situation with an empty water storage layer, water was still available in the substrate and a reduction of the soil moisture of 3 mm was observed for the 26th of June. For the situation with a full water storage layer, the soil moisture remained constant while the water depth in the water storage layer was reduced with 3 mm. This shows that on both days the same amount of water was evaporated and the only difference was where the water was obtained from and whether the soil moisture was effected or not. The cooling effect on the outdoor environment can thus not be explained by evaporation only.

Another important difference between the situation with a full and an empty water storage is the gradient between the substrate temperature and the air temperature. For the empty water storage, the substrate layer shows a comparable maximum temperature to the air, while for the full water storage the substrate remains almost five degrees cooler. A temperature gradient is needed to be able to cause cooling from the substrate to the air above. In combination with the observations of the soil moisture, it seems that the level of saturation of the substrate plays an important role in extent to which the cooling effect on the outdoor environment is sensible.

The observed time lag of approximately one hour is probably caused by the delay in the upward water flux by capillary irrigation. First the temperature of the substrate rises and water at the surface evaporates before the upward flow of water from the water storage to the substrate layer is activated. Since the soil moisture content remains almost undisturbed, the temperature of the substrate remains lower for the case with a full water storage.

3.5. Discussion on the cooling effect of a water storage layer

The aim of this chapter is to answer the following question: What is the contribution of the water storage layer on the cooling effect of a green-blue roof? To start with, based on the data obtained during the roof experiment, it became clear that a green-blue roof has a cooling effect on the indoor and outdoor environment during summer months compared to a conventional black roof. The indoor temperature was during the entire measurement campaign 1-2.5 degrees lower under the green-blue roof, except for three days after the heat wave. Also the roof surface remained even up to 17 degrees cooler and the cooling effect was also sensible up to 160cm above the roof surface causing a decrease in air temperature of maximum 6 degrees. These findings were supported by results from earlier research on the cooling effect of green roofs (see section 2.1.3) and therefore the collected measurements seem realistic and reliable.

The cooling effect of green and green-blue roofs seems to be induced by a number of thermal phenomena, such as solar shading by the vegetation depending on LAI (leaf area index), evapotranspiration, high plant albedo and the thermal resistance of the substrate layer [17]. However, there is one main difference between green roof and green-blue roofs, namely the presence of a water storage layer underneath the substrate layer. By comparing the thermal behaviour of a green-blue roof for the situation with a full and an empty water storage layer, we tried to understand to what extent the presence of water could enhance the cooling effect. To achieve this, a comparison was made between two periods in time; a week in June and a week in August. Although the periods showed similarities with respect to high maximum daily temperatures, little to no wind and high incoming solar radiation, these periods did of course not compare perfectly. By comparing two periods in time, small differences in e.g. humidity, number of sun hours, vegetation growth will always remain. Ideally, two identical green-blue roofs that were located next to each other, one with a full and one with an empty water storage, should have been used within this study. In that case it would have been unnecessary to compare two periods that took place in a different moment in time, resulting in less inaccuracies.

Nevertheless, based on the analysis of the temperatures for a full and empty water storage, it is still possible to draw some interesting conclusions regarding the contribution of the water layer to the cooling effect to the roof environment. In general it can be stated that the presence of water plays a role in enhancing the cooling effect of green-blue roofs since it increases the percentage of latent heat production and thus reduces the production of sensible heat. The following paragraphs will discuss the extent of this cooling effect on the indoor and outdoor environment and whether this can be useful to increasing the livability in urban areas.

Effect on the indoor climate

Based on the measurements of the indoor room temperature, no enhanced cooling effect was observed as a result of having a full water storage instead of an empty water storage. Independently from the presence of water in the storage layer, the indoor temperature was affected by changes in the outdoor temperature. The only observed difference was the delay in response, which became larger for the situation with a full water storage. By adding a water layer to the roof, the heat capacity of the roof system is increased, which makes the indoor climate slightly less sensitive to sudden changes in the outdoor temperature. This could be positive when temperature extremes only last for a short time, say two days, since the increased heat capacity of the roof system delays and dampens the effect on the indoor temperature. However, this also means that after a long period of heat the indoor temperature will cool down slower. Although this might sound undesirable, this is only the case for an indoor environment that behaves as a closed box. In reality, when the indoor temperature is higher than the outdoor temperature, the indoor temperature can easily and quickly be lowered to comfortable levels without increasing the energy consumption. As the indoor climate system refreshes the air inside the building several times a day and makes use of the cooler air from outside, the indoor temperature can be lowered rather quickly.

The increased heat capacity as a result of adding water should not be confused with an increased insulation capacity. Water is a conductor and does not insulate. Within the roof system it functions more like a buffer, since more energy is needed to increase the temperature of a water layer with one degree than what would be needed to increase the temperature of air. For the situation without water, the storage layer can be seen as a stagnant air layer. The stagnant air was expected to increase the insulation capacity of the roof system, but the effect of this has not become visible from our measurements.

The finding that adding a water storage layer does not enhance the cooling effect on the indoor environment is important, since it also implies that the energy consumption of the building will not be influenced by choosing a green-blue roof instead of a green roof.

Effect on the outdoor urban micro-climate
The effect of the two scenarios on the outdoor roof environment was measured at four elevations above the roof surface. Based on these measurement a cooling effect was observed of approximately two degrees up to at least 80 cm above the roof surface. This cooling effect could not be explained by a difference in amount of water that was used by evapotranspiration, since both scenarios showed similar values. Instead, the level of saturation of the substrate and whether the soil moisture was affected showed to be important. As long as water was available in the water storage layer, the soil moisture remained constant and enhanced cooling of the air was observed. But when the water content in the substrate layer was reduced, the maximum temperature of the substrate reached values equal to the air temperature. When the air and substrate have similar temperatures, the temperature gradient is zero and cooling of the air cannot take place. It would have been interesting to study a situation for which the substrate was dried out completely and no water was available at all for evapotranspiration. But a situation like that did not occur during the execution of the roof experiment.

Even though enhanced cooling of the outdoor climate was observed as a result of adding a full water storage layer to the roof system, it should be questioned how useful this is to the urban micro-climate and for mitigation of the UHI effect. A temperature decrease of 2 degrees up to 80 cm above the roof surface is significant and could be beneficial for the installment of solar panels or air intake for the indoor climate system in summer. But the temperature reduction at pedestrian level will probably only be minor. As shown by Peng and Jim [38], a cooling effect of 0.1-1.6 degrees at 1.2m above an extensive green roof results on a cooling of only 0.0-0.7 degrees at 1.2 m above street level. In addition, the maximum cooling effect at pedestrian level is negatively related to the building height. Vertical advection of cool air generated at green-blue roofs could be dispersed and diluted in its descent if the distance from the rooftop to the street is too high. At the same time, modelling studies have shown that large-scale implementation of green-roofs could bring neighbourhood-wide cooling of a few degrees [38].

To summarize, the presence of water in the water storage layer does not add to the indoor cooling effect of a green-blue roof compared to the situation without water being available. The enhanced outdoor cooling effect by the water storage layer is small and remains mainly sensible close to the roof surface, while the enhanced effect at pedestrian/street level is expected to be almost negligible. These findings show that the cooling effect of a green-blue roof will not be significantly larger than the cooling effect of green roofs. However, it should not be forgotten that the initial cooling effect of green(-blue) roofs compared to conventional black roofs is proven to be significant on both the indoor and outdoor roof environment. In the end, the main benefit of adding a water storage layer to the roof system can not be found in the aspects of heat mitigation or the reduction of energy consumption, but the focus should be on the water related aspect. The storage layer increases the water retention capacity of the roof system significantly and in addition the stored water also becomes available to the vegetation which will reduce the irrigation demand of the roof system. This will be treated in the next chapter.

4

Water storage and water consumption of green-blue roofs

4.1. Introduction

Urban areas are vulnerable to extreme rainfall due to the large percentage of impermeable surfaces and the constrained drainage capacity of the sewer system. As a consequence, pluvial flooding has become an increased risk for urban areas. Green-blue roof systems can play an important role in rainfall retention and the temporary storage of water since they consist of a vegetated top layer and a water storage layer below. Due to presence of the water storage layer, green-blue roofs allow in general for higher rainfall retention than green roofs. The maximum thickness of the water storage layer and the substrate layer that can be applied depend on the load capacity of the roof. Most flat roofs are designed for a load of 1 kN per m^2 [10] and are covered with a gravel layer of approximately 85 kg/m^2 [19]. When the gravel layer is replaced by a green-blue roof system, the roof gives room to a water storage layer of approximately up to 60 mm. Some roofs are designed to carry larger loads and thus offer space for a larger water storage or ticker substrate layer. In addition to water retention, the stored water can enhance the cooling effect as discussed in chapter 3. Although the cooling effect compared to a green roof is small, the effect compared to conventional black roof is significant. Thirdly, stored water from the water storage layer can also be used by the vegetation to overcome dry spells in summer and reduces the amount of external irrigation that is needed. Wilted and dried out vegetation is undesirable since it looses part of its cooling effect [41] as well as its aesthetic value and contribution to the urban ecosystem. Extra costs are made when wilted vegetation has to be replaced by new plants.

By adding a water storage layer to the roof system, improvement on the performance of these water-related functions is expected. However, these functions can also be in conflict with each other. To capture sudden extreme rain events, which usually occur during summer months, a minimum storage depth should be empty and available. Ideally, the available storage capacity should be equal to the expected precipitation. At the same time a sufficient amount of water should be stored and kept available in the water storage layer to meet the vegetation demand and the water demand for cooling during warm and dry periods during summer. Is it possible to fulfill both functions simultaneously? In some cases additional irrigation of the roof system might even be required, which means that water has to be provided from elsewhere. The question arises whether it is sustainable to increase the percentage of vegetation in cities, as this also increases the water demand during periods with water scarcity. To deal with the conflict between storing water and creating sufficient empty storage, a fine balance is needed. A sustainable green-blue roof system should be able to manage the water in such a way that as little water as possible is wasted, the run-off to the sewer system is reduced and preferable no external water sources are used. Especially towards a changing climate, it is important to obtain insights on the current and future water consumption of green-blue roofs, the challenges and potential strong points.

Research objective and questions
Within this chapter the aim is to visualise whether green-blue roofs are able to manage water in a sustainable way, now and towards the future. In addition, the use of a water storage layer should also be climate resilient and therefore the effect of the future climate will be taken into account as well. By studying the different functions and their interactions within the roof system, it will be possible to define the future challenges regarding sustainable water consumption. This will result in essential knowledge that can be used to optimize the application of green-blue roofs and the use of the water storage layer. The main objective of this chapter is captured in the following research question:

Which elements and uncertainties play an important role in making green-blue roofs, with a water storage capacity of 60 mm, more climate resilient and sustainable with respect to water consumption?

A green-blue roof with a water storage capacity of 60 mm was selected, as the design load for most roofs in the Netherlands allows for this. To support the main research question, three sub-questions have been formulated:

1. Which elements play an important role in rain water consumption and how will this change towards the near future (around 2050)?
    (a) How will the need for water storage change?
    (b) How will the water demand for cooling change?
    (c) How will the water demand for vegetation change?
2. What is the range of uncertainties of the climate predictions from the KNMI?
3. How climate resilient is a green-blue roof system with 60 mm water storage?
    (a) Which criteria should be defined to measure the water-related performance of green-blue roofs under different climate conditions?
    (b) What is the difference in present and future (around 2050) performance by using different climate scenarios?

Within this chapter it is the aim to formulate an answer to the questions above. To be able to answer these questions, first the methodology is described in section 4.2. A bucket model (a water balance model used within hydrology) is used to simulate the roof performance for different future climate scenarios. In section 4.3 the model results are analysed to understand which challenges green-blue roofs are expected to face towards the future regarding extreme rainfall, heat and drought. The results are discussed in section 4.4.

4.2. A bucket model in combination with climate scenarios

This section will describe the methodology which is used to answer the research questions as defined before. First of all, to study the climate resistance of a green-blue roof, the future climate should be studied. However the prediction of the future climate includes multiple uncertainties which can be reflected by the use of different climate scenarios. This will be explained in the first section 4.2.1. Secondly, criteria have to be defined to measure climate resistance of a green-blue roof with respect to its different functionalities. In other words, what is the performance of the roof under different conditions like heat, extreme rainfall and drought. The definitions of the required criteria are explained at section 4.2.2. By constructing a bucket model, the water storage capacity and water demand for a green-blue roof can be simulated for different climate scenarios and the performance of the roof can be determined. Details about the bucket model, the process of calibration and the required in- and output data can be found at section 4.2.3.

4.2.1. Four climate scenarios by KNMI

The three main functions of a water storage layer (1. to store rainfall and reduce sewer inflow during rain events, 2. to provide water for cooling and 3. to provide water for the vegetation) are all strongly affected by the local climate conditions. The duration of dry spells and the number of days with high temperatures define the water demand for vegetation and cooling. Whereas changing rainfall intensities relate to the minimum required water storage capacity. The frequency of occurrence and severity of droughts, heat waves and extreme rain events are all captured by the local climate. The ability to which a green-blue roof can fulfill its functions is affected by changes in the climate and therefore the future climate plays an important role in defining the climate resistance of a green-blue roof system.

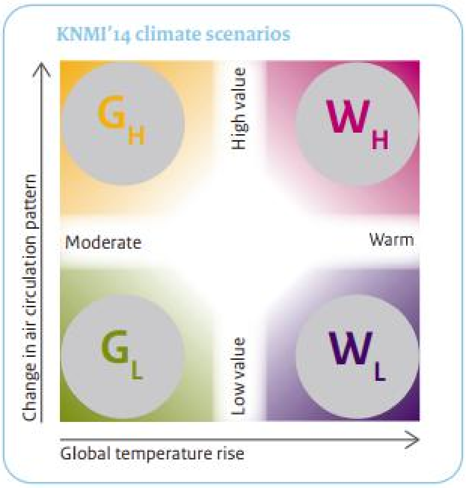

Figure 4.1: The KNMI has defined four climate scenarios which together give the boundaries between which climate change in the Netherlands is likely to occur. The four scenarios are: GH, GL, WH and WL. Mutual difference are caused by uncertainty in the rate of change in the air circulation pattern (high or low) and the global temperature rise (moderate or warm).

The effect of climate change is captured by climate models that for example give a prediction of changes in temperature and rainfall that can be expected towards the future. To be able to define the effect of climate change on the performance of green-blue roofs, this research makes use of the climate scenarios and transformed climate data provided by the Royal Netherlands Meteorological Institute (KNMI). Based on the results of the world-wide climate study from the IPCC report (2013), the KNMI climate scenarios translate this to the Netherlands. Based on 30 years of data that was collected for the current climate, between 1981-2010, the scenarios by the KNMI provide an estimate of the change in precipitation and temperature around the year 2050 and 2085 [30]. The combination of four different scenarios (GH, GL, WH, WL) gives the boundaries between which climate change in the Netherlands will most likely take place. This can also be seen as the uncertainty of the climate model as a whole. As given by Figure 4.1, the difference between the scenarios is caused by two main uncertainties: the rate of change in worldwide temperature increase (moderate (G) or warm (W)) and the possible change in air circulation (low value (L) or high value (H)). In general the temperatures will rise, which will result in drier summers for two of the scenarios (GH and WH). Furthermore it is expected that the total precipitation and number of extreme rain events will increase in winter, while during summer only the intensity of extreme rainfall events is expected to increase. This research will focus on the effect of climate change around the year 2050 (2035-2065) and therefore the following transformed climate data sets from KNMI for the station in Rotterdam are selected for further use within this study:

- Precipitation: 30 years around 2050 for four climate scenarios (daily data) [29]
- Potential evaporation (Makkink): 30 years around 2050 for four climate scenarios (daily data) [29]
- Maximum temperature: 30 years around 2050 for four climate scenarios (daily data) [29]

These data series will be used as input data for the bucket model which is explained in more detail in section 4.2.3.

4.2.2. Criteria to measure climate resistance of green-blue roofs

To be able to determine whether green-blue roof systems are climate resilient towards the future or not, criteria are required. These criteria have to be informative about the performance of green-blue roofs regarding water consumption and water storage under different conditions. To facilitate comparison of the roof performance for different climate scenarios, it is useful to start with a definition of the desired ideal roof performance. The ideal performance builds on the idea that a sustainable green-blue roof manages the water in a way that as little water as possible is wasted as runoff and preferable no external water sources are used. If some runoff still occurs the timing should be delayed to reduce the pressure on the sewer system. When comparing the actual roof performance for a certain climate scenario with the ideal performance, this gives information on the sustainability of the roof with respect to water use. How the performance on water consumption and water storage changes towards the future, and for different climate scenarios, will give the answer on how climate resilient green-blue roofs are. In the paragraphs below, the ideal performance on water consumption and water storage is given for situations with drought, heat or extreme rainfall. This results in three criteria that will be applied at the modelling stage (section 4.2.3) to study the effects of different climate scenarios on water consumption.

Ideal performance during extreme rainfall

Extreme rainfall is defined as a precipitation event, occurring during a period of time, with a total precipitation exceeding a certain threshold for a given location. The KNMI makes use of the following definition for an extreme rainfall event: an extreme rainfall event occurs when precipitation exceeds 25 mm/h. A day with extreme rainfall is registered when the precipitation exceeds 50 mm/day [27]. To become climate proof towards the future, Dutch municipalities have stated different strategies to adapt to the changing climate. The city of Amsterdam, for instance, started the project *Amsterdam Rainproof* with the objective to become fully rainproof by 2025. To reach that, they express the ambition to process a rain event of 60 mm/h in urban areas without damage to houses and infrastructure [3]. Another example is given by the municipality of Utrecht, who wants to prevent any kind of flooding in the urban areas for extreme events up to 20 mm/h [15]. Since most projects make use of different thresholds and criteria it is impossible to come up with one criteria that fits all. Within this research it is therefore decided to come up with a new threshold that focuses on the water retention ability of green-blue roofs in combination with the definition from the KNMI.

Due to the presence of a water storage layer, a green-blue roof can retain (part of the) rain event. As long as the valve is closed, runoff will occur only when the water depth exceeds the maximum storage capacity. For a storage layer with a depth of 60 mm, the maximum available storage capacity equals 60 mm, but this is only true for situations where the water layer is empty prior to the rain event. When the available storage is filled up, the maximum storage capacity is exceeded and the remaining water ends up in the sewer system without any delay.

An extreme rain event, as defined by KNMI, has an intensity of >25 mm/h. This indicates that prior to the event a minimum of 25 mm storage needs to be available in the water storage layer to capture the event. However, in reality the total depth of the rain event will be more than 25 mm since the duration of the extreme event will never be exactly 1 hour. On a daily basis the KNMI uses the threshold of 50mm/day to define a day with extreme rainfall. This would mean that the roof should be able to capture up to 50 mm of water to guarantee no runoff. However, to reduce the risk of pluvial flooding it is mainly important to reduce and delay the runoff with several hours up to a day, depending on the rain event. This results in a flattening of the peak discharge that has to be processed by the sewer system and pumping stations. As causing delay in runoff is the most important, it is not necessarily the aim to prevent all runoff. Since we are looking for a criteria that can be used as an indicator for the ability of green-blue roofs to capture extreme rainfall, the threshold of 25 mm is selected. By stating that, in an ideal case, the water storage layer should always have at least 25 mm of storage left, the roof is able to (partly) capture an extreme rain event with a maximum intensity of 25 mm/h. In case of a day with extreme rainfall (50 mm/day) some runoff to the sewer system is unavoidable, but the amount of runoff will at least be strongly reduced and partly delayed.

Criteria to measure water retention performance

To measure the water retention performance of green-blue roofs on capturing extreme rainfall, the available (empty) water storage capacity is measured daily. When the available water storage capacity per day is more than 25 mm, the roof is able to (partly) retain an extreme rain event. In addition also the water retention is calculated for each day. The water retention is the percentage of daily rainfall that is captured by the water storage instead of being discharged. The roof performance on water retention will be defined per month, averaged over 30 years of current and future climate data.

Ideal performance during heat

A heat wave is a prolonged period of extremely high temperatures for a specific area. However, there exists no universal definition for a heat wave as it relates to a particular region. The Dutch definition of a heat wave given by the KNMI is the following: *”A heat wave is a consecutive of at least 5 summer days, of which at least 3 tropical days. Summer days have a maximum temperature of 25°C or higher, whereas tropical days have a maximum temperature of 30°C or higher”* [26].

In an ideal situation, to enhance the cooling effect of green-blue roofs, the water storage layer at the roof should never become completely empty during a hot period like a heat wave. However, also when the temperature is not exceeding 30 degrees or when the warm period only lasts for 4 days, which means that we are not officially speaking of a heat wave, additional cooling by a green-blue roof could be of added value. Within this research it is therefore decided that heat starts to be a problem on both warm and tropical days, and therefore a threshold of 25 degrees will be used. When the maximum daily temperature equals or exceeds 25 degrees, cooling is desired independently of the duration of the warm period. To mitigate heat stress on these days the water storage should thus contain water.

Criteria to measure cooling performance

To measure the cooling performance of green-blue roofs on heat stress mitigation, the number of days with temperatures equal to or higher than 25 degrees are counted. For these *summer days* it is checked whether the water storage layer is empty or not. By providing water for evapotranspiration from the water storage layer, cooling is enhanced. In addition to the number of days for which cooling is achieved, also the cooling potential is determined. The cooling potential is defined as the percentage of *summer days* for which water is available in the water storage layer. Obviously, the inadequate cooling potential is the percentage of summer days for which no water is available and the water demand for cooling is not met. The roof performance on cooling will be defined per month, averaged over 30 years of current and future climate data.

Ideal performance during droughts

Since dry conditions develop for different reasons, there are several definitions of drought depending on the function that has been given to the water. A distinction can be made between four types of drought: a meteorological drought is a decrease in precipitation compared to the historical average of a specific area; a hydrological drought refers to continuously low water levels in rivers and reservoirs; an agricultural drought accounts for a shortage in water supply to crops; a socioeconomic drought occurs when the water demand exceeds the supply.

To apply a definition of drought to green-blue roofs, a specification of its water function is required. At a green-blue roof, a decrease of water can affect both the vegetation and the cooling effect of the roof on its environment. Cooling by evaporation can not take place when the water storage layer is empty and vegetation will start to wilt when the soil moisture content drops below the wilting point. Since the cooling performance of a green-blue roof is already captured by the criteria for heat, the focus regarding the performance during drought will be on the water demand for vegetation.

Due to the harsh environment and the thin substrate layer of extensive green roofs, sedum plants are frequently used on green and green-blue roofs in the Netherlands. Sedum plants are low-growing succulent plants that can grow rapidly when water is available yet also survive long periods without water. Because of its Crassulacean Acid Metabolism (CAM), sedum has a high drought tolerance which enables the plant to survive longer dry spells than non-CAM plants [42]. CAM plants close their stomata during the day and take up CO2 at night, when the air temperature is lower. Due to this strategy the water demand by the plant is reduced, making the plant more suitable to dry climates. The drought tolerance of plant species which frequently are applied on green roofs was studied by Nagase and Dunnett [35] in a greenhouse in the UK by temperatures above 20 degrees. They showed that forbes and grasses reach their permanent wilting point between 2 and 3 weeks after ending the water supply, while sedum plants can survive easily more than three weeks without watering. Depending on the sedum type and conditions, there is even proof that sedum can survive up to 100 days without water [12]. The exact duration of dry spells that vegetation on green(-blue) roofs can survive strongly depends on several climatic factors, like the amount and intensity of wind, solar radiation and temperature but also the applied vegetation mixture plays a role. Although sedum has proven its suitability to application on green roofs, the wide spread use of green roofs with a sedum-only coverage also has disadvantages. An ecological system with limited species diversity reduces the stability of the ecosystem while a diverse culture is often more advantageous in terms of stability and survival under dry conditions [35]. The application of a green-blue roof with an increased water storage capacity also creates new opportunities to enhance the diversity of plant cover.

With the aim to keep the vegetation healthy, but also facilitate for a wider mixture of plants than sedum-only, the following definition of drought is selected for further use within this research: *Drought occurs when the vegetation starts to face water stress and water is not readily available to the vegetation anymore.* The readily available water (RAW) content is the soil moisture content between field capacity and the point for which restricted growth starts to occur [36]. When the water content drops below RAW, the vegetation will face water stress. A dry spell is a consecutive of several days for which water stress occurs and the water storage layer remains empty. The dry spell is stopped when the water content in the substrate is recovered to a values above RAW. To make sure that most of the vegetation survives a dry spell, the dry spell should not last for longer than 3 weeks.

Criteria to measure drought performance

To measure the performance of green-blue roofs during droughts, as defined above, the following criteria is used: drought starts to cause danger to the vegetation survival on green-blue roofs when it lasts for longer than 21 days (3 weeks), during the growing-season (Apr-Sept). For each climate scenario the duration of dry spells is measured, as well as the frequency of occurrence for the period between April to September. A dry spell is a period for which the vegetation faces water stress and the water content drops below RAW. This means that the water storage layer is empty as well. The number of dry spells with a duration longer than 21 days will define the vulnerability for drought of the green-blue roof performance. The roof performance during drought will be defined based on a total of 30 years of current and future climate data.

4.2.3. The bucket model

To be able to measure the performance of the roof for different climate scenarios, a computational model of the roof system is required. Therefore a bucket model is constructed to simulate the water storage capacity and water demand for green-blue roofs. By running the model for different scenarios, the performance on water consumption and water storage as well as the climate resistance of the roof can be studied. This section will explain how the bucket model has been designed, the process of calibration and the required in- and output data.

Two layered bucket model

The most straightforward bucket model responds like a reservoir which fills by precipitation and empties by evaporation. If the bucket is almost empty, limited evaporation occurs, i.e. actual evaporation (E_a) has a lower rate than the potential rate (E_p). The concept of a bucket model compares well with the processes on a green roof [7].

To simulate a green-blue roof, it was decided to design a computational model that makes use of the concept of a bucket model. We assumed that the interactions between the different layers within a green-blue roof can be simulated by a bucket model that consists of two buckets above each other

(Figure 4.2). The upper bucket imitates the green layer with the substrate and vegetation. The bucket below imitates the water storage layer. The green layer on top receives water from precipitation (P) and looses water via evapotranspiration (ET). The amount of precipitation that is not directly used by vegetation or evaporated, will infiltrate in the substrate layer. When the substrate is saturated, water drains with some delay to the water storage layer underneath (Q_{delay}). An upward flux (Q_{cap}) is provided by the passive capillary irrigation system that feeds water back to the green layer as long as there is water available in the water storage layer and the green layer is not fully saturated.

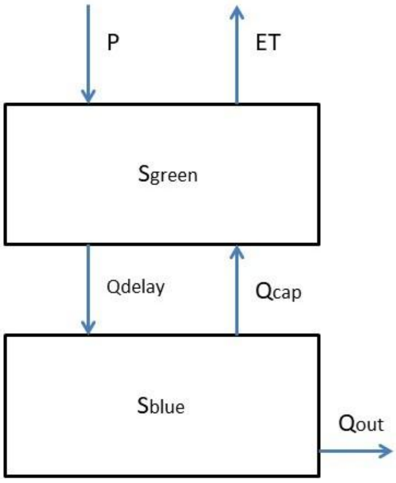

Figure 4.2: A simple bucket model of a green-blue roof system consisting of two layers: the substrate layer (top) and the water storage layer (down).

As long as water is available in the water storage layer (S_{blue}), the water content of the substrate remains constant and approximately equal to field capacity. This assumption is supported by soil moisture measurements which showed that a decrease in soil moisture only took place on days for which the water storage layer was completely empty, while otherwise it remained constant. For more details on the soil moisture measurements that were part of the roof experiment which was described in Chapter 3, see Appendix A. The actual evapotranspiration can be defined by multiplying the potential evapotranspiration (ET_p) with a crop coefficient (K_c) and a water stress coefficient (K_s). However, when the water content equals field capacity plants are healthy and do not experience water stress. The the water stress coefficient (K_s) thus equals one. As the water content of the green layer (S_{green}) remains constant in this case, the outgoing flux by evapotranspiration (ET) in Figure 4.2 equals the upward capillary irrigation flux (Q_{cap}) and the decrease of water depth (δS_{blue}) is therefore an indicator for daily evapotranspiration. The condition for the bucket model is given below:

$$\text{If } S_{blue} > 0: \qquad \begin{aligned} S_{green} &= \text{constant} \\ K_s &= 1 \end{aligned} \qquad \begin{aligned} ET &= ET_p * K_c \\ ET &= Q_{cap} = \delta S_{blue} \\ P &= Q_{delay} \end{aligned}$$

In the case of precipitation water will infiltrate into the substrate layer. However, since the water content in the green layer remains almost constant, all the rain water will drain to the water storage layer: $P = Q_{delay}$. Water can leave the water storage layer as runoff (Q_{out}) only when the maximum storage capacity is exceeded or when the outflow valve is lowered on purpose.

When the water storage is empty (S_{blue} = 0) we are speaking of a different situation. In that case, the upward capillary irrigation flux is zero and the soil water content in the green layer (S_{green}) gets reduced by evapotranspiration. From the soil moisture measurements it was observed that a 10 cm thick substrate layer can contain up to 16mm of water as long as water is available within the water storage layer (Appendix A). In other words, the total available water content (TAW), which is the maximum amount of water that a well drained substrate can hold against gravitational forces, equals 16 mm. When the water storage layer has dried out, the amount of water that is stored in the substrate is still available for evapotranspiration. However, reduction of the soil water content will influence the actual rate of evapotranspiration. Water is theoretically available until the wilting point, but crop water uptake is reduced well before the wilting point is reached. The reduction in water uptake starts when the water contents drops below the readily available water content (RAW). The relation between RAW and TAW is given by Equation 4.1. A value of 0.5 for the dimensionless factor p is commonly used for many crops.

$$RAW = TAW * p = TAW * 0.5 \tag{4.1}$$

From the moment that all the readily available water is used, water becomes more strongly bound to the soil matrix and is more difficult to extract. Soil water can no longer be transported quickly enough towards the roots to respond to the evapotranspiration demand and crops begins to experience water stress. From that moment onward ET_a reduces linearly with the reduction factor K_s (the water stress coefficient) until the wilting point is reached and no evapotranspiration is possible anymore. Equation 4.2 shows how K_s depends on TAW, RAW and D_r. D_r is the water shortage relative to the field capacity. K_s can range between 1 (no water stress) and 0 (wilting point reached).

$$K_s = (TAW - D_r)/(TAW - RAW) \tag{4.2}$$

Based on the above explanation for the situation in which the water storage layer has become empty, the conditions for the bucket model are given:

If $S_{blue} = 0$: $S_{green} \neq$ constant $ET = ET_p * K_c * K_s$
$K_s < 1$ $Q_{cap} = 0$

The empty water storage can be refilled by precipitation. Rain water will first be used to refill the substrate layer and bring back the water content to the TAW content. When the water content in the substrate is recovered, the additional amount of rain water will drain to the water storage layer where it gets stored.

Input and output data
As input for the bucket model, precipitation and potential evaporation data are required. Additionally, to be able to check the model output on the roof performance criteria as defined at section 4.2.2, temperature data is required as input as well. Daily data on precipitation, temperature and potential evapotranspiration (ET_p) for the dutch climate are all obtained from the KNMI. For the reference case, real measurements are used for the period 1981-2010. For the climate scenarios, transformed climate sets are used, as explained in section 4.2.1. Data on potential evapotranspiration, ET_p, is based on the Makkink equation for a short, well watered grass with sufficient nutrients as reference crop. A relation between the potential evapotranspiration for the reference crop and the actual evapotranspiration at the green-blue roof is found by multiplying with a crop coefficient and a water stress coefficient. The value for the water stress coefficient is already captured by the model and depends on the soil moisture content of the substrate which varies on a daily basis. The value for the crop coefficient is unknown but can be estimated by calibration (see next section).

Based on the accuracy of the available input data it was decided to make use of time steps of one day within the model. Internal fluxes like the infiltration delay of rainwater through the substrate and the capillary upward irrigation flux take place on a shorter timescale and therefore a time step of one day can easily be applied. Regarding rain events it will not be possible anymore, based on the input data, to make a distinction between rainfall intensities per hour (25 mm/h) and per day (50 mm/day).

As a minimum available water storage capacity of 25 mm was defined as criteria for the water retention performance, days that face more than 25 mm/day or more than 50 mm/day rainfall will be studied separately. It should however be realised that an intensity of 25 mm/day could be caused by one single heavy rain event of 25 mm/h, or several less heavy rain events during the entire day that sum up to 25 mm as well. However, on a daily time step, any event with an intensity larger than 25 mm/day is expected to cause runoff. Furthermore, it is possible to chose different valve positions over time. For example, it can be selected to open the valve during winter months and close it during summer. For the first model runs it was decided to keep the valve closed for the entire time, resulting in a maximum storage capacity of the water storage layer of 60 mm. No valve management is selected yet.

The model output is a time series which includes daily values for runoff and the water depth at the water storage layer. Also the model counts the number of days with high temperatures, an empty water storage or extreme rainfall. Based on the output, it is possible to check whether the roof faces heat, drought or extreme rainfall and how the roof system responds to this based on the criteria that have been defined before.

Model calibration

Model calibration was required to find the best-fit parameter for the crop coefficient, K_c. Since the vegetation at the green-blue roof consists for a large part of sedum, the average crop coefficient for the roof will presumably be close to the crop coefficient that belongs to sedum. Unfortunately, in literature no agreement has yet been reached on the value of the crop coefficient for sedum plants. Locatelli et al. [31] studied a green roof in Denmark that was covered with sedum and came up with crop coefficient of 0.78 during summer and 0.62 during winter. Starry et al. [42] points out that there are also significant differences in behaviour between various sedum species, like Sedum Kamtschaticum and Sedum Album, on water use and evapotranspiration. For three different sedum types they estimated a crop coefficient of 0.27-0.69 during spring, 0.29-0.85 during summer and 0.59-0.79 during autumn.

For the bucket model an estimate of the crop coefficient is required for green-blue roofs under Dutch climate. For the calibration process manual parameter assessment based on 'Trial and Error' was performed. The model output for runoff (Q_{out}) and the water storage depth at the storage layer (S_{blue}) for the period from 16th of June til 30th of September were compared with measurements from the roof experiment that were obtained for the same period. To assess the predictive skill of the bucket model, the Nash-Sutcliffe model efficiency coefficient (NSE) and the RMSE-observations standard deviation ration (RSR) are used [46]. The best NSE and RSR values for runoff and water storage depth were found for a crop coefficient of 0.8. This resulted in a NSE for runoff and water storage depth of respectively 0.62 and 0.91. An extended explanation of the calibration process is given at Appendix B.

Modelling 4 scenarios

To understand the water consumption performance of a green-blue roof system with 60 mm storage capacity, now and towards the future, the bucket model is used to model different climate scenarios. First, the current climate data is used as input to understand the roof performance of the past 30 years. This case will be referred to as the reference case (REF) and the data is based on 30-years historical data for the period 1981-2010. Additionally, the four climate scenarios of the KNMI, as defined in section 4.2.1, are used as input. This results in the roof performance for a 30-years period around the year 2050. Table 4.1 gives an overview of the five model runs that will be performed:

Model run	Label	Climate data
1	REF	Current situation (1989-2019)
2	GH	Climate scenario GH (2035-2065)
3	GL	Climate scenario GL (2035-2065)
4	WH	Climate scenario WH (2035-2065)
5	WL	Climate scenario WL (2035-2065)

Table 4.1: An overview of the five model runs, their labels and the climate data they rely on

4.3. Model results: green-blue roof performance on water use

This section will show the model results after running the bucket model for the different climate scenarios. Before analysing the model results on the roof performance, it is important to take a look at the climate induced changes in precipitation and temperature that are predicted by the climate scenarios around the year 2050 (section 4.3.1). This will already give an indication of the challenges on water consumption that can be expected. In section 4.3.2 the actual performance of the roof on water consumption and water storage is shown for different climate scenarios and compared to the reference case.

4.3.1. Climate induced changes of extreme rainfall, temperature and drought

Based on 30 years of data of the reference case and the four climate scenarios, the change in average monthly precipitation and the occurrence of warm days is shown in Figure 4.3. The average monthly rainfall is the highest between August and December and the lowest during spring. April receives on average the least precipitation, namely less than 50 mm per month. When comparing the differences between the reference scenario and the four climate scenarios, the effect of climate change will most likely result in higher monthly precipitation averages for the entire year, except for the summer period (June-August). The reduction in precipitation in summer is mainly visible for scenario GH and WH, for which the change in air circulation is larger which is expected to result in drier summers. The four climate scenarios together show the uncertainty of the future predictions, in which scenario WH represents the largest precipitation increase during winter and precipitation decrease during summer.

Also the maximum daily temperature will be affected by climate change. Figure 4.3 (right) shows the average number of days per month with temperatures above 25 degrees. Warm days occur currently mainly between May and September (reference scenario). Based on the climate scenarios, an increase in the number of days with high temperatures should be expected. For scenario WH the increase in warm days is the highest, resulting in a new average of 13.5 days with temperatures above 25 degrees in July.

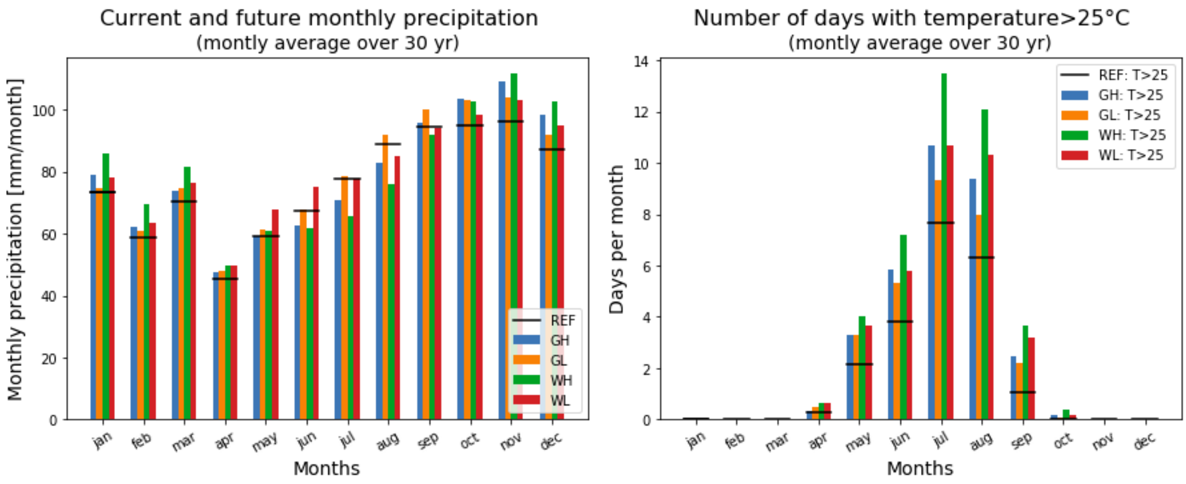

Figure 4.3: (left) Average monthly precipitation at the green-blue roof and (right) the number of days per month with temperatures above 25 degrees. The monthly values are an average over 30 years of data. The predictions by four climate scenarios (GH, WH, GL, WL) around 2050 are compared to the reference case (REF) for 1981-2010.

Based on the climate induced changes in precipitation and temperature, the frequency of occurrence for dry spells is also expected to change. As drought is a result of little precipitation and high evapotranspiration, the chance that droughts occur will increase when the chance on rainfall decreases while temperatures increase. The most significant droughts are expected to happen for scenarios GH and WH, since these scenarios predict drier summer months in combination with the large increase in days with high temperatures.

Besides the average changes in monthly precipitation it is also useful to understand how the frequency of occurrence for *extreme rainfall events* will change. Therefore the number of days per month over the total of 30 years with precipitation intensities of more than 25mm/day and 50mm/day are shown in Figure 4.4. Please remember that due to the fact that the model makes use of daily time steps, we will focus on days for which the total daily rainfall is more than the available water storage threshold of 25 mm. As becomes clear from Figure 4.4 (left), rainy days with more than 25mm precipitation occur currently more often for the period of July til November, with a clear peak in August. In general the occurrence of rainfall with an intensity of 25 mm/day will increase year-round for all scenarios towards the future. This increase is the strongest in autumn and winter months for scenarios WH and WL.

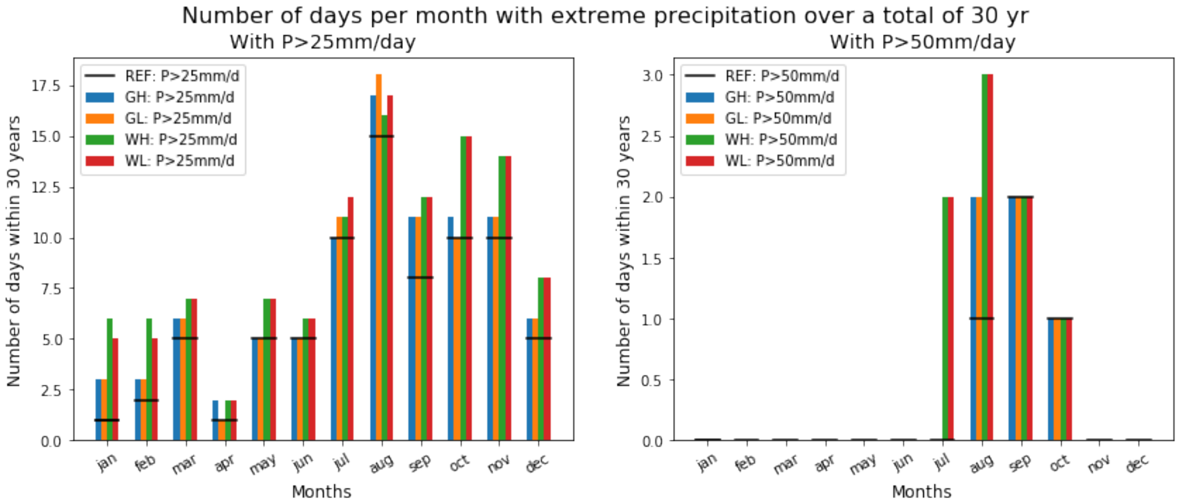

Figure 4.4: The number of days per month over a total of 30 years with daily precipitation exceeding 25 mm/day (left) and 50 mm/day (right). The occurrence of heavy rainfall is the highest in August, with more than 15 days with P>25mm/day over 30 years. This equals a return period of two years. The predictions by four climate scenarios (GH, WH, GL, WL) around 2050 are compared to the reference case (REF) for 1981-2010.

Days with extreme rainfall (>50 mm/day) do not occur all year round, see Figure 4.4 (right). Based on the reference case, extreme rainfall seems to occur only during late summer and autumn, for the months August, September and October. Future predictions however show that days with extreme rainfall of this intensity will occur more often and also earlier in summer. This results in an increase of days with extreme rainfall for July and August. Scenario WH and WL give the highest increase in occurrence of extreme rain events. Especially for scenario WH, which also predicted a lower monthly average for the summer months, this indicates less but more intense rainfall events during summer months towards 2050. However, it should be noticed that days with rainfall >50 mm/day are rather scarce. For the reference scenario this happened in total four times within the 30 year data series that was analysed. This makes it more difficult to draw firm conclusions on the observed trends regarding rain events with intensities as large as 50 mm/day. However, based on the observations for extreme rain events of >25 mm/day it can be stated that to stay or become climate resilient with regards to extreme rainfall, sufficient water storing capacity must be available mainly from July til November.

4.3.2. Roof performance on water consumption and storage for 4 scenarios

The paragraphs below will show the spread in roof performance for the four different climate scenarios during extreme rainfall, heat and drought. The performance of the reference case is added as a reference to make the sensibility to climate change in 2050 more apparent. When we compare the actual performance on water consumption and storage based on the defined criteria with the ideal desired performance, it becomes clear how climate resilient the roof system will be towards the future. Also it shows if, when and where challenges are expected to arise. The results are based on the bucket model for a green-blue roof with a permanently closed valve and a water storage of 60 mm.

Performance during extreme rainfall

Based on the criteria to measure the water retention performance of green-blue roofs, the available (empty) water storage capacity is modelled for every single day per year, over a period of 30 years. Figure 4.5 (left) shows the average available storage capacity per month (averaged over 30 years) for the different scenarios. When the available storage capacity of the water storage layer is more than 25 mm, the roof is able to (partly) retain a rain event of 25mm/day and thus fulfills the criteria on water retention performance during extreme rainfall.

For the reference case the available storage capacity is on average sufficient (>25mm) for only for 4 months a year, namely from May to August. Based on the climate predictions, the available storage capacity is expected to increase during these months for almost all climate scenarios. The combination of less precipitation, high temperatures and high evaporation rates, will probably result in a quicker drying of the water storage layer and therefore less water is stored during the summer months. This results in an increase of the available storage capacity for months which currently already show a sufficient available storage capacity. Besides, September is also expected to become slightly better capable of storing extreme rain events for the scenarios GH, WL and WH. However, for the period from October til May the roof is not well able to capture and store (extreme) rainfall, and this will not improve as a consequence of climate change. The low retention performance during winter is a result of the decision to close the valve permanently. As evapotranspiration rates are low in winter, the water storage layer is not able to empty itself and remains full of water most of the time. To enhance the retention performance valve management could be an option. The effect of such a measure and others is discussed later in this report at Chapter 5.

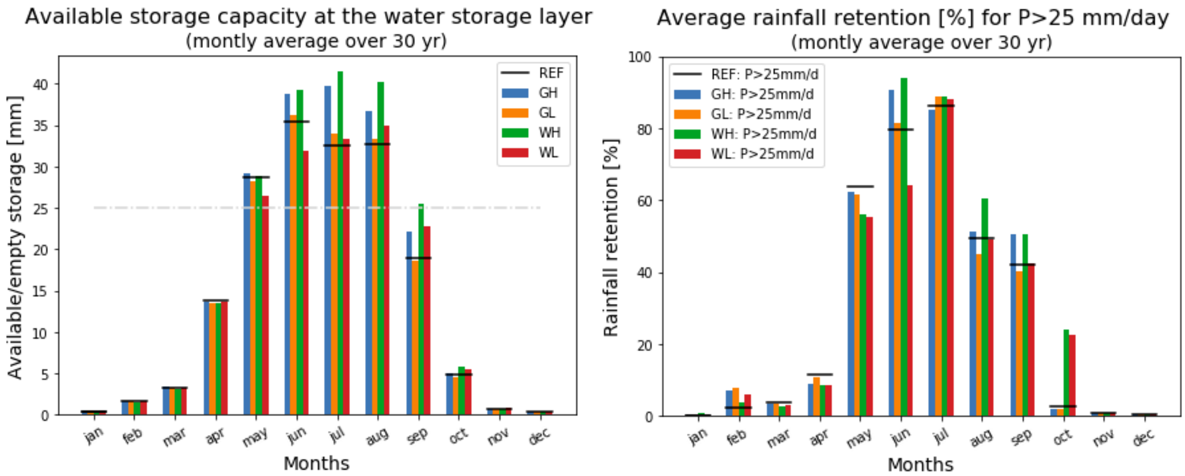

Figure 4.5: (left) Available storage in the water storage layer per month. The water retention performance during extreme rain events can be fulfilled when at least 25 mm of storage is available. (right) Average monthly rainfall retention in percentage for days with a rainfall intensity of P>25 mm/day. The monthly values are an average over 30 years of data. The predictions by four climate scenarios (GH, WH, GL, WL) around 2050 are compared to the reference case (REF) for 1981-2010.

Figure 4.5 (right) shows the monthly retention capacity for days that faced more than 25 mm or 50 mm precipitation per day. The rainfall retention is the percentage of the daily rainfall that is stored on the roof instead of being runoff to the sewer system. For months with a large available storage capacity, the rainfall retention can be up to 80-90%, while during winter the retention is nearly zero on rainy days. The yearly average retention for days with P>25mm/day is no higher than approximately 30% for both the reference case and the climate scenarios. Especially during the months October and November, when the occurrence of rainy days with P>25mm/day is relatively high and will increase towards the future, the retention capacity is insufficient for the situation with a permanently closed valve.

From the climate induced changes in precipitation, we have also seen that the days with extreme rainfall (P>50mm/day) will occur more frequently and mainly earlier in the year, in July and August. The expected shift of extreme precipitation to mid-summer is actually beneficial as more storage is expected to be available in these months. The retention performance in July and August for the climate scenarios does therefore not show a reduction compared to the performance for the reference scenario.

Performance during heat waves

To measure the cooling performance by water for green-blue roofs, the number of days per year with temperatures above 25 degrees are measured as well as the number of days for which in addition the water storage layer was empty. The climate induced change in temperature results in an increase of days per month with maximum temperatures above 25 degrees for the period from May to September. Not surprisingly, this increase is also clearly visible when we look at the number of days per month with both high temperatures and an empty storage, see Figure 4.6 (left).

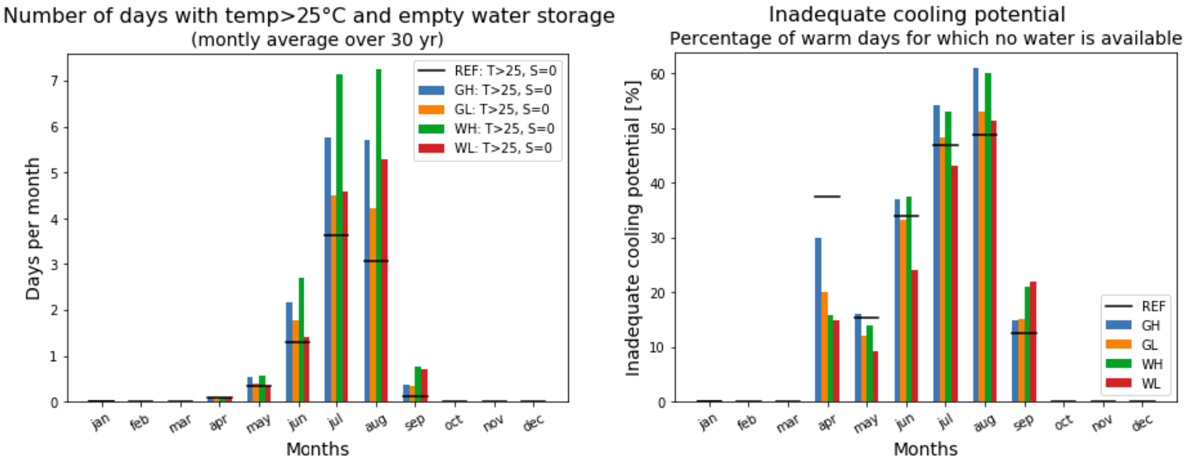

Figure 4.6: (left) The number of days per month with temperatures above 25 degrees and an empty water storage averaged over 30 years of data. (right) The inadequate cooling potential is the percentage of summer days with temperatures above 25 degrees for which no water is available for cooling and the cooling demand is thus not met. The predictions by four climate scenarios (GH, WH, GL, WL) around 2050 are compared to the reference case (REF) for 1981-2010.

The inadequate cooling potential for the different scenarios is given in Figure 4.6 (right). The inadequate cooling potential is the percentage of warm summer days for which no water is available in the water storage layer and the cooling demand can thus not be met. The reference case shows that during July and August the water storage layer does not contain water for 50% of the days for which high temperatures were measured. In general, the inadequate cooling potential will change with about 5-10% towards the future in both negative and positive direction. However, the inadequate cooling potential also gives a skewed picture. If we look at the inadequate cooling potential of the reference case for April, in 38% of the cases that high temperatures are measured, water is not available for cooling. However, from the left figure we see that the actual number of days for which this was the case, average over 30 years, is very small. Percentage wise, the future scenarios are not expected to perform much worse, but in absolute values the total number of days with high temperatures and an empty water layer will clearly increase. The roof and its environment are thus expected to face heat more often towards the future, as cooling by water will not always be possible.

Performance during droughts

To study the performance during droughts, the duration of dry spells is measured as well as the frequency of occurrence in the period from April to September. A dry spell is a period for which the water content is lower than RAW and the vegetation faces water stress. In addition the water storage layer is empty. The number of dry spells with a duration longer than 21 days will define the vulnerability to drought of the green-blue roof.

Figure 4.7 presents the number of dry spells per month that lasted for longer than 21 days over a total of 30 years of data. For the reference case the first dry spells have a chance to occur in June and no later than August. Scenarios GL and WL only predict an increase in the occurrence of dry spells in July, while scenarios GH and WH show a clear increase for all summer months including May. This strong increase for scenario GH and WH is a result of the predicted decrease in summer precipitation and increase in temperatures.

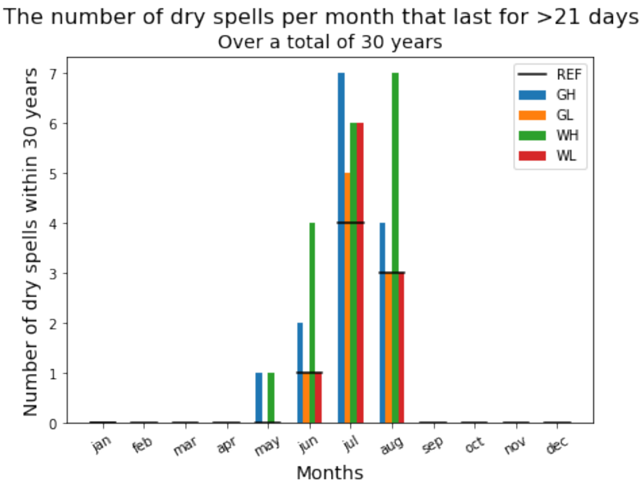

Figure 4.7: Monthly occurrence of dry spells that lasted for more than 21 days over a period of 30 years. When six dry spells have occurred in July spread over 30 years, this implies a probability of occurrence of 0.2. The predictions by four climate scenarios (GH, WH, GL, WL) around 2050 are compared to the reference case (REF) for 1981-2010.

The largest total number of dry spells with a duration longer than 21 days was found for scenario WH, namely 19 dry spells within 30 years. This is also the scenario that resulted in the longest dry spell, lasting for 47 days continuously.

4.4. Discussion on water performance and climate resistance of green-blue roofs

It was the aim of this chapter to answer the following question: Which elements and uncertainties play an important role in making green-blue roofs more climate resilient and sustainable with respect to water usage?

To start with, based on the model results it becomes clear that the different climate scenarios give a wide spread in their predictions of the roof performance on water consumption. Together they represent the uncertainty in climate model predictions for the Netherlands and for extreme cases this uncertainty becomes more visible. Especially scenario GH and WH result in more harsh conditions for the roof to fulfill its water-related functions. These two scenarios assume a larger change in the air circulation pattern above the Netherlands. Stronger increases in the frequency of westerly winds in winter lead to stronger precipitation increases, more wet days and less cold nights, while enhanced easterly winds in summer result in dryer and warmer conditions. The effect of this change becomes mainly visible during summer when the water demand for irrigation and heat mitigation start to play a role as well. Better drying conditions, influenced by temperature, humidity and wind, result more often in a completely dry roof, which could be problematic for vegetation survival and heat mitigation by the roof system. A stronger change in air circulations seems to have a larger influence on the roof performance than a higher increase of global temperature, as the latter is the case for scenario WH and WL. This suggests that the climate sensitivity of the roof system is higher for a change in air circulations while it is more robust regarding changes in the global temperature.

Furthermore, there is a clear relation and interaction between the different water-related functions of a green-blue roof which affect the performance on water use. As was expected, the roof performs good on rainwater retention when the water storage is empty, but at the same time this is undesirable regarding the water need for vegetation and cooling. Not surprisingly, the same problem occurs the other way around. However, it starts to become interesting when we focus on the timing of the main challenges regarding the different functionalities.

Not necessarily every dry spell forms a danger to vegetation, while at the same time the increased water storage capacity could be very useful when the occurrence of extreme rainfall is expected to increase. Based on the results, the main challenges regarding extreme rainfall retention are related to the expected increase of extreme rain events in June and July and the current insufficient retention capacity in September and October. As an attempt to anticipate to these predicted challenges, solutions could for example be the increase of the available storage capacity, by introducing operational water control or a combination of both.

It was promising to see that another effect of climate change is actually the increase of available storage capacity in the months June and July. As a consequence the water retention performance will very likely not be reduced, which is good. At the same time it is important to make sure that the reduction in water availability in the summer months does not result in water stress for the vegetation. To guarantee vegetation survival it could be an option to supply additional water by irrigation when dry spell lasts for more than 2 or 3 weeks, depending on the type of vegetation. However since the risk of extreme rain events will increase for those months, it would not be advised to fill the water storage layer completely by irrigation since this makes the roof less resilient to extreme rainfall. Similar to irrigation for vegetation, it would also be an option to actively supply water to the roof on days with high temperatures but an empty water storage. Meanwhile, based on the results from Chapter 3, it can be questioned if and how much the presence of water in the water storage layer will actually contribute to additional cooling. This could be a reason to only focus on fulfilling the water demand for vegetation, and neglect the insufficient water availability for cooling.

In September and October, the current retention capacity of extreme rainfall is almost zero and therefore not satisfactory. Climate change will most likely result in an increase of monthly precipitation, while the occurrence of extreme rain events will remain the same or even increase. For the situation with a permanently closed valve the water retention performance for these months will remain insufficient towards the future. Due to low evaporation rates in winter, the water storage is not able to empty itself in time after a rain event. If two heavy rain events follow each other rapidly, the water from the first event has not have been evaporated yet, reducing the initial storage capacity of the water storage layer when the second event occurs. To increase the retention performance during these months, it would be beneficial to actively reduce the amount of water that is stored. To achieve this, operational water control should be introduced. The effect of this measure on water retention, the cooling performance and water demand by vegetation will be discussed later on in Chapter 5 *How to improve the performance of green-blue roofs?*.

To summarize, the four climate scenarios give a clear spread in their predictions for water performance during extreme conditions. The different water functionalities show a clear relation, which sometimes results in conflicts especially in the summer months. However, there is also a positive link between two expected challenges. For example the increase in extreme rainfall in July and August, while due to increased temperatures the storage capacity also increases in those months. By thinking carefully about which functions are the most important for specific green-blue roofs, it will become easier to understand, based on the above results, where main challenges can be expected towards 2050. This will also be helpful when measures have to be selected to optimize the roof performance on water consumption in combination with its main function. If the main reason why the roof is constructed is the enhance water retaining performance, different measures might be selected to make the roof future proof than when the aesthetics, appearance and life span of the vegetation layer is the most important.

5

How to improve the performance of green-blue roofs?

This chapter will discuss possible improvements that can contribute to making green-blue roofs more resilient to climate change. Based on the findings from Chapter 3 it was already stated that green-blue roofs do not result in a much cooler indoor and outdoor environment than green roofs, while the difference in temperature compared to a conventional black roofs is more significant. The main reason to implement green-blue roofs, instead of green roofs, thus is related to the improved ability to storing and retaining rainwater instead of enhancing the cooling effect. Based on modelling results from Chapter 4 the relation and conflict between the water demand for vegetation and cooling and the demand for water storage became clear. Improvement of the water retention capacity by emptying the water storage layer of green-blue roofs can have a negative effect on the resistance of the vegetation to drought. This mutual relationship makes it challenging to select the right measures to improve the roof performance, without negatively affecting any of the other beneficial properties. Depending on the main objective, which underlies the choice of implementation of a green-blue roof, different improvements can be selected. The following sections will discuss several measures and their ability to improve water retention, cooling, vegetation survival or a combination of those.

5.1. Valve management to enhance water retention

The water retention performance of green-blue roofs could be enhanced in some specific cases by introduction of operational water control, or in other words *valve management*. Valve management means that the valve of the water storage layer is opened and closed in a controlled manner to allow drainage from the roof. This section will give examples of how valve management can be applied to improve rainfall retention throughout the year without negatively affecting the irrigation demand which is needed to keep the vegetation healthy and alive.

As was concluded based on the modelling results at Chapter 4, the main challenges regarding extreme rainfall retention are related to the expected increase of extreme events in June and July and the current insufficient retention capacity in September and October. For a green-blue roof with a storage of 60 mm, the retention capacity of extreme rainfall in September and October is almost zero as the water storage is full with water when the valve is kept permanently closed. As climate change will most likely cause both an increase of monthly precipitation and an increase of the occurrence of extreme events, the water retention capacity will remain low if no additional measures are taken. Due to low evaporation rates in winter, the water storage is not able to empty itself in time after a rain event. If two heavy rain events follow each other rapidly, the water from the first event has not been evaporated yet. The reduced initial storage capacity of the water storage layer is disadvantageous when a second event occurs. To increase the retention performance during these months, the amount of water that is stored in the water storage layer must actively be reduced. This can be achieved by applying valve management.

What is the chance that two extreme rain events (P>25 mm/day) occur quickly after each other?
Based on earlier assumptions (section 4.2.2) it was stated that at least 25 mm of available storage is needed to enable a green-blue roof to retain a heavy rain event. For the hypothetical case where the water storage is filled up completely after an extreme rain event and the evapotranspiration rate is 3 mm/day, it takes approximately 8 days before the roof is ready to capture a next extreme event. The value of 3 mm/day is realistic in summer months but will be reduced to almost zero in the winter. By analysing the 30 years of precipitation data that was obtained from the KNMI between 1981 and 2010 the following could be observed: 14 times a second rain event with an intensity of P>25 mm/day followed within 8 days after the first extreme rain event. In 2004 there were even four of these events within 9 days. The chance that two events occur rapidly after each other is the highest in August and also high in September-November. These observations emphasize the need of emptying the water storage on purpose from August onward.

Currently, valve management is already applied to several green-blue roofs in the Netherlands. One of the methods that is used is designed by designed by Metropolder Company [32]. According to their approach, the valve is kept closed from the first of March until the first of October, while from October onward the valve is open as long as it remains dry. When it starts raining, the valve closes automatically when more than 6 mm of rainfall occurred in the past three hours. The valve is re-opened when it is has been dry for at least six hours after the rain event. This method works well to reduce and delay the peak runoff to the sewer system. However, as a consequence of climate change, the current selected start and end date of this measure will probably be affected.

To show the effect of valve management on the water retention capacity of green-blue roofs in combination with climate change, valve management is added to the bucket model that was used in Chapter 4. Different from how the model was used in Chapter 4, valve management is now added to the model in such a way that the valve is no longer permanently closed during the winter period. As the model is limited to the use of daily time steps, it was decided to lower the valve, causing runoff from the roof to the sewer system, on all the days without precipitation during the autumn and winter months. To start with, the following months were selected for applying valve management: January, February, September, October, November and December. While the roof still functions as a temporary storage during rainy days, the storage capacity is recovered as soon as possible after a rain event by applying valve management so the roof is ready to capture a next event. But successful implementation of valve management should not lead to a reduction in performance of other water-related functions of a green-blue roof, like providing water for cooling and vegetation. Therefore it has been studied if and how the timing of valve management throughout the year will be affected by climate change, without reducing the performance on cooling and vegetation survival.

By running the model with valve management for different months and climate scenarios, it was possible to select the months for which valve management results in an optimization of the retention performance without negatively affecting the severity of droughts and vegetation survival. Especially in the case of a dry early spring, it is important to start in time with capturing and storing water in the water storage layer so it can be used to bridge long and dry periods. April, which is seen as the start of the growing season, receives on average the least precipitation (see Chapter 4, Figure 4.3), based on current data as well as for the different climate scenarios. As a consequence, water must be already be retained on the roof no later than the beginning of March, so enough water can be stored upfront to the start of the growing season. Although the application of valve management til the end of March enhances the retention capacity in that specific month, this will have a negative effect on the sensitivity to droughts and this is therefore undesirable.

From the model results from Chapter 4 it was observed that dry spells of more than 21 days have no likelihood of occurrence after August for all four climate scenarios. As the growing-season is defined from April to September, introduction of valve management from September onward will probably have no effect on vegetation survival throughout the winter period. This is proven as well by running the model for the situation with valve management starting from September onward. Actually, if we continue using the criteria for drought resistance by monitoring the number of dry spells that last longer than 21 days, it is also possible to start valve management already in August. This will not lead to an increase in the number of long-lasting dry spells for any of the climate scenario's compared to the situation in which valve management is started in September. This would imply that the vegetation survival on the roof will not be affected by the application of valve management already in August, instead of September. However, when this situation is studied in more detail, it becomes clear that the number of single days with an empty water storage in August will increase, as well as the number of dry spells that lasts for more than two weeks. When more vulnerable and water demanding vegetation is present that, for example, requires water every two weeks, it might not be desirable to actively reduce the amount of stored water in August by applying valve management. The small increase in rainfall retention performance that could be achieved is counteracted by the reduction in drought resilience that would be the result as well. Depending on the main function of the roof and the drought resistance of the applied vegetation types, it could be decided to implement valve management already in August. However, when in addition also cooling by water plays an important role, valve management should not be implemented earlier than in September since August is known as a month with high temperatures for which the presence of water is desired.

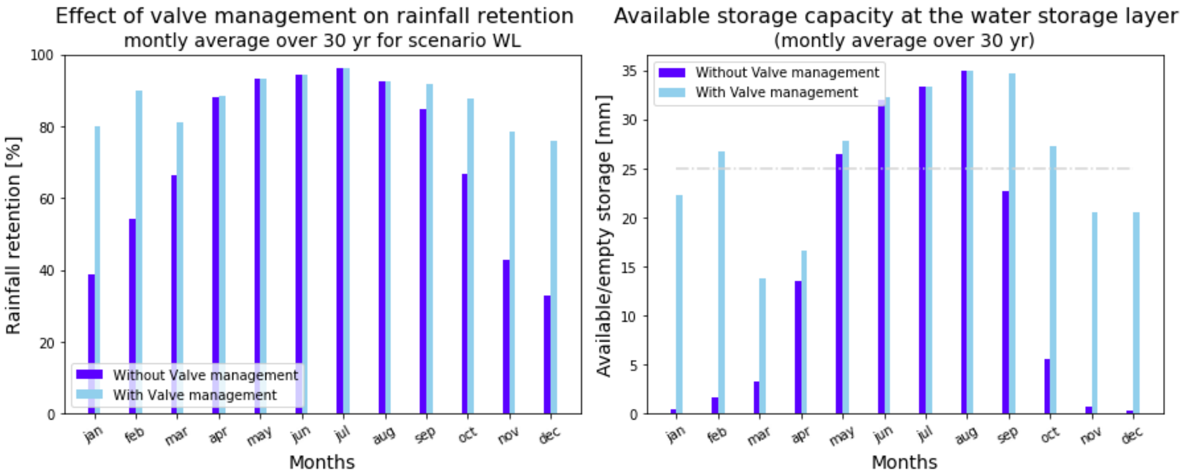

Figure 5.1: (left) The effect of valve management on the average monthly rainfall retention of the roof. (right) The effect of valve management on the monthly average available storage capacity at the water storage layer. Valve management is applied from September up to and including February. An empty storage of 25 mm is always sufficient to capture an extreme rain event. The monthly values are an average over 30 years of data and represent the climate scenario WL for 2035-2065. Comparable results were found for the other climate scenarios.

Valve management from September up to and including February can enhance the retention performance of green-blue roofs significantly during the winter period, as can be seen at Figure 5.1. Without valve management, so with a closed valve all year round, the average retention capacity on rainy days was only between 30-60% during the winter months, see Figure 5.1 (left). By applying valve management, the average retention performance was increased to up to 80% for the winter period. This means that 80% of the total amount of rainfall has temporarily been stored in the roof system instead of being discharged immediately. As a result of valve management there is on average at least 20 mm of storage available all year round, except for March and April, see Figure 5.1 (right). This is again a large improvement compared to the situation without valve management. With this type of valve management, the roof is however still not able to retain 100% of the yearly rainfall. This can be explained by the fact that the model makes use of daily time steps. If it is raining for several days on a row, the valve will be opened no earlier than on the first entirely dry day that follows. In the case of a rainy week on which it rains every day about 5-10 mm, the water storage gets completely filled and flows over to the sewer system. This is not necessarily a problem, since the roof is not facing heavy or extreme rainfall on these days. By using smaller time steps, it would be possible to adjust the valve on for example an hourly basis. This enables optimization of the system in which it becomes possible to anticipate better to extreme rain events.

Of course, also other ways of applying valve management are possible. Instead of emptying the roof quickly after a rain event, it is also possible to empty the roof upfront to a rain event when rainfall predictions are taken into account. Unfortunately, some disagreement between rainfall predictions and the actual rainfall remains existing, especially when the rainfall depth has to be predicted for a specific and relative small location like the surface of one single roof.

To conclude, valve management from September up to and including February can enhance the retention performance of green-blue roofs significantly during the winter period. Given the expected challenges on water retention during heavy rain events in the future, this measure can certainly contribute to a solution for the situation in October. Also the retention performance in September will be enhanced slightly when valve management is started from September onward. The vegetation survival will not be affected by this measure as long as the valve is kept permanently closed no later than from the beginning of March up to approximately August, if relative drought resistant vegetation is used. The starting date for valve management in August or September could be redetermined every year based on actual conditions like the temperature and amount of rainfall that occurred during the previous weeks.

5.2. Ways to enhance the cooling effect of green-blue roofs

To reduce heat stress in urban areas, as proven in Chapter 3, the cooling effect of a green-blue roof is not significantly larger than for green roofs although some additional cooling can be provided by having water available in the water storage layer. To achieve this enhanced cooling, water should therefore always be freely available on warm days. From Chapter 4 it was learned that this is not always the case during the summer months. A solution could be to actively supply water to the roof on days with high temperatures. The required amount of water needed to meet the water demand for cooling can be calculated by making use of the bucket model.

Based on the earlier definition for heat, water has to be added to the roof when the water storage is empty on days with temperatures above 25 degrees. Assuming that the evapotranspiration rate on very warm summer days is approximately 3 mm/day, the water storage layer must store and supply at least this amount of water. However, when the water storage is empty, the water content of the substrate is probably also reduced. The required water demand therefore equals the water deficit in the substrate plus 3 mm of water that has to be stored at the water storage layer so it is freely available for evapotranspiration. By modifying the bucket model slightly, heat stress can be mitigated by adding water to the roof on warm days for which water deficit occurs. This results in a yearly required water supply to the roof for the 30 years for which data was available. In some years the water demand for cooling is almost negligible, while for other years the amount is larger. To illustrate how much water is required to be able to mitigate heat, also during the most heat stressed years, the average and the maximum yearly water demand for each climate scenario are presented in Table 5.1.

Climate	**Average yearly water demand to mitigate heat**			**Maximum**
scenario	[mm/yr]	[m^3/yr]	[L/yr]	[mm/yr]
REF	28,5	14,3	14270	87,9
GH	46,2	23,1	23120	117,3
GL	34,5	17,3	17250	91,7
WH	54,3	27,2	27160	118,5
WL	33,8	16,9	16880	100,1

Table 5.1: To meet the water demand for heat mitigation during warm days, the required external water supply per year is determined by using the bucket model. The average and maximum yearly water demand in this table. For the reference scenario the yearly average over 30 years is 28.5 mm/yr, while the maximum yearly demand that was observed equaled 87.9 mm/yr. The demand increases for the climate scenarios. Note: the values in liters and m^3 belong to a roof with a surface of 500 m^2

The results show that quite some water is required to meet the water demand during warm days in a year that faces a lot of heat stress: up to 118.5 mm/year for scenario WH. This is the same as refilling the entire roof with a depth of 60 mm twice during summer. Averaged over the 30 years the yearly water demand is much less and towards the future 34.5 to 54.3 mm/year has to be supplied for scenario GL and WH respectively. For a roof with a surface of 500 m^2 the yearly averaged water demand varies between 17-28 m^3 for the different climate scenarios. A quick calculation based on the current water prices in the Netherlands [11] shows that the yearly water costs will be less than 30 euro's, even for scenario WH which has the highest water demand. Although the costs of a measure like this remain small, the implementation is a bit more complex: within the bucket model only the minimum required amount of water is supplied, which in reality requires accurate monitoring of the actual circumstances at the roof. Weather predictions have to be used and a water tap or other source for irrigation should be installed. The use of drinking water to irrigate the roof is of course not a sustainable choice during periods of water shortage and heat stress. What other sources than drinking water could be used, and where should this water be obtained from? What happens if the water consumption in urban areas is restricted because of water shortage? These are all questions that need to be answered before this measure could be implemented.

Meanwhile, based on the results from Chapter 3, it can be questioned if and how much the presence of water in the water storage layer will actually contribute to additional cooling. This could be a reason to only focus on the water demand for vegetation, and neglect the insufficient water availability for cooling as the effect is not that large. Some studies on heat mitigation in urban areas actually show that not water but shade is the most effective measure to reduce the Physiological Equivalent Temperature (PET) [24, 47]. PET is a physiologically meaningful index of the perceived heat sensation of people. Measurements show a reduction in PET of 12 to 22 °C in spaces shaded by trees and buildings compared to sunlit areas, while water bodies and grass reduce the PET up to 4 °C maximum compared to impervious areas [24]. Although the substrate layer of a green-blue roof absorbs the incoming solar radiation and creates shade for the underlying concrete roof structure, this does not result in a significant reduction of the outdoor air temperature and PET. As long as the roofs do not contribute to more shading on street level their contribution to the reduction of PET sensed by urban citizens remains small [47]. The comfortable interval is between 18-23 °C and any temperature above 29°C is sensed as warm [18]. A reduction of 35°C to 31°C at the roof top will therefore not change much to the perceived heat sensation of people on street level.

However, when limited urban space is available for the implementation of comfortable parks with trees at street level, the solution could still be found on top of buildings. Green roofs and green-blue roofs do improve the thermal comfort level at the roof top level with some degrees. By improving the accessibility of green-blue roofs in combination with sun screens or trees that provide shade, rooftops can be transformed into comfortable locations where residents can escape from the heat stressed urban environment. Modelling studies have even shown that large-scale implementation of green-roofs could bring neighbourhood-wide cooling of a few degrees [38]. The combination of green-blue roofs and shade can therefore contribute to enhanced life quality of urban residents and could increase the attractiveness of densely built urban areas.

5.3. Additional irrigation to meet water demand by vegetation

Based on the results from chapter 4 it was also observed that the extent and frequency of droughts will increase towards the future which will cause challenges regarding vegetation survival on green-blue roofs. Dry spells do not necessarily form a danger to the vegetation cover as long as they do not last too long. But when the water buffer is used up, water stress is the consequence. Possible solutions to prevent the vegetation against wilting and even dying are the use of more drought resistant vegetation types, irrigation or reducing the percentage of roof surface that is covered by the vegetation. Increasing the depth of the water storage layer could also be an option, but this requires sufficient load-bearing capacity of the building structure. The following sections will discuss the pro's and con's of the different mitigation techniques.

5.3.1. Presence of a water storage layer reduces the need for irrigation

The ability of a green-blue roof to temporarily store water can be advantageous to overcome short and longer dry spells. To visualize the benefits of adding a water storage layer to the roof, the roof performance with respect to irrigation demand is determined for a green-blue roof as well as for a green roof. A green roof can be approached by a green-blue roof with a storage layer of only 5 mm (an approximation of the drainage layer below a green roof) and this approach is used within the bucket model. Results for the green roof are compared to the performance of a green-blue roof with a storage capacity of 60 mm. Without a water storage layer, dry spells become remarkably more problematic to the vegetation as can be noticed in Figure 5.2. For the reference scenario, the green roof faced a total of 31 dry spells over 30 years that lasted longer than 21 days, while the green-blue roof faced only 8 of such long lasting dry spells. Besides the larger amount of serious dry spells, also the timing of occurrence of these dry spells is different for a green roof, as dry spell already can occur in April. Figure 5.2 shows the situation for the reference case, but for the different climate scenarios the increase in number of dry spells will even be larger.

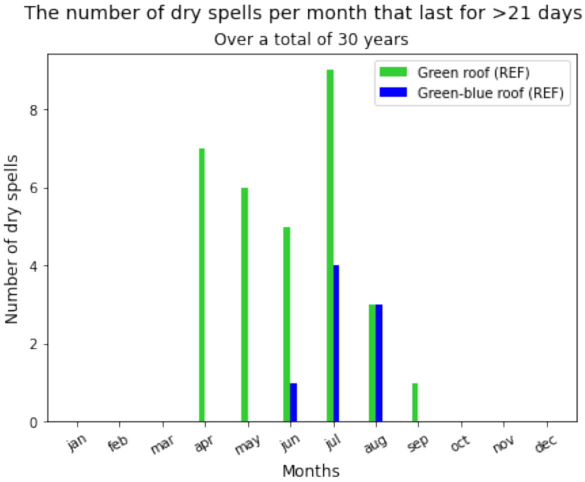

Figure 5.2: Monthly occurrence of dry spells that lasted for more than 21 days over a period of 30 years at a green roof and a green-blue roof. The monthly values represent the reference scenario REF for 1981-2010.

By adding a water storage layer to the roof system the amount of water needed for irrigation is reduced and the difference compared to a green roof can be calculated by making use of the adjusted bucket model. Irrigation will be carried out on the 14th day of a dry spell, since most vegetation will reach its wilting point after 2-3 weeks and it is important to water the vegetation before it starts to wilt. For a green roof the amount of irrigation is limited to the maximum saturation content of the substrate. After 14 dry days the saturation deficit is large and approximately 15 mm of water can be added for each irrigation event. The bucket model is designed such that the water content is refilled til the saturation capacity during irrigation. The same is done for the green-blue roof with a water storage layer of 60 mm. Although it would be possible to completely fill the water storage layer until its maximum capacity of 60 mm, this is not recommended. By completely filling the water storage layer, the available storage is reduced and the roof becomes less capable of retaining extreme rain events. Therefore it is decided to apply the same irrigation strategy for the green-blue roof as for the green roof; water is supplied until the water content is reestablished to field capacity. The amount of water needed for irrigation for a green roof and green-blue roof with an area of 500 m^2 is given in Table 5.2.

	Average yearly irrigation demand for vegetation				**Maximum demand**	
Climate	*Green roof*		*Green-blue roof*		*Green*	*Green-blue*
scenario	[mm/yr]	[m^3/yr]	[mm/yr]	[m^3/yr]	[mm/yr]	[mm/yr]
REF	31,2	15,6	8,3	4,1	65,1	28,3
GH	36,3	18,2	11,9	6,0	73,5	29,6
GL	32,7	16,4	8,6	4,3	69,0	29,7
WH	40,0	20,0	12,8	6,4	74,2	54,1
WL	33,4	16,7	8,0	4,0	70,0	29,8

Table 5.2: The required amount of irrigation per year is determined for a green roof (without the ability to store water) and for a green-blue roof (60mm water storage). The average and maximum yearly water demand are given for both roof systems. Note: the values in m^3 belong to a roof with a surface of 500 m^2

The amount of water that is needed for irrigation of a green-blue roof (see Table 5.2) is significantly less than the water demand needed to mitigate heat (Table 5.1). The yearly required water supply for the reference scenario for the green-blue roof is 8.3 mm/year , while for heat mitigation 28.5 mm/year was required. Again it can be observed that although the average water demand over 30 years is relative low, the maximum yearly demand can be significant higher, sometimes even a threefold of the yearly average. When comparing the results between the green roof and the green-blue roof it can be observed that the amount of water that needs to be supplied to the green roof is roughly three times more than for the green-blue roof. This is the direct result of the absence/presence of the water storage layer. What also can be observed is the difference in water demand for the various scenarios. Compared to the reference scenario the most optimistic scenarios, GL and WL, do not show a significant increase in water demand, while the more pessimistic scenarios, GH and WH, show an increase in the water demand of almost 50%.

Although the presence of a 60 mm thick water storage layer already reduces the need for irrigation significant, especially compared to a green roof, additional irrigation will still be necessary. Comparable to irrigation for heat mitigation, again the question arises where to get the water for irrigation from. Another option is to enlarge the water storage itself, so no additional irrigation is required.

5.3.2. Enlarge the water storage

For the situation with a water storage of 60 mm additional irrigation remains required to keep the vegetation alive, although not on a yearly basis. Depending on the climate scenario that is selected, irrigation has to be applied once every two years (REF scenario) up to almost annually (WH scenario). A logical question is therefore whether this water demand problem could be solved entirely by simply increasing the water storage capacity of the roof system. Without taking into account the load-bearing capacity of the building, different values for the water storage depths have been applied to the bucket model. To make irrigation (after 14 days) redundant for all climate scenarios, the water storage depth should be increased to 220 mm. In that case, the water buffer is large enough to make sure that the roof will always have enough stored water available that the vegetation will never experience water stress for more than 14 days on a row. A water storage depth of 170 mm would also be sufficient to make irrigation unnecessary for the scenarios GH, WH and WL, while this is still to small for the reference scenario and scenario GL.

The required increase of the water storage depth puts additional loading on the building structure, which is not always possible on existing buildings and requires additional strengthening. This also increases the costs and is therefore not always desirable. A cheaper alternative would be to increase the water storage on ground level instead of on the roof. This could be achieved by installing extra water storage tanks next to the building or in the ground from where water can be pumped back to the roof.

5.3.3. Vegetation types and diversity affect drought resilience

Instead of increasing the water availability to meet the water demand by increasing the water storage, it would also be an option to reduce the water demand by selecting more drought resistant vegetation. The green-blue roof which was used for the roof experiment is covered with various vegetation types like sedum, herbs, grasses and even small crops. This large diversity in vegetation is not common for extensive green roofs. Due to the harsh environment and the thin substrate layer of extensive green roofs, sedum plants are mainly selected for use on green and green-blue roofs in the Netherlands. The long-term success of sedum in green roof systems has been attributed to their drought tolerance and CAM (Crassulacean Acid Metabolism). Sedum plants are low-growing succulent plants that can grow rapidly when water is available yet also survive long periods without water. These plants can switch from C3 photosynthesis to CAM-cycling to CAM-idling in response to water deficit [42]. During CAM photosynthesis, the stomata in the leaves remain shut during the day which reduces water loss through evapotranspiration. At night the stomata opens to collect carbon dioxide which is stored in the plant for daytime use. This mechanism enables the plant to survive longer dry spells, and the wilting point is substantially lower than wilting points measured for non-CAM plants. While CAM metabolism makes the plant more drought resistant, the limited transpiration during the day also decreases the cooling effect on the air temperature during daytime [41].

Although sedum has proven its suitability to application on green roofs, the wide spread use of sedum-only green roofs also has disadvantages. A mono-culture is often less favorable than a diverse mixture of vegetation types in terms of attractiveness as a natural habitat for insects and birds and in terms of greater survival under dry conditions [35]. At the same time, it is shown that sedum species can function as a nurse plant to neighboring plants that are less drought resistant. Sedum album, a frequently used sedum specie on green roofs, has shown to reduce the maximum growth of neighbor plants during favorable growth conditions, while it increases the performance of neighbors during summer water deficit [6].

Based on the drought tolerance of a vegetation mixture that also includes forbes and grasses, it was decided to apply irrigation already after a dry spell of 14 days (section 5.3.1. However, when a roof with solely sedum plants is used, the frequency of irrigation could be reduced. Depending on the sedum type and conditions, there is even proof that sedum can survive up to 100 days without water [12] which would make irrigation redundant.

On the other side, the application of a green-blue roof with an increased water storage capacity, instead of a extensive green roof, also creates new opportunities to preserve plant diversity and create a healthy urban ecosystem. As is shown in Appendix C, a large variety of vegetation types was able to survive on the green-blue roof at the faculty of Civil Engineering, and even butterflies, bumblebees and birds were spotted on the roof. To let green-blue roofs contribute to a more healthy and attractive natural habitat for insects and birds, not only the size but mostly the diversity of the vegetation is important. Different from supplying irrigation, it is therefore also possible to reduce the surface covered by vegetation a little, while maintaining the same amount of water storage. In that way, more water remains available for the vegetation and it is not necessary to switch to sedum-only covered roofs. Imagine 40% of the roof surface being covered with pavement to facilitate a roof terrace for people to sit and meet. In that case only 60% of the area is covered by substrate. The volume of the water storage remains the same, but a smaller area of substrate and vegetation stands in direct contact with the water layer by the passive capillary irrigation system. This might reduce the evaporation rate from the roof, while the retention capacity of the roof as a whole is not reduced and the water remains available for the vegetation over a longer period of time. However, additional research is recommended to prove the efficiency of a measure like this on vegetation survival during droughts.

5.4. Combine measures and close the water cycle locally

As long as a green-blue roof with a water storage layer of 60 mm is applied, the water demand for cooling and/or irrigation will probably not be fulfilled throughout the summer months, and towards the future this unmet water demand is actually expected to increase. Although on a yearly basis enough water should be available by precipitation to meet the water demand during summer, the difference in timing between precipitation and evapotranspiration causes the main challenge. Ideally it should be possible to close the water cycle locally, which makes the supply of water from elsewhere unnecessary. In that way, the roof performance during heat and drought cannot be negatively affected by possible restrictions on water use. By being self-sustainable in water consumption, there is no risk of creating a conflict on water use with other water consuming stakeholders in the urban area when green-blue roofs are implemented in the urban area on large scale.

To close the water cycle locally, more precipitation from the winter has to be retained for consumption during summer. The most straightforward solution would be to improve the water retention capacity of the roof itself, without reducing the ability to temporarily store extreme rain events. Instead of increasing the size of the water storage layer on top of the roof, which is expensive and not always possible, it is also an option to place extra water storage tanks next to the building or in the ground.

The required size of the water storage depends on the functions for which water is used. In the previous sections the water demand for irrigation was calculated for heat mitigation and vegetation survival separately. A similar calculation on water demand can be made when irrigation for heat mitigation and vegetation are combined, and also valve management is applied as explained before. The average and maximum yearly water demand for this combination of measures is given in Table 5.3 for each climate scenario. The values show that the additional storage does not need to be excessively large.

Climate scenario	**Average water demand** [mm/yr]	[m3/yr]	**Maximum water demand** [mm/yr]	[m3/yr]	**Minimum rainfall surplus** [mm/yr]	[m3/yr]
REF	29,9	14,9	72,1	36,0	219,412	109,7
GH	47,6	23,8	113,5	56,8	246,428	123,2
GL	36,2	18,1	100,0	50,0	229,98	115,0
WH	55,5	27,7	118,4	59,2	253,04	126,5
WL	34,7	17,4	99,3	49,7	230,776	115,4

Table 5.3: To meet the water demand for both heat mitigation and vegetation, the required external water supply per year is determined by using the bucket model. The average and maximum yearly water demand are given. The values are comparable to the water demand for heat mitigation only. The most right column shows the minimum yearly rainfall surplus, or in other words the runoff from the roof. The surplus is always more than the maximum water demand. Note: the values in m^3 belong to a roof with a surface of 500 m^2

For an average year of the most pessimistic climate scenario (WH), 55.5 mm/year of water is needed to meet the yearly water demand for both vegetation and heat mitigation. For a roof of 500 m^2 this equals 28 m^3 of storage which could be achieved by the use of water barrels, a water tank or an underground storage. During a extremely dry and warm year the maximum yearly water demand can accidentally be much higher. Table 5.3 shows that for scenario WH the maximum yearly water demand can reach 118 mm/year. This will not only ask for a larger water storage, but also it should be wondered if the rainfall surplus is enough to provide in this need for water. The most right columns of Table 5.3 give the minimum rainfall surplus for each scenario, and it becomes directly clear that this is still more than twice as much as the maximum water demand. This supports the idea that the local rainfall surplus can be used for irrigation.

It should be realized that it is important to minimize the amount of water that is supplied for irrigation to the absolutely necessary amount. Otherwise the water storage becomes oversized and needless expensive. The stored water can be pumped up from the water storage to the roof when irrigation is required. This measure is also well suitable for existing green-blue roof systems that need to become more resilient towards the future. By increasing the water storage on ground level it is not necessary to change the construction or roof system, while the roof is able to perform better during drought and heat.

Another alternative is to connect blue roofs with green-blue roofs. This measure might be less effective than storage on ground level but it can also contribute to an increased water availability. When a building has roofs on different elevations, the highest roof levels could be used for the application of blue roofs. The lower levels, that also are visible from the building itself, can be designed as green-blue roofs. When the water level at the green-blue roof starts to go down, water from the blue roof can be used as refill. This water supply can continue until the blue roof is dried up. The only point of attention is the fact that open water evaporation from the blue roof will be higher than evapotranspiration from the vegetation layer so by the time that the green-blue roof has dried out, the blue roof is probably empty as well. It is therefore important to constantly refill the green-blue roof. The effectiveness and attractiveness of this measure depends strongly on each individual case and the amount of roof surface that is available.

On the road to sustainability it will become increasingly important to close the water cycle locally. To achieve that, the main starting point is to know how much water is needed, how the water demand can be reduced and how much water is available. A second step is to check if the shortage in water demand can be solved by taking measures like constructing additional storage on top of the roof or by using storage on (or under) ground level. The above examples show that, already by applying relative small adaptation measures, a closed cycle belongs to the achievable possibilities.

6

Conclusion and recommendations

6.1. Conclusions

The main objective of this research was: *to investigate how implementation of green-blue roofs can be made climate resilient by defining its strengths and weaknesses regarding temperature management and water consumption and come up with possible ways to improve the system*. In the attempt to achieve this objective, three main questions were defined that focus on the effect of green-blue roofs on temperature, the future water storage and consumption and potential measures that can make the roof system more climate resilient. The answers on these questions is given below.

1. What is the contribution of the water storage layer to the cooling effect of a green-blue roof?

Compared to a conventional black roof, the cooling effect of green and green-blue roofs can cause a reduction of the indoor temperature of up to 2.5 degrees during summer. It was expected to find an *enhanced* cooling effect on the indoor environment when the water storage layer of the green-blue roof was full of water, but the measurements obtained from the roof experiment were not convincing in proving this. For the green-blue roof with a full water storage as well as with an empty water storage, the indoor temperature below the green-blue roof was clearly effected by the outdoor temperature, independently from the presence of water in the water storage layer. However, by adding a water layer to the roof, the heat capacity of the roof system is increased, which made the indoor climate slightly less sensitive to sudden changes in the outdoor temperature as a delay in response was observed. As a consequence of the increased heat capacity it will take longer to warm up the entire roof system, including the water layer, but it will also take more time to release the heat after a warm period. This could be a positive quality when temperature extremes only last for a short time, say two days, since the increased heat capacity delays the response of the indoor temperature to the outdoor temperature. However, after a longer period of heat this quality becomes less relevant and actually causes a slower cooling down of the indoor environment compared to the outdoor environment when outdoor temperatures drop again. Although this might sound undesirable, this is only the case for an indoor environment that behaves as a closed box. In reality, the thermal envelope of the building and available climate systems play a role as well. When the indoor temperature is higher than the outdoor temperature, the indoor temperature can easily and quickly be lowered to comfortable levels without increasing the energy consumption. As the indoor climate system refreshes the air inside the building several times a day and makes use of the cooler air from outside, the indoor temperature can for example be lowered rather quickly.

The increased heat capacity as a result of adding a water layer to the roof system should not be confused with an increased insulation capacity. Water is a conductor and does not insulate. Within the roof system it functions more like an energy buffer. For the situation without water, the storage layer can be seen as a stagnant air layer. In contrast to adding a water layer, a larger stagnant air layer might contribute to an increased insulation capacity of a green-blue roof compared to a green roof. However, as this was not the focus of our study, our measurements were not suitable to visualizing this effect.

The finding that adding a water storage layer to the roof system does not significantly enhance the cooling effect on the indoor environment is important, since it also shows that the energy consumption of a building will not be reduced strongly by selecting a green-blue roof instead of a green roof. However, compared to a conventional black roof, the cooling effect of a green-blue roof on the indoor room environment is still significant.

Besides the indoor effect, the cooling effect on the outdoor environment has also been studied. As result of adding a full water layer to the roof system, an additional cooling effect of approximately two degrees up to at least 80 cm above the roof surface was observed. By way of comparison, the outdoor air temperature at 160 cm above a green-blue roof surface can be up to 6 degrees cooler than above a conventional black roof. For enhanced cooling by the water storage layer, the level of saturation of the substrate showed to be important. As long as water was available in the water storage layer, the soil moisture content remained high and enhanced cooling of the air was observed. However, when the water content in the substrate layer was reduced due to water shortage, the temperature gradient between the air and substrate became zero and enhanced cooling of the air did not occur anymore. Due to the presence of a water storage layer, more water remains available for a longer period, resulting in more enhanced cooling than in case of a green roof without water storage.

Even though enhanced cooling of the outdoor climate was observed as a result of a full water storage layer, the question remains how useful this is for mitigation of the UHI effect. The additional outdoor cooling effect of two degrees is not very large and remains mainly sensible close to the roof surface and on local scale. When only one single green-blue roof is applied, the enhanced cooling effect at pedestrian/street level is expected to be minor. This cooling effect could become more significant on city scale when a lot of green(-blue) roofs are applied. At the same time, any reduction of the air temperature just above the roof surface could be beneficial for the installment of solar panels or air intake for the indoor climate system in summer. But in the end, based on the limited enhanced cooling effect, the largest benefit of adding a water storage layer to a roof system should not be attributed to aspects of heat mitigation and the reduction of energy consumption. Instead the strength of a green-blue roof, compared to a green roof, should mainly be found in the enhanced quality of rainfall retention and the supply of water to the vegetation layer during dry periods.

2. Which elements and uncertainties play an important role in making green-blue roofs, with a water storage capacity of 60 mm, more climate resilient and sustainable with respect to water consumption?

Three main water-related functions of green-blue roofs have been defined, which are: to store rainfall and reduce the sewer inflow during rain events, to provide water for cooling and to provide water for vegetation. As definition it was used that a green-blue roof is climate resilient if it can continue to fulfill its water-related functions towards the future. The results from the bucket model have shown that the roof performance on water consumption depends strongly on the predicted climate induced changes in precipitation intensity and frequency of occurrence, as well as changes in temperature. The uncertainties in future roof performance are a direct result of the uncertainties within climate models. The four climate scenarios defined by the KNMI represent the spread and uncertainty in climate predictions for the Netherlands around 2050. Especially climate scenario GH and WH predict more harsh conditions for the roof, as these scenarios assume a larger change in air circulation patterns above the Netherlands which results in much drier and warmer summer months towards the future. As a consequence the roof faces will face problems in fulfilling its water-related functions. This finding suggests that the climate sensitivity of the roof system to air circulations is larger while the roof is more robust regarding changes in the global temperature.

Furthermore, the different water functionalities show a clear mutual relation, which sometimes results in conflicts, especially during summer when the water demand for cooling and vegetation starts to play an important role. The risk that dry spells with a duration of 3 weeks or more will occur, is going to increase mainly in July and August for all climate scenarios. This is a direct effect of less rainfall and higher temperatures, resulting in an water storage which is more often empty during summer. This is not only problematic for vegetation survival but also for heat mitigation. June, July and August are also the months for which the largest increase in number of heat stressed days is expected to occur. But on about 50% of these very warm days, there will be no water available for enhanced cooling since the water storage layer has dried out. Although an empty water storage makes the roof less prepared to dry spells and heat waves for which stored water is required, the roof performance on rainfall retention gets enhanced. The main challenges regarding rainfall retention are related to the expected increase of extreme rain events in June and July and the insufficient retention capacity in September and October in case of a permanently closed valve.

The performance of a standard green-blue roof with a water storage depth of 60 mm will go down, for all of the four climate scenarios around 2050. Based on these findings, it can be concluded that adaptation measures are required to make green-blue roofs climate proof.

3. What are suggested improvements to make implementation of green-blue roofs more climate resilient and future-proof?

Depending on the main objective, which underlies the choice of implementation of a green-blue roof, different improvements can be selected. For example, if the main reason to construct a green-blue roof is because of its enhanced water retaining performance, different measures might be useful to make the roof future-proof than when the aesthetics and appearance of the vegetation layer are the most important. Constructional constraints and operational costs for specific roofs also play a role.

To enhance the water retention performance during autumn and winter periods, operational water control, or valve management, is an effective measure to apply. Valve management means that the valve of the water storage layer is opened and closed in a controlled manner to allow drainage from the roof. By (partly) emptying the water storage layer, additional storage is made available to capture rainfall. The vegetation survival will not be affected by this measure as long as the valve is kept permanently closed no later than from the start of March up to approximately August or September. The date on which valve management can be applied again in August or September could be redetermined every year based on actual conditions like temperature and the amount of rainfall of the previous weeks.

Possible solutions to prevent the vegetation against wilting and even dying during long lasting dry spells are the use of more drought resistant vegetation types, the application of irrigation or by reducing the percentage of roof surface that is covered by vegetation. In the case of irrigation, a locally closed water cycle should ideally be the goal, as this makes the supply of water from elsewhere unnecessary. In that way, the roof performance during drought cannot be negatively affected by possible restrictions on water use. By being self-sustainable in water consumption, there is no risk of creating a conflict on water use with other water consuming stakeholders in the urban area when green-blue roofs are implemented in the urban area on large scale. To close the water cycle, additional storage is required. This could for example be achieved by installing an extra water tank or rain barrels on ground level and pump water up to the roof when it is needed. Another option would be to increase the depth of the water storage layer on the roof to approximately 170-220 mm, but this requires sufficient load-bearing capacity of the building structure, which can be expensive and is not always an option on existing buildings.

To enhance the cooling effect of green-blue roofs, water could be applied to the roof by irrigation on days for which temperatures are very high but the water storage layer is empty. By keeping the substrate wet, enhanced cooling just above the roof surface potentially causes advantageous conditions for solar panels and the air intake of climate systems, but this has to be investigated more. However, as the enhanced cooling effect on the urban environment and on street level is expected to remain minor, other measures like creating shade will probably be more efficient regarding urban heat mitigation. But, when limited urban space is available on ground level, the multi-functional use of roof tops can still form a solution. By improving the accessibility of green-blue roofs in combination with sun screens to provide shade, rooftops can be transformed into comfortable places where residents can escape from the heat stressed urban environment. The combination of (large-scale implementation of) green-blue roofs and shade can contribute to enhanced life quality of urban residents and could increase the attractiveness of densely built urban areas.

To conclude: it's not about green-blue roofs, its about green-blue buildings!

Although the cooling effect of green-blue roofs is not significantly better than for green roofs, the enlarged water storage capacity of green-blue roofs enables increased water retention and robustness regarding drought. Climate change will however lead to larger challenges regarding pluvial flooding, the urban heat island effect and drought, and therefore additional adaptation measures are required to make sure green-blue roofs can still contribute to a better and more resilient urban area towards the near future. Depending on the main objective, which underlies the choice of implementation of a green-blue roof, different measures are available to improve the performance on water retention and drought resistance. But in the end, its all about integration. A green-blue roof does not stand on its own: its part of a building. One of the solutions is to simply enlarge the water storage capacity so extreme rainfall can be captured and water is always available for irrigation and to maximise the cooling effect. But why not combine this with other water-related functions within the building? Green-blue roofs should not only become climate-proof, but they could also start to contribute to a more future-proof and sustainable building.

6.2. Recommendations

Green-blue roofs can definitely play a role in making urban areas more climate resilient, although additional measures are required to keep green-blue roofs climate-proof and their buildings future-proof. Below some recommendations are given on topics that require extra attention for future research with the aim of substantiating the sustainable and future-proof application of green-blue roofs.

- A variety of measures have been proposed that can contribute to making green-blue roofs more climate-proof in terms of water retention, cooling and vegetation survival. Depending on the main objective of a roof, different measures can be more relevant for specific regions than others. To support decision-makers, like roof owners and municipalities, in their choice between the various measures, a cost-indication of the various measures should become available.
- As a large part of the paved surface in cities is privately owned, the municipality can encourage the implementation of green(-blue) roofs by subsidies. However, the contribution to for example mitigating pluvial flooding is much less for green roofs than for green-blue roofs. It would be interesting if municipalities start to distinguish between different roof types regarding the financial support they provide. As it is certain that urban droughts and pluvial flooding will become an increasing challenge in Dutch cities, a municipality could adjust the regulations to make implementation of green-blue roofs more attractive than the application of other roof types.
- Even if the cooling effect of green-blue roofs is not always sensible at street level, enhanced cooling just above the roof surface can be very beneficial with respect to, for example, air intake for the indoor climate system or for the application of solar panels. A slightly lower air temperature can result in more efficient energy production and cost reductions. Further research is needed to substantiate and quantify the benefits for architectural elements of a building (location of climate systems, windows, etc) as a result of implementation of green-blue roofs.
- Increasing the well-being of both people and the natural environment has received increased attention in the past years, also in urban areas. The application of green-blue roofs with an increased water storage capacity, instead of a extensive sedum-only covered green roofs, creates new opportunities to preserve plant diversity and provides room to a healthy and attractive natural habitat for insects and birds. Appendix D gives an impression of the vegetation diversity and ecosystem that was realised on the green-blue roof that was used within this research. Additional research on the positive contribution of green-blue roofs to a healthy urban environment is advised.
- Previous studies on green(-blue) roofs have mainly focused on the interaction of the roof with the (urban) climate, water retention and thermal effects. By adding a water storage layer to the roof system, it becomes also interesting to investigate possible interactions between the water storage and water-related functions within a building, like toilet-flushing, local water purification,

etc. This could lead to a larger desired water storage, which not necessarily needs to be located on top of the roof. Underground storage and other smart storage solutions might result in more cost efficient solutions, especially in countries where water is scarce and expensive. Additional research on how green-blue roofs can contribute to a locally closed water cycle at building or neighbourhood level is advised.

- Based on this research, at Dutch climate conditions, it appears that green-blue roofs are favorable compared to green roofs in terms of rainwater retention and drought resistance. However, it is also shown that the roof performance and climate resilience strongly depends on the local climate conditions and how these will change. Whereas westerly winds are expected to cause an increase in rainfall amount and intensity in the Netherlands, other challenges might arise elsewhere around the globe. Especially different shifts in timing of dry spells compared to the timing of extreme rainfall can turn out into very different challenges regarding the water-related functions of green-blue roofs elsewhere. To say something about the climate resilience of green-blue roofs in different regions and climates, the local climate effects should be investigated.

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A

Soil moisture and evapotranspiration

The water content of the substrate plays an important role in the retention capacity of the green layer during rainfall and the water availability during dry out events. When the soil is completely saturated, the maximum water content is reached. This is also called the field capacity or the total available water content (TAW), which is the maximum amount of water that a well drained soil can hold against gravitational forces. When the substrate is completely saturated before a rain event occurs, the retention capacity of the soil is zero. Water that percolates into the soil will directly cause runoff at the drainage layer. When the water content is not maximum, the substrate can retain and store part of the rainfall in the soil pores. Runoff will occur when the water content has increased to maximum values again.

During dry out events, water evaporates from the substrate until almost no water is present in the pores between the soil particles. Vegetation will start to face water stress when the water content drops below the readily available water content (RAW). RAW is the fraction of TAW that a plant can extract without difficulties. When the water content reduces below RAW, water becomes stronger bound to the soil matrix and is more difficult to extract by the vegetation. This also results in a reduction of evapotranspiration.

For the design of the bucket model it is important to know how the water content varies over time and what the values for TAW is. Information on this is obtained via two methods: soil moisture measurements and Lysimeter measurements. Both methods and their results are discussed below.

Soil moisture measurements

The soil moisture fluctuations at the substrate are measured by three Hobo soil moisture sensors. The average of the three sensors is given in Figure A.1. As can be observed from this figure the soil moisture remains rather constant with values between 0.145 and 0.175. The maximum observed soil moisture is approximately 0.2 m^3/m^3 while the lowest measured value is 0.03 m^3/m^3. On average the soil moisture content hovers around 0.16. For a substrate depth of 10 cm this means that 16mm of water is stored within the substrate. One clear drop in soil moisture is visible for the 30th of June, which is the result of a dry out event. The substrate was completely saturated and water was available in the water storage layer on the 18th of June. However, after several warm and dry days the water storage layer dried up and remained dry from the 26th until the 30th. From that moment onward, only water that was present in the substrate was available for evapotranspiration. As a result it can be observed that, while the soil water content was hardly affected until the 26th, after the 26th the soil water content dropped quickly during the next days. The soil water content reached a minimum of 0.03 m^3/m^3, which equals about 3 mm in a soil depth of 10 cm, before the water content was restored again by the rain event that occured on the 30th of June. These observations suggest that the soil water content remains almost constant as long as water is available in the water storage layer, although small fluctuations of 0.02 m^3/m^3 are visible. However, when the water from the water storage layer is dried up, the soil moisture is affected heavily and gets reduced rapidly. Furthermore, the soil moisture measurements suggest a TAW of approximately 16 mm for a roof with a substrate depth of 10 cm. These are important findings that can be used for the design of the bucket model.

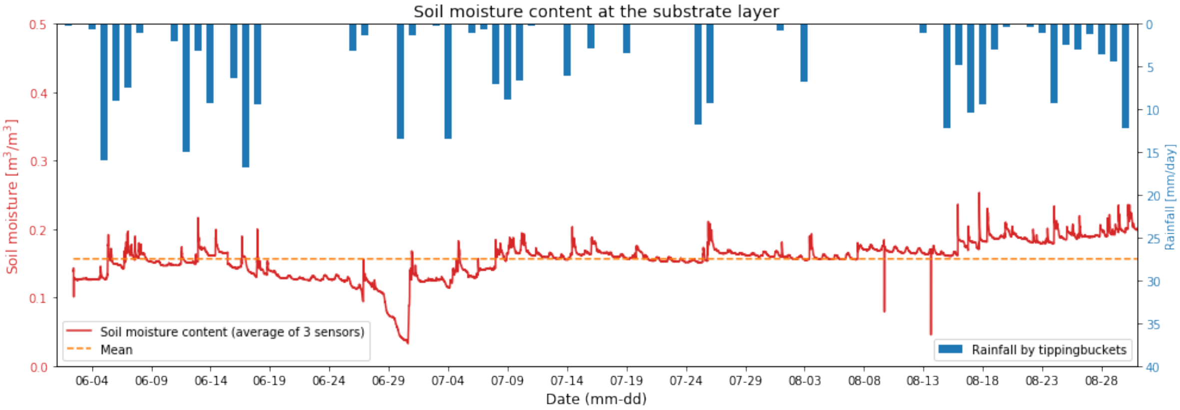


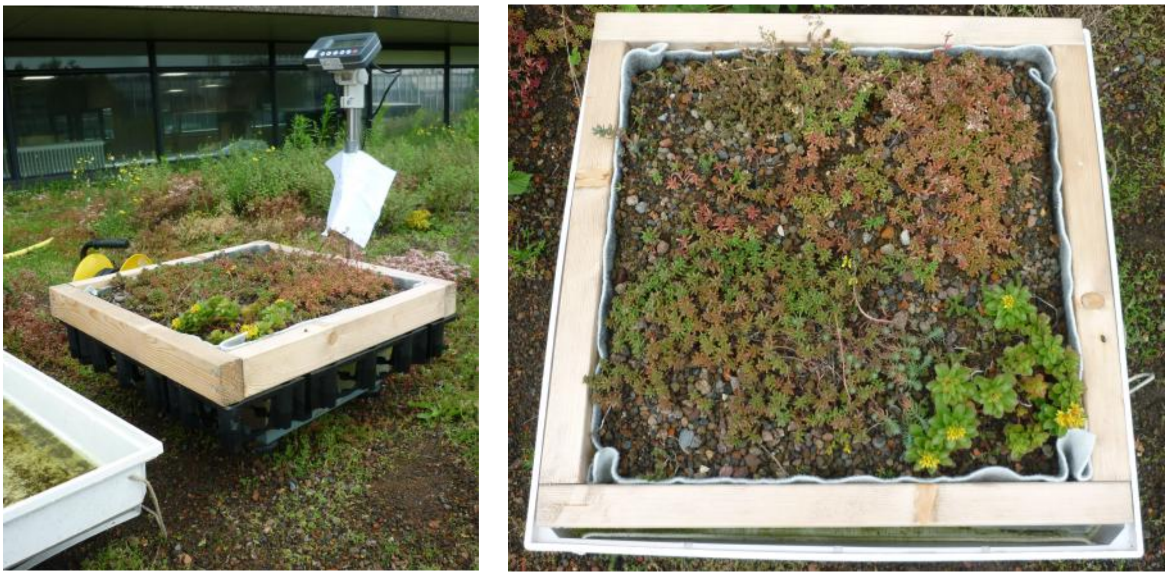
Figure A.1: The soil moisture content is measured by three Hobo soil moisture sensors. This figure shows the average of the three sensors and the mean soil moisture over this time period. Most of the peaks can be explained by rain events on that particular day. A clear drop in soil moisture is observed from June 26th-30th as a result of the dried out water storage layer.

Lysimeter measurements

Soil moisture is reduced by evapotranspiration from the soil and vegetation or by drainage. To measure the actual evapotranspiration at the green-blue roof a simple weighing lysimeter was constructed. A lysimeter is a measuring device which can be used to measure the amount of actual evapotranspiration which is released by the vegetation. By recording the amount of precipitation that an area receives and the amount water lost through drainage, the amount of water lost to evapotranspiration can be calculated based on changes in mass. Due to limitations in time and cost, it was decided to make a lysimeter from materials that were readily available. A sample of the substrate layer of 55 cm by 55 cm was placed on top of plastic crates that are similar to the ones used at the roof system. This sample was placed in a white plastic tray that, together with the plastic crates, functioned as water storage layer. The tray was put on a scale on a daily basis after which the weight was read out manually and this was repeated three times. The same procedure was repeated for the substrate layer alone (see Figure A.2a). The lysimeter measurements were executed for a period of 5 weeks resulting in 20 measurements of mass increase or reduction between the 16th of June until the 17th of July. In combination with rainfall data this resulted in daily values for evapotranspiration.

The same dry-out event between the 18th of June and the 30th of June that was measured by the soil moisture sensors was also captured by the lysimeter experiment. Based on the difference in substrate weight between the saturated and dried out condition it was possible to come up with an approximation of the TAW. On the 18th of June, right after a heavy rain event, the mass of the substrate layer was 27.413 kg. The minimum substrate weight was measured on the 30th of June, after a long dry period and just before the next rain event, and by then the substrate was 4.533 kg lighter than for the completely saturated situation. With a surface of 30.25 dm^2 this indicates a water content reduction of 15 mm. This value is supported by the value that what was found based on the soil moisture sensors. As it is unlikely that the water content was zero on the 30th of June, the TAW has to be slightly larger than 15 mm.

From the lysimeter experiment it was also possible to approximate the actual evapotranspiration at the green-blue roof. By comparing the actual evaporation with the Makkink reference evapotranspiration collected by the KNMI at Rotterdam Airport (at ca. 7 km distance), an attempt was made to relate these values to each other. As the Makkink reference evapotranspiration is based on well watered grass, this does not directly relate to evapotranspiration from the sedum covered green-blue roof. By multiplying the reference value with a crop and water stress coefficient, the KNMI values can be related to the actual evapotranspiration at the green-blue roof. This relation was important, as the KNMI provides long data series on evapotranspiration that could be used as input to the bucket model.



(a) Weighing process of Lysimeter

(b) Top view of the lysimeter

Figure A.2: (a) The substrate layer, supported by the plastic crates, is put on a scale to measure its weight. Based on the weight that was measured on the day before and in combination with rainfall data, the increase or decrease in weight implies a certain value for daily evapotranspiration. (b) Top view of the lysimeter. The vegetation coverage contains mainly of different sedum plants that also are available at the green-blue roof.

After analysing the lysimeter measurements it was unfortunately concluded that the evapotranspiration measurements were not always in line with the values that were found from the soil moisture measurements and the sensors that monitored the water depth at the water storage layer. The measured variations of the water depth by the lysimeter were quite in line with the values that were found for the green-blue roof as a whole. But, the variations in water content of the substrate layer given by the lysimeter were very different than what was measured by the soil moisture sensors for the same days. Whereas the water content was almost constant for the soil moisture sensors, the lysimeter showed larger variations, even once a soil moisture decrease of 4 mm/day. On that specific day, the total daily evapotranspiration by the lysimeter was 7.5 mm/day, which is comparable to open water evaporation of 7 mm/day on warm summer days in July [28]. Also, compared to the Makkink evapotranspiration, this would suggest a crop coefficient of almost 1.4 which does not make sense for a surface covered by sedum. Even though there is little agreement in literature on the exact crop coefficient for sedum, all studies mention crop coefficients that are smaller than one. It can therefore be wondered whether the lysimeter measurements for the water content in the substrate were disturbed by boundary effects.

One of the things that might have influenced the measurements is the fact that the entire lysimeter was placed on a small platform. This was done to make it easier to move the lysimeter onto the scale every morning. However, it also enabled warm air to warm the tray from the sides and partly from below. In addition, as the edges of the white plastic tray did not reach up to the top of the substrate layer, wind/air was better able to enter the area underneath the substrate layer, the water storage layer. As air movement can enhance evapotranspiration significantly, this might have caused the unexpected high daily evapotranspiration values that were found on some days. In comparison, at a normal green-blue roof, the air layer underneath the substrate is very likely almost entirely stagnant as wind cannot easily enter the space at the water storage layer. Lastly, the gaps between the edge of the plastic tray and the edge of the substrate surface maybe has enabled some additional open water evapotranspiration which resulted in much higher evapotranspiration values than what is realistic for a real green-blue roof with a larger surface area and comparatively fewer edges. The above explained circumstances might explain how a evapotranspiration value of more than 7 mm/day was found, but they still do not explain why the substrate showed larger variations in the water content than was measured by the soil moisture sensors. In the end it was therefore decided not to use these lysimeter measurements in the approach to find a realistic crop coefficient. Instead, the crop coefficient is defined as a result of model calibration (see Appendix B).

B

Calibration of the bucket model

Python programming language was used for the design of the bucket model. The bucket model was designed based on the concept and processes that take place at a green-blue roof. For the case of the bucket model, there was however one parameter which remained unknown, namely the crop coefficient. Since the vegetation at the green-blue roof consists for a large part of sedum plants, the average crop coefficient for the roof was expected to be close to the crop coefficient that belongs to sedum. Unfortunately, in literature no agreement has yet been reached on the value of the crop coefficient for sedum plants. Locatelli et al. [31] studied a green roof in Denmark that was covered with sedum and came up with crop coefficient of 0.78 during summer and 0.62 during winter. Starry et al. [42] points out that there are also significant differences in behaviour between various sedum species, like Sedum Kamtschaticum and Sedum Album, on water use and evapotranspiration. For three different sedum types they estimated the crop coefficient between 0.27-0.69 during spring, 0.29-0.85 during summer and 0.59-0.79 during fall.

To come up with one value for the crop coefficient, model calibration was needed to find the best-fit parameter for this coefficient. Model calibration is the process of adjustment of the model parameters to obtain a model that satisfies certain criteria. To assess the predictive skill of the bucket model, the Nash-Sutcliffe model efficiency coefficient (NSE) is used. NSE is an efficiency criteria which is frequently used in hydrologic modeling studies as well as for green roofs in specific [4, 7, 46]. To assess the predictive skill of the model the simulated model results were compared with observed measurement data. NSE is then the absolute difference between the observed and predicted values which is normalized by the variance of the observed, see Equation B.1.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{mean})^2} \tag{B.1}$$

Where, for the case of discharge measurements, O_i is the observed discharge, P_i is the predicted discharge by the model and O_{mean} is the mean of the observed discharge. The range for NSE lies between 1 and -∞, with 1 being a perfect fit. Values for NSE between 0.5 and 0.75 are awarded as satisfactory to good, while values above 0.75 represent a very good model performance [46]. However, using the NSE criterion as only criterion has disadvantages, as the differences between the observed and predicted values are calculated as squared values. As a result larger values in a time series can be overestimated whereas lower values are neglected depending on the dominant error of the model under examination [46]. For runoff predictions this can lead to an overestimation of the model performance during peak flows Therefore also an error index criteria is used: the RMSE-observations standard deviation ratio (RSR). RSR normalizes the RMSE with the standard deviation of the observed values. RSR varies from the optimal value of 0, which indicates zero RMSE and therefore perfect model simulation, to a large positive value [34]. RSR values lower than 0.7 are satisfactory. Calculation of RSR is given by Equation B.2.

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}(O_i - P_i)^2}}{\sqrt{\sum_{i=1}^{n}(O_i - O_{mean})^2}} \tag{B.2}$$

For the calibration process manual parameter assessment for the crop coefficient based on 'Trail and Error' was performed. The model output for runoff (Q_{out}) and the water storage depth at the storage layer (S_{blue}) over the period from 16th of June til 30th of September were compared with observed values that were obtained from the roof experiment measurements for this specific period. Figure B.1 shows the predicted runoff by the model and the observed runoff from the measurements. Figure B.2 shows the predicted water depth at the water storage layer and the observed water depth. The highest Nash-Sutcliffe values for runoff and water storage depth were found for a crop coefficient of 0.8. This resulted in a NSE and RSR for runoff of 0.62 and 0.61 respectively and a NSE and RSR for water storage depth of respectively 0.91 and 0.30. This relates to satisfactory results for runoff and very good results for the modelled water storage depth. Subjective assessment of the runoff hydrograph in Figure B.1 shows that although the timing is good, the runoff is often slightly overestimated. The modelled water depth slightly over- and underestimates compared to the observed data, but the overall result is very promising.

Calibration resulted in a crop coefficient of 0.8, which is quite in line with values that were found in literature for summer periods. In the bucket model the crop coefficient will be kept constant for the entire year, although in reality the crop coefficient reduces during winter. However, since the evapotranspiration also reduces significant towards the winter months, the sensitivity of the actual evapotranspiration to the crop coefficient gets small in winter. It has therefore been decided that the assumption of a constant crop coefficient is satisfactory.

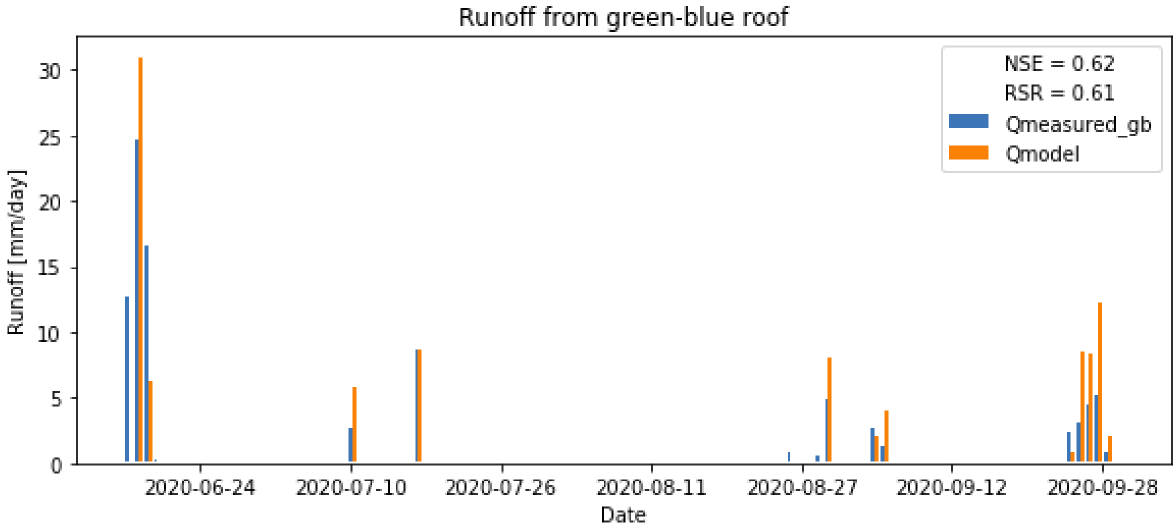


Figure B.1: Model calibration on runoff over the period from 16th of June til 30th of September. The best fit between the predictions and observations was found for Kc=0.8, resulting in NSE=0.62 and RSR=0.61 (satisfactory model result). The modelled slightly overestimates the peaks, but the timing of the peaks is good.

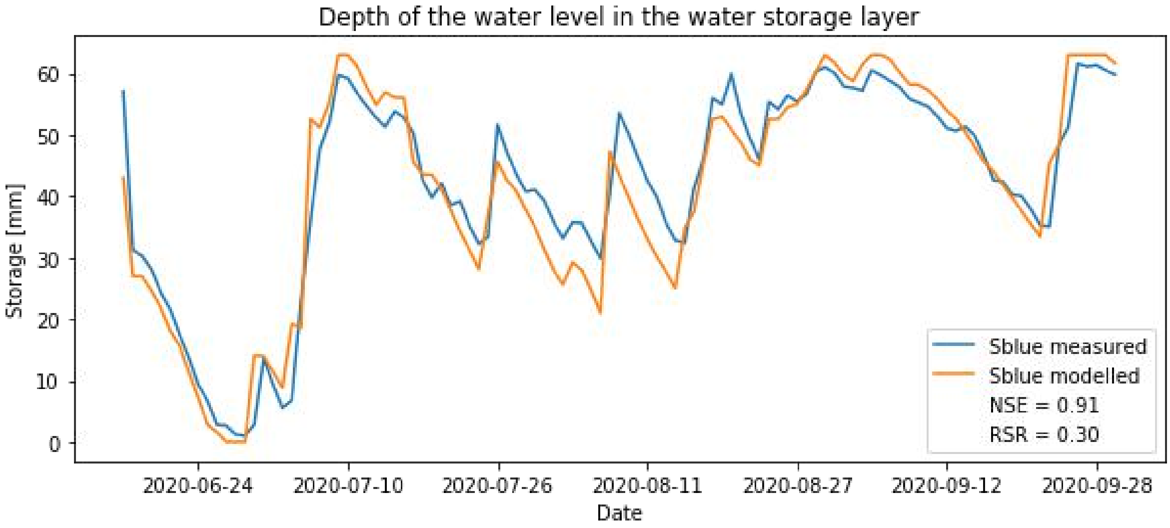


Figure B.2: Model calibration on storage over the period from 16th of June til 30th of September. The best fit between the predictions and observations was found for Kc=0.8, resulting in NSE=0.92 and RSR=0.3 (very good model result).

C

Vegetation diversity and ecosystem

The application of a green-blue roof with an increased water storage capacity, instead of a extensive green roof, creates new opportunities to preserve plant diversity. Although sedum has proven its suitability to application on green(-blue) roofs, the wide spread use of sedum only green-blue roofs also has disadvantages. A mono-culture is often less favorable than a diverse mixture of vegetation types in terms of attractiveness as a natural habitat for insects and birds and in terms of greater survival under dry conditions. In addition, the Crassulacean Acid Methabolism (CAM) of sedum plants enhance the drought resistance, but also limit transpiration and thus the cooling effect on the outdoor air temperature during the day.

On the green-blue roof at the faculty of Civil Engineering at the Delft University of Technology a large variety of vegetation types have been planted. Observations during the summer of 2020 have shown the ability of several crops to survive, which might be surprising. Since the aim of this study was not to investigate the suitability of different plants on green-blue roofs, the following images will only serve as an illustration of the possibilities that may arise regarding vegetation diversity. Some crops that did very well on our roof were: chives, strawberries, radish, garlic and lavender. Additional research on crop growth might contribute to new developments in the field of Urban Agriculture. Furthermore, green-blue roofs have shown to contribute to a more healthy and attractive natural habitat for insects and birds. Butterflies, bumblebees and several birds were spotted on the roof (see pictures).

(a) Strawberries, almost ready to pick

(b) Radish ready to be eaten

Figure C.1: The pictures a and b give an impression of the vegetation diversity that can be found on the green-blue roof at the faculty of Civil Engineering. Pictures are made by the author.

(a) Flowering chives

(b) Sugar beans

(c) Sedum can be colorful as well

(d) Bumblebee attracted by flowering lavender

(e) A mixture of grasses and flowers

(f) More flowers

Figure C.2: The pictures a-f give an impression of the vegetation diversity that can be found on the green-blue roof at the faculty of Civil Engineering. Pictures are made by the author.

D

Specifications of measurement devices

Several measurement devices have been used for the data collection during the roof experiment, as explained in Chapter 3. Below the specifications for each of the mentioned measurement devices is given.

TMCx-HD temperature probe

The TMCx-HD temperature probe can be used in air, soil or water and works with the HOBO data loggers. For the roof experiment, 2x4 TMCx-HD temperature probes were used to measure the air temperature at four elevations above both roof surface.

Range	-40°C to 100°C in air, -20°C to 50°C in water
Accuracy	0.15-0.25°C from 0 to 50°C
Resolution	0.002-0.03°C at 25 °C
Drift	<0.1°C per year

HOBO TidbiT MX2204 Temperature Logger

The HOBO MX2204 TidbiT temperature logger can be used to measure the temperature of water and air. During the roof experiment 12 of these temperature loggers were installed underneath the roof to measure the indoor air temperature in the four lecture halls that were located underneath the conventional black roof and the green-blue roof. In combination with the HOBOconnect application for mobile phones and Bluetooth, it was possible to read out the temperature logger.

Range	-20°C to 60°C in air, -20°C to 50°C in water
Accuracy	0.25°C from -20 to 0°C, 0.2°C from 0 to 70°C
Resolution	0.01°C
Drift	<0.1°C per year

FLIR A310 IR temperature sensor

Two FLIR A310 infrared temperature sensors were used to monitor the temperature of the roof surface of both the green-blue roof and the conventional black roof during the roof experiment. Both cameras were mounted to the facade of the adjacent building while they pointed towards both roof surfaces. More product information can be found on the website of *flir.com* .

Object temperature range	-20°C to 160°C
Accuracy	2°C or 2% of reading
IR Resolution	320 x 240 pixels

HOBO Rain Gauge Data Logger

A total of 8 rain gauges were installed on the roofs. The rain gauges are battery powered and collect rainfall, time and duration data. They can record rainfall up to 127 mm/hour.

Maximum rainfall rate	127 mm/hour
Callibration accuracy	1.0% (up to 20 mm/hour)
Resolution	0.2 mm
Housing	15.24 cm aluminum bucket

OPTIFLUX 2050 C/W Electromagnetic flowmeter

Two electromagnetic flowmeters have been installed: one on the drainage pipe from the green-blue roof and one on the drainage pipe from the conventional black roof.

Resolution	5 L
Measurement accuracy	0.5% of the measured value
Pressure range	till 40 bar

EC5 Soil Moisture Smart Sensor S-SMC-M005

Three soil moisture sensors were used to measure the soil moisture in the substrate layer of the green-blue roof.

Range	0 to 0.550 m^3/m^3 in soil
Resolution	0.0007 m^3/m^3
Accuracy	0.031 m^3/m^3
Soil probe dimensions	89 x 15 x 1.5 mm

E

Bucket model in python language

This appendix gives the python script that has been created to simulate the green-blue roof by applying the concept of a bucket model. The coding for the bucket model itself is given below, so anyone interested in using this model is free to copy and apply the model, in combination with referring to this report and the author. The scripts that were used to prepare the input data, to analyse the output data and to create figures that were used within this report, have not been included to this appendix. Feel free to contact the author in case more detailed information is desired.

Data preparation
Start with data preparation to create the input to the bucket model: *BucketModel(Input, Storage, Plot)*. The input consists of a dataframe called 'Input', an array called 'Storage' and wether it is desired to create plots 'True/False'. The input data should consist of the daily data with a time step of 1 day.

Input; a dataframe consisting of the following four columns

- Time ['YYYYMMDD']
- Precipitation ['mm/day']
- Makkink evapotranspiration ['mm/day']
- Maximum daily temperature ['degrees/day']

Storage; gives information on the initial storage and maximum storage capacity of the different water storing layers (see also the model itself for details) In this case for example: Storage = np.array([40, 60, 27, 15, 15])

Plot; if it is desired to create plots of the model chose 'True'

Bucket model in Python language

```
#!/usr/bin/env python
# coding: utf-8

# In[1]:

#Import the necessary packages
get_ipython().run_line_magic('matplotlib', 'inline')
import numpy as np
import matplotlib.pyplot as plt
import matplotlib as mpl
import pandas as pd
from datetime import datetime
from datetime import date

# In[2]:

def BucketModel(Input, Storage, Plot):

    #input values
    df = Input
    P = df['P'].tolist()
    ET = df['ET'].tolist()
    T = df['T'].tolist()

    Sblue_in = Storage[0]         # Initial storage in the blue layer [mm]
    Sblue_max_close = Storage[1]  # Maximum water storage in blue layer for closed valve [mm]
    Sblue_max_open = Storage[2]   # Minimum water storage in blue layer when open valve [mm]
    Sgreen_in = Storage[3]        # Inital storage in green layer [mm]
    Sgreen_max = Storage[4]       # Maximum storage in the green/substrate layer [mm]

    #Fixed parameters
    Sblue_min = 0                 # Minimum storage in blue layer
    Sgreen_min = 0                # Minimum storage in green layer
    TAW = Sgreen_max              # Total available water content
    RAW = TAW * 0.5               # Readily available water content
    Kc = 0.8                      # Crop coefficient defined from calibration

    # allocate variable parameters
    tmax = len(P)                 # Number of time steps
    Sblue = np.zeros(tmax)        # Water depth at water storage layer [mm]
    Sgreen = np.zeros(tmax)       # Water stored in substrate/green layer [mm]
    Qleak = np.zeros(tmax)        # Drainage from green layer to blue layer [mm/day]
    Qcap = np.zeros(tmax)         # Capillary rise from blue layer to green layer [mm/day]
    Qout = np.zeros(tmax)         # Outflow from blue layer to sewer system [mm/day]
    ETa = np.zeros(tmax)          # Evapotranspiration from green layer [mm/day]
    Ks = np.zeros(tmax)           # Water stress coefficient per day [-]
    Sbluemax = np.zeros(tmax)     # Max storage capacity depending on position of valve [mm]
    Valve =  np.zeros(tmax)       # Position of valve (open or closed)

    # To check and count the criteria for drought, heat and rainfall
    T25 = np.zeros(tmax)          # Days with T>25 degrees get value 1
    Sempty = np.zeros(tmax)       # Days with empty water storage get value 1
    Pextreme25 = np.zeros(tmax)   # Precipitation on days with P>25 mm/day
    Pextreme50 = np.zeros(tmax)   # Precipitation on days with P>50 mm/day
    Pnumber25 = np.zeros(tmax)    # Days with P>25 mm/day get value 1
    Pnumber50 = np.zeros(tmax)    # Days with P>50 mm/day get value 1
    Heat = np.zeros(tmax)         # Days with T>25 and Sblue=0 get value 1
    Irrigation = np.zeros(1)      # To store the total amount of applied irrigation
    Irr_number = np.zeros(1)      # Days on which irrigation is applied


    # Set initial storage Sgreen and Sblue
    Sblue[0] = Sblue_in
    Sgreen[0] = Sgreen_in

    dt = 1 #day

    for i in range(0,tmax):
        Pdt = P[i] * dt
        ETpdt = ET[i] * dt * Kc  # Multiply Makking ET with the crop coefficient (Kc)
```

```

        # Uncomment following lines if you want to apply valve management:
        # Valve open on dry days (P=0) in the months Jan, Feb, Sept Oct, Nov, Dec
#          if df.index.map(lambda x: x.month)[i] == 1 //
#             or df.index.map(lambda x: x.month)[i] == 2 //
#             or df.index.map(lambda x: x.month)[i] == 8 //
#             or df.index.map(lambda x: x.month)[i] == 9 //
#             or df.index.map(lambda x: x.month)[i] == 10 //
#             or df.index.map(lambda x: x.month)[i] == 11 //
#             or df.index.map(lambda x: x.month)[i] == 12:
#             if P[i] == 0:
#                 Valve[i] = 1
#             else:
#                 Valve[i] = 0

        if Valve[i] == 0:
            Sbluemax[i] = Sblue_max_close
        else:
            Sbluemax[i] = Sblue_max_open

        # For situations with water available in the water storage layer:
        # Sblue>0 , no water stress, Sgreen = Sgreen_max because of constant water content
        if Sblue[i] > 0:
            Ks[i] = 1

            # For situations with rain (P>0)
            if Pdt > 0:
                Sgreen[i] = Sgreen[i] + Pdt
                Qleak[i] = max(Sgreen[i]-Sgreen_max, 0)
                Sgreen[i] = Sgreen[i] - Qleak[i]
                Sblue[i] = Sblue[i] + Qleak[i]
                ETa[i] = ETpdt * Ks[i]
                Qcap[i] = ETa[i]
                Sblue[i] = max(Sblue[i] - Qcap[i], 0)
                Qout[i] = max(Sblue[i]-Sbluemax[i], 0)
                Sblue[i] = Sblue[i] - Qout[i]

            # For situations without rain (P=0)
            else:
                ETa[i] = ETpdt * Ks[i]
                Qcap[i] = ETa[i]
                Sblue[i] = max(Sblue[i] - Qcap[i], 0)
                Qout[i] = max(Sblue[i]-Sbluemax[i], 0)
                Sblue[i] = Sblue[i] - Qout[i]

        # For situations without water available in the water storage layer:
        # Sblue=0 , depening on water content in substrate water stress occurs (Ks<1),
        # possible reduction of Sgreen, only refill of Sblue in case of enough precipitation
        else:

            #For situations with rain (P>0)
            if Pdt > 0:
                Sgreen[i] = Sgreen[i] + Pdt
                Qleak[i] = max(Sgreen[i]-Sgreen_max, 0)
                Sgreen[i] = Sgreen[i] - Qleak[i]
                Sblue[i] = Sblue[i] + Qleak[i]
                #Check if water stress occurs:
                if Sgreen[i] > RAW:
                    Ks[i] = 1
                else: #Sgreen[i] < RAW
                    Ks[i] = (TAW - (Sgreen_max-Sgreen[i]))/(TAW - RAW)
                ETa[i] = ETpdt * Ks[i]
                # Check if water is available in the water storage layer after the rain event:
                if Sblue[i] == 0:
                    Qcap[i] = 0
                    ETa[i] = min(abs(Sgreen[i]-ETa[i]), ETa[i])
                    Sgreen[i] = Sgreen[i] - ETa[i]
                else: #Sblue[i] > 0
                    Qcap[i] = Sblue[i]
                    Sgreen[i] = Sgreen[i] + Qcap[i]
```

```
                    ETa[i] = min(abs(Sgreen[i]-ETa[i]), ETa[i])
                    Sgreen[i] = Sgreen[i] - ETa[i]
                    Qleak[i] = max(Sgreen[i]-Sgreen_max, 0)
                    Sgreen[i] = Sgreen[i] - Qleak[i]
                    Sblue[i] = Sblue[i] + Qleak[i]
                    Qout[i] = max(Sblue[i]-Sbluemax[i], 0)
                    Sblue[i] = Sblue[i] - Qout[i]

            #For situations without rain (P=0)
            else:
                #Check if water stress occurs:
                if Sgreen[i] > RAW:
                    Ks[i] = 1
                else: #Sgreen[i] < RAW
                    Ks[i] = (TAW - (Sgreen_max-Sgreen[i]))/(TAW - RAW)
                ETa[i] = ETpdt * Ks[i]
                ETa[i] = min(abs(Sgreen[i]-ETa[i]), ETa[i])
                Sgreen[i] = Sgreen[i] - ETa[i]
                Qout[i] = max(Sblue[i]-Sbluemax[i], 0)
                Sblue[i] = Sblue[i] - Qout[i]

        # Uncomment following lines if you want to apply irrigation for vegetation survival:
        # Irrigate after a dry spell of 21 days, untill the substrate layer is saturated
    again
#         if Sgreen[i-21]<RAW and Sgreen[i-20]<RAW and Sgreen[i-19]<RAW and //
#         Sgreen[i-18]<RAW and Sgreen[i-17]<RAW and Sgreen[i-16]<RAW and Sgreen[i-15]<RAW //
#         and Sgreen[i-14]<RAW and Sgreen[i-13]<RAW and Sgreen[i-12]<RAW and //
#         Sgreen[i-11]<RAW and Sgreen[i-10]<RAW and Sgreen[i-9]<RAW and Sgreen[i-8]<RAW //
#         and Sgreen[i-7]<RAW and Sgreen[i-6]<RAW and Sgreen[i-5]<RAW and Sgreen[i-4]<RAW //
#         and Sgreen[i-3]<RAW and Sgreen[i-2]<RAW and Sgreen[i-1]<RAW and Sgreen[i]<RAW:
#             Irr = Sgreen_max-Sgreen[i]
#             Irrigation = Irrigation + Irr
#             #Sblue[i] = Sbluemax[i]
#             Sgreen[i] = Sgreen_max
#             Irr_number = Irr_number + 1rr_number = Irr_number + 1

        # Uncomment following lines if you want to apply irrigation for heat mitigation:
        # Irrigate on days with high temperatures and an empty water storage.
        # Refill untill substrate is saturated and 4 mm of water is stored in the blue layer
#         if Sblue = 0 and T > 25:
#             Irr = Sgreen_max-Sgreen[i] + 4
#             Irrigation = Irrigation + Irr
#             Sblue[i] = Sblue[i] + 4
#             Sgreen[i] = Sgreen_max

        #Store parameters for the performance on water retention, heat mitigation and
    vegetation survival
        if T[i]>= 25:
            T25[i] = 1             # Count days on which high temperatures occur
        if Sblue[i] == 0:
            Sempty[i] = 1          # Count days on which the water storage is empty
        if T[i] >= 25 and Sblue[i] ==0:
            Heat[i] = 1            # Count days on which heat stress is a problem
        if P[i] >= 25:
            Pextreme25[i] = P[i]   # Measure precipitation on days with P>25 mm/day
            Pnumber25[i] = 1       # Count days on which P>25 mm/day
        if P[i] >= 50:
            Pextreme50[i] = P[i]   # Measure precipitation on days with P>50 mm/day
            Pnumber50[i] = 1       # Count days on which P>50 mm/day

        if i<tmax-1:
            Sblue[i+1]=Sblue[i]
            Sgreen[i+1]=Sgreen[i]

    if Plot == ’True’:
        fig, ((ax00, ax0, ax1, ax2, ax3, ax4, ax5)) = plt.subplots(7,1 , figsize=(20, 20))

        ax00.bar(df.index.values, P, label=’P’)
        ax00.set(xlabel=”Date”, ylabel=’Precipitation [mm/day]’, title=’Precipitation at the
    green-blue roof’)
        ax00.set_xlim([datetime(2000, 1, 1), datetime(2000, 12, 31)])
```

```
        ax00.legend()

        ax0.bar(df.index.values, ET, label=’ET (Makkink)’)
        ax0.bar(df.index.values, ETa, label=’ETa (=ET*Kc*Ks)’)
        ax0.plot(df.index.values, Ks, label=’Ks (between 0-1)’)
        ax0.set(xlabel=”Date”, ylabel=’Evaporation [mm/day], Ks [-]’, title=’Evaporation at the green-blue roof’)
        ax0.set_xlim([datetime(2000, 1, 1), datetime(2000, 12, 31)])
        ax0.legend()

        ax1.bar(df.index.values, Qout, label=’Q model’)
        ax1.set(xlabel=”Date”, ylabel=’Runoff [mm/day]’, title=’Outflow runoff from green-blue roof to sewer system’)
        ax1.set_xlim([datetime(2000, 1, 1), datetime(2000, 12, 31)])
        ax1.set_ylim(0,60)
        ax1.legend()

        ax2.plot(df.index.values, Sblue, label=’Stored water at Sblue’)
        ax2.plot(df.index.values, Sgreen, label=’Stored water at Sgreen’)
        ax2.set(xlabel=”Date”, ylabel=’Water depth [mm]’, title=’Water depth in the water storage layer and substrate layer’)
        ax2.set_xlim([datetime(2000, 1, 1), datetime(2000, 12, 31)])
        ax2.legend()

        ax3.bar(df.index.values, T25, label=’Temp>25’)
        ax3.set(xlabel=”Date”, ylabel=’1 = Temp>25’, title=’Days on which the temperature exceeds 25 degrees’)
        ax3.set_xlim([datetime(2000, 1, 1), datetime(2000, 12, 31)])
        ax3.legend()

        ax4.bar(df.index.values, Sempty, label=’Storage empty’)
        ax4.set(xlabel=”Date”, ylabel=’1 = empty storage, 0 = full storage’, title=’Days on which the water storage layer is empty’)
        ax4.set_xlim([datetime(2000, 1, 1), datetime(2000, 12, 31)])
        ax4.legend()

        ax5.bar(df.index.values, Heat, label=’Empty storage and temp>25’)
        ax5.set(xlabel=”Date”, ylabel=’1 = No cooling effect’, title=’Number of times with empty water storage and temp>25’)
        ax5.set_xlim([datetime(2000, 1, 1), datetime(2000, 12, 31)])
        ax5.legend()

    result = {’YYYYMMDD’: df.index.values, ’P’: P, ’Storage’:  Sblue, ’Qout’: Qout, ’T25’: T25, ’Sempty’: Sempty, ’Heat’: Heat, ’Pextreme25’: Pextreme25, ’Pextreme50’: Pextreme50, ’Pnumber25’: Pnumber25, ’Pnumber50’: Pnumber50, ’Sgreen’: Sgreen}
    df_result = pd.DataFrame (result, columns = [’YYYYMMDD’,’P’, ’Storage’, ’Qout’, ’T25’, ’Sempty’, ’Heat’, ’Pextreme25’, ’Pextreme50’, ’Pnumber25’,’Pnumber50’, ’Sgreen’])
    df_result = df_result.set_index(’YYYYMMDD’)

    return(df_result)


# In[ ]:
```

To give an example of the output from the bucket model, Figure E.1 shows the figures plots that have been created for the reference scenario for the very dry year of 2003 (with a permanently closed valve). To create these figures in the function *BucketModel(Input, Storage, Plot)*, the input for *Plot* is set on *’True’* and limitations for the x-axis are given in the script above. The figure plots show the yearly precipitaiton, makkink and actual evapotranspiration, the value for K_S, the discharge to the sewer system, the water storage in the water storage layer and the substrate layer and the days on which water stress or heat stress are faced. In the month August (2003) the water storage as well as the substrate layer were completely dried out, but this was restored again in September after some heavy rain events.

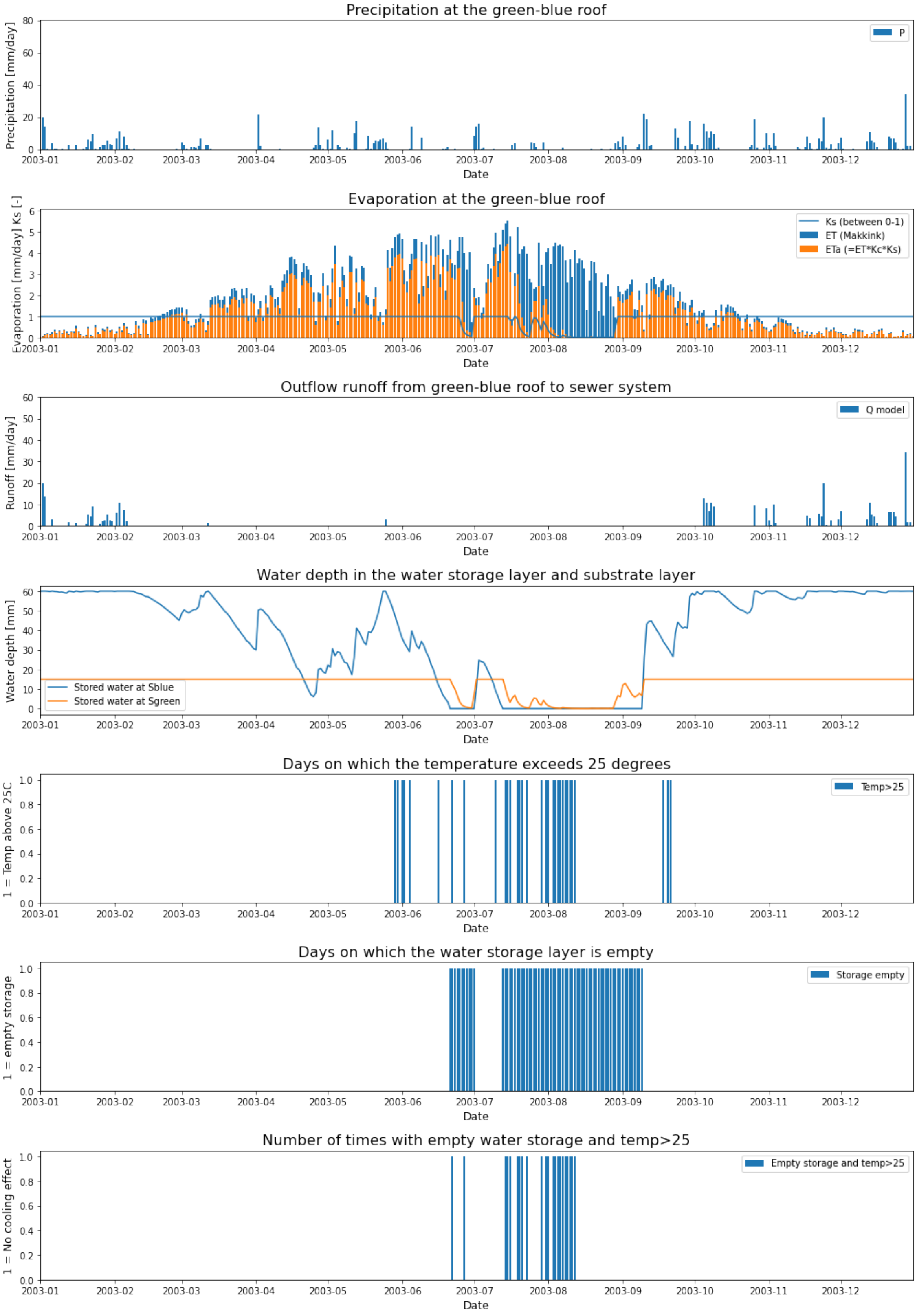


Figure E.1: Example of the visual output from the bucket model for the reference scenario for the year 2003