Bachelor Thesis Civil Engineering

Hydrological performance of smart blue-green roofs by means of EPA SWMM

UNIVERSITY OF TWENTE.

ska-pa

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Colophon

This document contains the final report of the thesis of the Bachelor of Civil Engineering at the University of Twente.

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Preface

I hereby provide to you my bachelor thesis 'Hydrological performance of smart blue-green roofs by means of EPA SWMM'. This final product concludes the bachelor's program in Civil Engineering at the University of Twente. With the use of literature and expert input, I have investigated 'blue-green roofs' and developed a model that compares the hydrological performance of this novel system with conventional roofs, which hopefully contributes to raising awareness of the possibilities of sustainable urban drainage systems (SUDS).

This research was conducted at Ska-pa B.V. from November 15th 2021 to February 18th 2022. Due to current COVID-19 measures, it was discouraged to work every day at location. However, I still experienced what a company such as Ska-pa is like to some degree. First of all, I would like to express my gratitude to everyone at Ska-pa who welcomed me and helped me complete this thesis. Thereafter, I would like to thank my external supervisor(s) at Ska-pa for introducing me to their work and getting me acquainted with a few of their projects, especially Johan Boxem. Their time and effort are appreciated.

I would like to thank Karina Vink from the University of Twente for her passionate and energetic guidance during this thesis. Setting up contacts with experts and providing detailed information on my topic is really appreciated. I enjoyed investigating a system that is currently rarely used but has a lot of potentials.

Ultimately, I wish the reader a pleasant reading of my bachelor thesis. Feel free to contact me if any further questions or comments arise regarding this research.

Stijn Hermen Rick Plegt
February 2022, Tubbergen

Abstract

Because of climate change, extreme weather conditions such as heavy rainfall and severe droughts will occur more frequently. Urban areas are especially sensitive to these consequences. By 2050 the Dutch government, provinces, municipalities, and waterboards aim to make the country climate-proof and water-robust. Hence adequate solutions are required in urban areas. The smart blue-green roof system is perhaps such a solution. This research aims to investigate the hydrological performance of smart blue-green roofs in comparison with conventional roofs.

Blue-green roofs possess all benefits that green roofs possess. Major benefits are thermal comfort, surface runoff reduction, improved air quality, noise reduction, improved health and well-being, enhanced biodiversity, and economic benefits. Additionally, blue-green roofs include a water retention box under the vegetation and soil layer that consists of plastic crates where excess rainwater can be stored. On top of that, the system includes a smart valve system that responds to forecasted weather to optimally retain or release water.

For this research, the EPA Storm Water Management Model (SWMM) was selected as the modelling platform for investigating the hydrological performance of smart blue-green roofs in comparison with conventional roofs. Several periods were modelled. These periods include: an extremely dry year in 1959; an extreme 1-hour precipitation event of 70 mm; an extreme two-day precipitation event of 160 mm; and an extremely wet summer in 2011. According to this study, the performance of blue-green roofs can be twice as good as conventional roofs, depending on the period. Thus, the study indicates that smart blue-green roofs are definitely worth taking into account during the design phase of constructions, as they contribute to transforming urban areas into climate-proof and water-robust areas.

Table of Contents

Table of Figures

Table of Tables

Table of Equations

Glossary

This glossary provides frequently used key concepts and names including its description for clarification.

‘t Bölke	*Location in Enschede where Ska-pa B.V. develops a new project.*
Centrumkwadraat	*The name of the project of Enschede where the municipality aims to improve the inner city.*
Resilio	*The RESILIO project in Amsterdam transforms 10.000 m^2 of rooftop space into smart blue-green roofs.*
MetroPolder	*MetroPolder is a Dutch company that revives cities through smart water management, leveraging stored rainwater for cooling, growing, and fostering nature within the city.*
Smart blue-green roofs	*Smart blue-green roofs can store more rainwater than conventional, or even green roofs. Under the vegetation layer there is a crate system in which the water is stored. The water reaches the plants through the soil and a filter layer. The smart valve system can decide to retain or release the water.*
Conventional roofs	*Conventional roofs are roofs without ‘blue’ or ‘green’ aspects in their structure. Also referred to as ‘grey’ roofs.*
SUDS	*SUDS (Sustainable urban drainage systems) are water management practices that aim to implement natural water processes into drainage systems.*
Runoff	*Runoff is the draining away of water from a specific surface.*
SWMM	*EPA’s (the United States Environmental Protection Agency) Storm Water Management Model is a globally used program to plan, analyse, and design stormwater runoff.*
KNMI	*KNMI is the Dutch national weather service. They mainly focus on weather forecasting and monitoring weather, climate, air quality, and seismic activity.*
Percolation	*The movement of water through soil and the unsaturated zone into and through the pores of materials in the zone of saturation.*
LID control	*LID controls are low-impact development practices designed to capture runoff and provide some combination of detention, infiltration, and evapotranspiration to it.*

1. Introduction

1.1 Context

‘t Bölke has been a well-known nightlife venue in Enschede for a long time. The COVID-19 crisis has made a great impact on the place. The owners concluded that the location needs a change for the benefit of them and the city. The municipality of Enschede commissions this project. They cooperate with developers and designers from Ska-pa B.V., Dura Vermeer Bouw Hengelo, and ZECC Architecten B.V. These parties will develop the place into an inspiring living, work, and recreation environment. They concern themselves with a mixed residential program, fitting for young and old people but also for new and old inhabitants of Enschede. The program will be filled with catering industry and prospective workplaces. The complex will connect well with the location because it is car-free, near the train station, and near the northern access route to the inner city. The design of the complex is illustrated in Figure 1.

Figure 1: Design complex (ZECC Architecten, 2021).

On the 1st of June 2021, the contract between the parties was signed. The intended start of execution is around Q2-2023 and the project should be finished around Q4-2024. The municipality of Enschede is developing a future-proof city. They are developing dynamic locations focused on the feeling of inner-city, near the train station and all the other conveniences a city can offer. Durability is an important factor in this project. The municipality has come up with a new name for this to be improved inner city: ‘Centrumkwadraat’ (Gemeente Enschede, 2021).

The current problem is that the municipality of Enschede desires Ska-pa B.V. to make a solution for water storage on rooftops that fits within this project. The complex should deal with 20 mm water per m^2 of paved roof surface. However, the company does not know yet what system fits best within the whole project. Because of climate change, extreme weather conditions such as heavy rainfall and severe droughts will occur more frequently. Hence why fitting solutions are needed to help with this worldwide problem. By 2050 the Dutch government, provinces, municipalities, and waterboards aim to make the country climate-proof and water-robust (Deltaprogramma, Nationaal, 2021). Ska-pa is most likely in the future obligated to consider climate change to a higher degree than currently with the 20 mm water storage per m^2.

To keep the city cool and absorb excess rainwater more green spaces are needed. However, locations for green spaces are limited in the city. An innovative way of thinking can transform unused space on rooftops into smart blue-green roofs (Resilio, 2021). These roofs retain excess rainwater, but also provide space for new nature, add biodiversity, and create a future-proof city.

In conclusion, blue-green water storage systems on rooftops of the complex are perhaps an adequate solution to transform Enschede into a climate-proof and water-robust city. This thesis focusses on the water retention effectiveness of blue-green roofs in comparison with conventional roofs.

1.2 Problem statement

Urban areas in Europe will experience severe consequences due to climate change. These areas will experience climate change in the form of direct effects as a result of increasing temperatures and changed precipitation dynamics and indirect effects resulting from perturbations and climate change-linked events elsewhere. Additionally, the urban temperature is heavily influenced by the urban heat island effect. This phenomenon is seen as a major problem of urbanisation. 'There are three parameters of urbanisation that have direct bearing on this effect (Taha, 1997), namely, (1) increasing amount of dark surfaces such as asphalt and roofing material with low albedo and high admittance, (2) decreasing vegetation surfaces and open permeable surfaces such as gravel or soil that contribute to shading and evapotranspiration and (3) release of heat generated through human activity (such as cars, air-condition, etc.)' (Kabisch, Korn, Stadler, & Bonn, 2017). Some areas will experience the phenomenon to a higher degree because the factors are not equally distributed. Another effect of climate change is the increase in the frequency of flood peaks. In addition, the sea level will rise and coastal flooding will increase as a result of the increase in windstorm frequency. Because most of Europe's urban areas are located on floodplains or along coasts, these two climate change effects will have major impacts on European cities. However, these impacts will differ across Europe. Northern Europe is expected to experience more precipitation, whereas Southern and Central Europe are expected to experience a reduction in precipitation (Stagl, Mayr, Koch, Hattermann, & Huang, 2014) and (Olsson, 2009). An increase in heavy precipitation events will results in urban drainage systems exceeding their capacity more frequently which causes economic loss, discomfort and occasionally loss of lives (Semadeni-Davies, Hernebring, Svensson, & Gustafsson, 2008). Also, climate change influences important factors to habitat quality and development of urban biodiversity, namely, population dynamics, species distribution patterns, species interactions, and ecosystem services (Bellard, Bertelsmeier, Leadley, Thuiller, & Courchamp, 2012).

Thus, the municipality of Enschede wants to transform the city into one that focusses on climate adaptation and future-proofing for weather extremes. In cooperation with Ska-pa B.V., Dura Vermeer Bouw Hengelo, and ZECC Architecten B.V., the municipality of Enschede searches for water storage systems on rooftops that reduce climate change effects. A blue-green roof can be such a solution. This thesis will entail research on blue-green water storage systems for rooftops and eventually a conclusion on the effectiveness of such a system.

1.3 Research objective

The research objective is to investigate the water retention effectiveness of blue-green roofs in comparison with conventional roofs. Understanding how blue-green roofs—but also other water systems for rooftops—work is important to explore the strengths and weaknesses of blue-green roofs. This information is key in supporting the conclusion on the effectiveness of blue-green roofs. The system should fit within the project goals and criteria. However, future adjustments to these goals and criteria are considered to reinforce the conclusion.

1.4 Scope

This Bachelor thesis focuses on developing and analysing two water storage system models for rooftops for Ska-pa B.V. and potentially other companies. Other water storage systems are neglected as this thesis is purely focused on rooftops. The first model will be developed using blue-green roof characteristics and the second model uses conventional roof characteristics. For both models, the building structure from project 't Bölke is considered. The main focus lies on the water quantity as this is the most important criterium of Ska-pa's project. There are many more aspects that are important in making recommendations for Ska-pa such as water quality and economic benefits. However, in this thesis, these aspects are mainly investigated through literature research.

Using the problem statement and the research objective the main research objective is constructed in the following question:

- *What is the effectiveness of blue-green roofs in comparison with conventional roofs regarding water retention?*

With the help of the following sub-questions, and by answering them in order, a model can be developed that helps make recommendations to Ska-pa:

Ska-pa B.V. takes current water retention criteria into account. However, these criteria will be sharpened in the future to reach the goal of being climate-proof and water-robust by 2050 (Deltaprogramma, Nationaal, 2021). Knowledge of the current and future criteria regarding water storage is required to construct a future-resistant conclusion.

1) *What are the current and future criteria for water storage systems for rooftops for Ska-pa's projects?*

Information, including the strengths and weaknesses, on several types of water storage systems for rooftops, is required in supporting the decision for blue-green roofs.

2) *What types of water storage systems for rooftops exist and what are their strengths and weaknesses?*

When information on blue-green roofs is investigated, the modelling phase is next. In this phase, the outcome will be data on the performance and effectiveness of blue-green roofs in comparison with conventional roofs.

3) *How do blue-green and conventional roof systems perform according to the model SWMM?*

1.5 Reading guide

In this chapter, the general introduction for this thesis is provided. This paragraph further outlines the functions of upcoming chapters. In chapter '2. Methodology' provides a brief overview of the methodology, including research questions. Accordingly, in chapter '3. Criteria water storage system for rooftops' current and future criteria are determined and elaborated upon to build on realistic results. Subsequently, in chapter '4. Green, blue and white roofs' information on green, blue and white roofs is gathered to better understand its benefits. Thereafter, in chapter '5. EPA SWMM model' the modelling phase with SWMM is elaborated upon, including model structure, input data and parameter estimation. Then, in chapter '6. Results' the observed effects of the blue-green and conventional roof in several periods are outlined. Ultimately, in chapter '7. Discussion', '8. Conclusion' and '9. Recommendations' the thesis finishes with a discussion, conclusion and recommendations for further research.

2. Methodology

In this chapter, a methodology is formulated that has been used to answer the research questions in the previous chapter. A brief overview per research sub-question is provided with methods to answer these questions. Thereafter, a clear overview of the methodology steps that were taken is provided in the form of a flow chart.

2.1 Research methods

As mentioned in 'chapter 2. Methodology' each sub-question is elaborated upon in further detail.

1) *What are the current and future criteria for water storage systems for rooftops for Ska-pa's projects?*

To answer this sub-question, expert input, together with some literature study, is required. The exact goal of Ska-pa its project is needed before recommendations are to be made. One criterion is that the building should be able to deal with 20 mm water per m^2 paved roof surface. The municipality of Enschede aims to make the inner city future-proof. Durability is an important factor in this goal. Hence why it is required to know the importance of this project in the municipality's goal. The first step is to discover the criteria that Ska-pa and Dura Vermeer are obligated to reach. Ska-pa and Dura Vermeer are focused on profit which could play a massive role in the criteria. The second step is to investigate the goals of the municipality of Enschede, as they aim to make the inner city future-proof. This big project is called 'Centrumkwadraat'. By using a literature study the goal of this project is investigated. The criteria currently are way milder than they will be in the future. According to Ska-pa B.V., the criterium of 20 mm will soon increase to 55 mm, whereas in Amsterdam the criterium is already around 80 mm. Within this step, an expert interview will be executed with the municipality of Enschede. This interview aims to discover the current water storage criteria, but also the future and predicted water storage criteria that are to be implemented to tackle climate change consequences.

2) *What types of water storage systems for rooftops exist and what are their strengths and weaknesses?*

In the previous sub-question, the criteria from Ska-pa will be made clear. Also, the criteria that the municipality is to obligate Ska-pa in future projects will be clear. The following sub-question will be answered using a literature study. There are multiple ways of storing water on roofs. In this sub-question information on water storage systems for rooftops and their characteristics is worked out. The overall strengths and weaknesses of a green roof are taken into account to make the concept clear for the reader. These aspects include enhanced humidity, enhanced water regulation in case of extreme rainfall and droughts, decreased surface temperature, conservation of biodiversity, etc. One can imagine that during hot summers green roofs could lead to fire hazards. Currently, there are no rules regarding this matter. However, some rules are likely to be implemented in the future. This significant matter is taken into account in this step. Thereafter, the strengths and weaknesses of blue roofs are investigated. Ultimately, the combination of blue-green roofs that Resilio (RESILIO, 2021) uses is investigated.

3) *How do blue-green and conventional roof systems perform according to the model SWMM?*

With the information and criteria gathered in the previous sub-questions the blue-green and conventional roof systems are modelled in SWMM. The model program EPA SWMM is used because of its open access, user-friendliness and large user community support. Other models like Mike SHE and Hydrus-1d are too complex or closed access. At first, an introduction of the program is needed to be able to create a sufficient model. Learning all the ins and outs of the program is integrated into this first step. In Appendix A information on the program is gathered. After this step is executed sufficiently, the model is constructed. Ultimately, the results of the model are investigated and conclusions are made on the performance of the blue-green roofs regarding water storage in comparison with conventional roofs.

2.2 Flow chart

As mentioned in 'chapter 2. Methodology' a flow chart is provided to give a clear overview of the methodology for this Bachelor's thesis. The flow chart is illustrated in Figure 2.

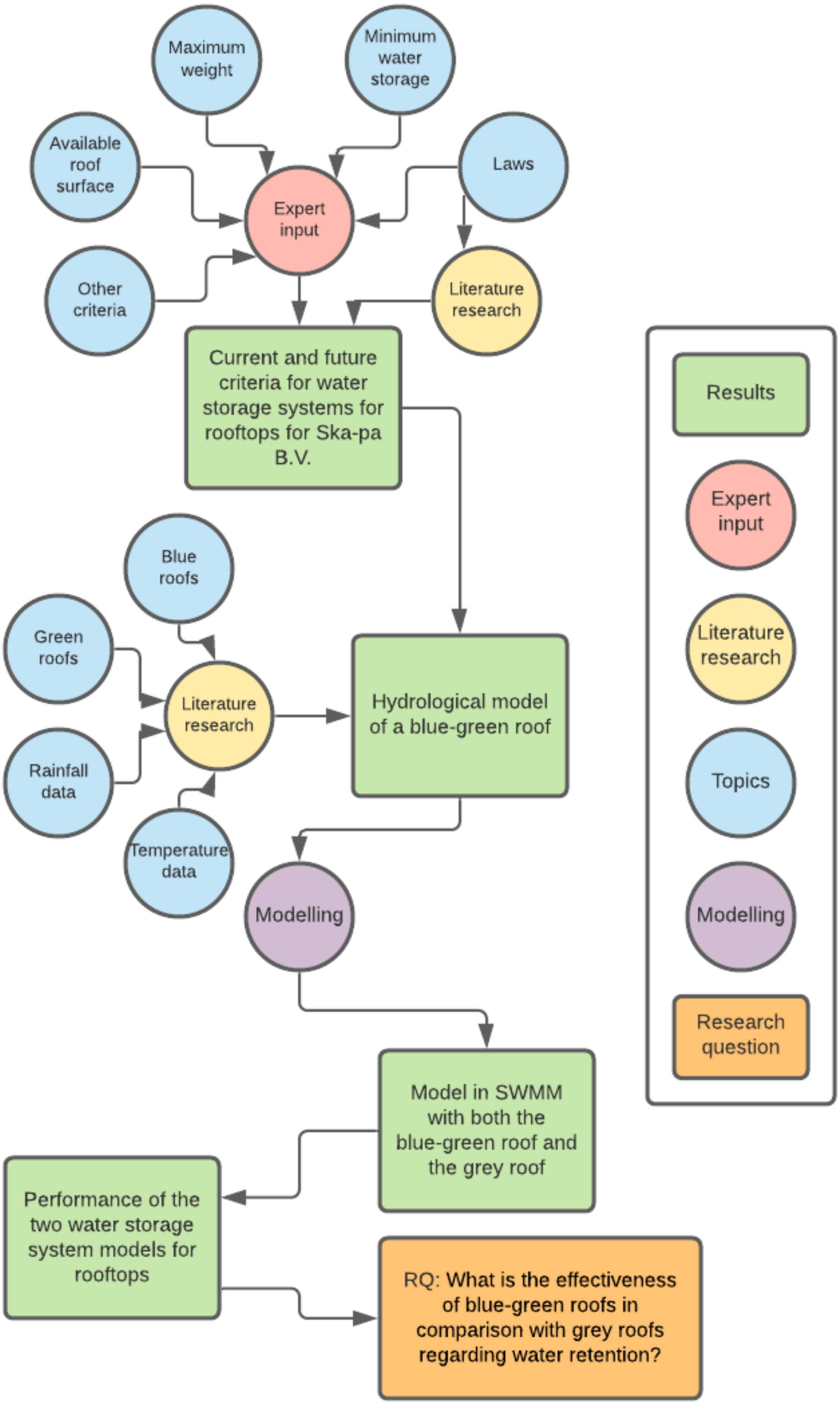

Figure 2: Flow chart research methodology

3. Criteria water storage system for rooftops

As stated in 'chapter 2.1 Research methods', the first step in this thesis is determining the current and future criteria on water storage systems for rooftops. Accordingly, this chapter will elaborate more upon these criteria in the following subchapters.

3.1 Durable city of Enschede

The municipality of Enschede aims to further develop and convert the city into an attractive place to stay, live and work. Durability and greenery are important elements in this process. Implementing these elements in the city requires water, sewerage, and climate adaptation to be in order. The right amount of water at the right places enhances the attractiveness of the city. High-quality sewerage enhances the health and well-being of residents. Climate adaptation is required to pleasantly stay, live and work in the city and surroundings in the future. (Gemeente Enschede, 2021)

Due to the massive amount of 'grey' surfaces in urban areas, extreme precipitation events are challenging for cities to survive without economic and sometimes even human damage. Preferably these challenges are tackled with 'green' measures like wadis, green roofs, etc. As this Bachelor's thesis is aimed at water storage systems for rooftops and the city of Enschede wants more 'green' elements in its city, one criterion for Ska-pa's project at 't Bölke is a green roof. Ska-pa has the ambition of making 50% of the open surface green. However, there are some limitations regarding greenery on rooftops. Some vegetation species, like thorny roots, are destructive to roofs because their roots damage the concrete or the insulation on top of it (Mnif, 2021).

3.2 Heat stress

As stated in the last paragraph, urban areas are mainly 'grey' surfaces. In hot and dry periods the differences in temperature in urban areas and countrysides can get up to 10°C (Döpp, 2011). This phenomenon is the 'urban heat island effect'. The new project at 't Bölke is located in the middle of the city of Enschede. Hence why this location experiences a high degree of heat stress. Green elements are required to decrease the effects of this phenomenon. In Figure 3 the thermal sensation, measured on the hottest summer day in 2015, around the area at 't Bölke is illustrated.

Figure 3: Thermal sensation 't Bölke. Source: (Twents Waternet, 2015).

3.3 Water storage

Due to climate change, extreme precipitation rates have increased. The return period of precipitation events of 70 mm in one hour is once every hundred years (Twents Waternet, 2015). Additionally, the return period of precipitation events of 160 mm in two days is once every thousand years (Twents Waternet, 2015). The consequences of these precipitation events in the area around 't Bölke are depicted in Figure 4 and Figure 5, respectively. As one can see this specific area is more vulnerable to extreme short precipitation events, as 'grey' surfaces process an abundance of water poorly.

Figure 4: Water depth 't Bölke at precipitation event of 70 mm in one hour. Source: (Twents Waternet, 2015).

Figure 5: Water depth 't Bölke at precipitation event of 160 mm in 2 days. Source: (Twents Waternet, 2015).

The consequences of climate change are getting worse in the coming years. Hence why the municipality of Enschede has adjusted its water storage standard. The municipality has published its water and climate adaptation plan for 2022 till 2026. For every m^2 hard surface—like streets and roofs—a facility should store 55 mm water (Gemeente Enschede, 2021). Preferably these facilities use green measurements. However, the old water storage standard of 20 mm still stands for project 't Bölke as the agreements have been signed before the new water and climate adaptation plan was published.

Water storage systems filled with water exercise a massive force on rooftops. Therefore it is important to investigate the weight of the water storage systems filled and have knowledge on the maximum loads the roofs can sustain. The complex at 't Bölke is already designed, so knowledge on the maximum loads is known (Bramel, 2021). In Table 1 the data is given. Especially the data on flat roofs is of high importance in discovering whether green roofs fit within the project or not.

Table 1: Data maximum loads complex 't Bölke. Source: (Bramel, 2021).

Flat roofs	**Terrace**	**Courtyard incl. ground**
Finished product (incl. solar panels and water storage system):	Finished product:	Finished product:
2.0 kN/m^2 200 kg/m^2	2.0 kN/m^2 200 kg/m^2	15.0 kN/m^2 1500 kg/m^2
Variable load:	Variable load:	Variable load:
1.0 kN/m^2 100 kg/m^2	2.50 kN/m^2 250 kg/m^2	4.0 kN/m^2 400 kg/m^2

3.4 Other guidelines

For profit-focused companies like Ska-pa, economical costs are decisive. Therefore, research on direct and indirect costs as a result of water storage systems. Green roofs are costly at first. However, after a certain period, the technology will become profitable. More on this in 'chapter 4.1.7 Economic benefits'.

3.5 Current and future criteria

As mentioned in 'chapter 3. Criteria water storage system for rooftops', it is important to develop knowledge on current and future criteria regarding water storage systems, especially when climate change has made such a global impact. In this subchapter, the current and future criteria are briefly described.

Currently, there typically are no guidelines on the percentage of green spaces. However, Ska-pa has the ambition of making 50% of the open surfaces in their project at 't Bölke green. In the future, these so-called ambitions will most likely convert to guidelines because greenery decreases surface temperature and retains rainwater, which is crucial in climate adaptation.

The municipality of Enschede has published its water and climate adaptation plan for 2022 and 2026. In this plan, it is stated that new or renovated facilities should store 55 mm water for every m^2 hard surface, where this guideline currently stands on just 20 mm water. For the project at 't Bölke the 20 mm guideline still counts. However, in future projects, Ska-pa should take the 55 mm guideline into account.

The loads which roofs can deal with are key in choosing fitting water storage solutions. Green roofs can exercise a massive force on rooftops. Thus, the developer should reconsider the strength of the rooftop constructions. Conversely, the developer should consider a lighter water storage system.

Economical costs are decisive for profit-focused companies like Ska-pa. Therefore, developers should investigate the direct and indirect costs that come with water storage systems like green roofs. More on this in 'chapter 4.1.7 Economic benefits'.

4. Green, blue and white roofs

In the previous chapter, the criteria that Ska-pa is obligated to take into account are worked out. In this chapter information on green, blue, and white roofs are gathered. Information on these systems is key for understanding the benefits of the systems. Furthermore, information on conventional roofs is gathered as blue-green roofs will be compared with conventional roofs in the modelling phase. Ultimately, information on blue-green roofs is gathered to be implemented in the modelling phase.

4.1 Green roofs and their benefits

There are plenty more benefits of vegetated roofs. All benefits are briefly described one by one in the following subchapters. Most of these benefits are not relevant to the modelling section of this thesis. However, they are important to raise awareness about green roofs, which can definitely play an important role for companies like Ska-pa B.V.

4.1.1 Surface temperature

Vegetation can play a major role in cooling down urban areas. According to a study performed by Bowler et al. urban parks have a cooling effect in the range of 1 °C during the daytime. The study indicates that larger parks have a larger impact (Bowler, Buyung-Ali, Knight, & Pullin, 2010). Surface temperatures of water are lower compared to vegetated areas. However, both these areas are cooler than streets and roofs (Leuzinger, Vogt, & Körner, 2010). Vegetation systems like green roofs and walls have a direct advantage, namely, that these systems can be added as a complement to existing blue and green infrastructure. According to Alexandri and Jones, green walls reduce the street canyon and wall temperatures by 10 °C during the day in hot and dry climates (Alexandri & Jones, 2008).

4.1.2 Surface runoff

As mentioned earlier a consequence of climate change is the increase in the intensity and frequency of floods. Especially in urban areas, extreme rainfall presents a challenge. In urban areas, the water infiltration rate in the ground is reduced, which increases runoff and thus the flood risk. Currently, the most used solution to this problem is ‘grey’ infrastructure. However, these infrastructures are no longer able to keep up with the increasing rate of heavy rainfall due to climate change. By using sustainable urban drainage systems (SUDS), like green roofs, the surface runoff is reduced to a further extent. Additionally, green roofs have indirect positive effects like the reduction of pollutants.

4.1.3 Air quality

Urban air quality is reduced by air pollution emissions from industry, transport, and other sources. Green roofs have a big influence on air quality. Air quality is in relation to the amount of dust, particulates, and nitrates (NO_x) in the air (Peck & Callaghan, 1999). There are minor economic benefits of these processes, however, this is neglected in ‘chapter 4.1.7 Economic benefits’, because of its minor impact. Vegetation, in particular trees, can remove pollutants from the atmosphere. Through leaf stomata uptake and interception of airborne particles this process is performed (Irga, Burchett, & Torpy, 2015). Furthermore, vegetation can act as a physical barrier that prevents the penetration of pollutants into specific areas (Salmond, et al., 2013). Also, vegetation contributes to air purification by transforming matters from the air like CO_2 into oxygen.

4.1.4 Noise reduction

Noise pollution in urban areas is an important factor for humans’ overall well-being. Green roofs can act as a sound barrier. The vegetation increases the sound transmission loss by up to 10 and 20 dB more in the low and mid-frequency ranges in comparison with non-vegetated roofs (Connelly & Hodgson, 2013). Green roofs thus absorb sound and provide a quieter environment, both inside and outside a building.

4.1.5 Health and well-being

Nature-based solutions can improve the health and well-being of citizens through certain elements in natural environments. These elements facilitate psychological relaxation and stress relief, according to several epidemiological studies. This subchapter elaborates more on the health benefits. One important thing to note is that any type of greenery in urban settings is meant with urban green space.

Aesthetically pleasing natural environments improve mental relaxation and restoration. Close contact with nature can trigger positive effects on high-stress levels by positively shifting persons emotional state ((Ulrich, Aesthetic and Affective Response to Natural Environment, 1983); (Ulrich, et al., 1991)). Nature its stimuli help restore persons' mental fatigue ((Kaplan, The restorative benefits of nature: Toward an integrative framework, 1995); (Kaplan, Meditation, Restoration, and the Management of Mental Fatigue, 2001)). Several studies have provided results that indicate chronic stress level reduction by green spaces. The researchers used diurnal cortisol patterns in their studies. Applying this key performance indicator studies concluded that urban green spaces reduce adults' stress levels ((Roe & Aspinall, 2011); (Thompson, et al., 2012); (Beil & Hanes, 2013)).

Human immune systems are enhanced by natural elements. Visiting forests comes with beneficial immune responses, which even include the expression of anti-cancer proteins (Li, et al., 2008). This result suggests that natural environments or certain factors in green spaces improve human immune systems. Nature spreads specific allergens or bacteria. Children who are exposed to the highest degree of nature in their first year of life are less likely to have recurrent wheeze and allergic sensitisation (Lynch, et al., 2014). Other studies have demonstrated that an increase in biodiversity around homes is linked with a reduced risk of allergy ((Ruokolainen, et al., 2014); (Hanski, et al., 2012)). Another study has shown that urban areas with more trees have positive effects on asthma prevalence (Lovasi, Quinn, Neckerman, Perzanowski, & Rundle, 2008).

Green spaces thus enhance mental health state and human immune systems. There is more evidence on the health and well-being benefits of green spaces. Green spaces reduce cardiovascular morbidity and mortality, reduce the prevalence of obesity and type 2 diabetes, improve pregnancy outcomes, reduce mortality and increase life span.

4.1.6 Biodiversity

Green roofs can represent anthropogenic habitats. Their vegetation is similar to natural habitats on cliffs. Urbanisation and human activities have resulted in fragmented natural habitats and declines in biodiversity (Köhler & Ksiazek-Mikenas, 2018). Specific design and maintenance of green roofs can extend the species spectrum. The concept of 'stepping stones' can be implemented in the design of green roofs. These 'stepping stones' act as connections for wildlife in urban areas. Biodiversity support, by hiring well-educated roof gardeners who perform annual maintenance and make necessary adjustments, shapes the plant and animal communities on the roofs and in surrounding cities ((Lundholm, 2015); (Yang, et al., 2015)).

4.1.7 Economic benefits

The economic benefits of green roofs are an important aspect for profit-focused companies like Ska-pa. Property values close to woodland cover are increased by 7.1% (Garrod, 2002). Moreover, greenery and trees could add another 15% to 25% to the total value of properties (CTLA, 2003). Green roofs are not able to provide the same benefits as woodlands and forests. However, extensive green roofs could still increase property values between 2% and 5% (Bianchini & Hewage, 2012).

Vegetation on buildings can act as an insulation layer. Green roofs save between 1.8 kWh/m^2 to 6.8 kWh/m^2 in cooling energy (Lee, Larson, Ogle, & Sailor, 2007). Additionally, green roofs annually save

2.64 m^3 gas per m^2 of greenery (Groendak, 2015). These energy savings could vary among vegetation types, however, there is no data available. According to Milieu Centraal the cooling energy price is €0.22/kWh in the Netherlands (Milieu Centraal, 2021). Thus, the annual cooling energy savings vary between €0.40/m^2 and €1.50/m^2. The average Dutch gas price is €0.87/m^3 (Atriensis, 2021), resulting in annual heating energy savings of €2,30/m^2.

Conventional roofs have an expected lifespan of 20 years (Evans, 2008). In contrast to green roofs, this is extremely low. The expected lifespan of green roofs varies from 40 to 55 years ((Acks, 2006), (Clark, Adriaens, & Talbot, 2008), (Kosareo & Ries, 2007), (Saiz, Kennedy, Bass, & Pressnail, 2006)). The cost process of re-roofing a conventional roof varies from €75/m^2 to €130/m^2 (Dakdekker-Weetjes, 2021), depending on several factors. In conclusion, green roofs are economically beneficial in the long run taking the lifespan into account.

Green roofs traditionally do not include solar panels. However, if the two technologies are combined the building can reap the benefits of both. Research from Germany and Switzerland shows that this combination is beneficial (LivingRoofs, 2017). First of all, the microclimate of green roofs reduces the urban heat island effect, which in its turn provides a cooler environment that allows solar panels to perform more efficiently (EPA, 2021). Furthermore, green roofs can reduce dust and air pollutants, as mentioned in 'chapter 4.1.3 Air quality'. These processes enhance the performance of solar panels by up to 6%, depending on sunlight strength, and reduce the maintenance required (Green Roof Technology, 2015). Additionally, solar panels create shaded areas beneath them. Rain will create a more damp area in front of the solar panels and a drier area in the back, provided that the solar panels are positioned at an angle. These circumstances would induce a 'habitat mosaic', allowing a wider variety of flowers to flourish which attracts a variety of fauna (LivingRoofs, 2017). Thus, combining solar panels with green roofs leads to a variety of benefits that even enhance their performances. Altogether, the individual benefits of solar panels and green roofs subsist, and the combination of the two experiences supplementary benefits. On top of these supplementary benefits, the payback period of the combination is surprisingly on par with the payback period of just solar panels. An economic analysis was performed by Civil and Environmental Engineering students, which resulted in initial costs and payback periods for roofs including solar panels, green roofs, and lastly the combination of the two. Installation costs, maintenance costs, electricity savings, etc. were taken into account in the analysis, resulting in the payback period of just solar panels to be 13 years, 73 years for just a green roof, and also 13 years for the combination. Needless to say, the initial costs of the combination are greatest. However, the payback period is equivalent to just solar panels. This is due to potential savings in installation and maintenance costs, in addition to the savings from both technologies. (Kessling, Cohen, & Jasso, 2017)

Installation of green roofs increases costs. These costs mainly include the fee for professional gardeners, water use, cleaning, and repair. However, if managed well, the economic benefits of green roofs outweigh the maintenance costs (Chen, Shuai, Chen, & Zhang, 2019). Therefore, developers should involve the agricultural sector.

Components from green roofs such as plants and other growing media can act as fuel that catches fire or support the spread of a fire. From performed tests on growing media several conclusions are made. Firstly, green roofs do not add a considerable amount of fire load, even with intensive greening. Obviously, this is relevant for insurance costs as these costs remain the same because green roofs present almost the same fuel load as conventional roofs. 'It is estimated that such roofs present almost the same fuel load as roofs covered by a PMB membrane with no fire retardants, adding up to 95% of the available fuel'. Secondly, the fire performance of green roofs is comparable to bitumen roofs. Vegetation components of green roofs can produce heat at a very high rate, but for a shorter period of time than bitumen membranes. Further research on the flammability of green roofs could give a more realistic view of the fire risks of roofs. Nonetheless, green roofs do not bring a substantial amount of fire risk. (Gerzhova, Blanchet, Dagenais, Ménard, & Côté, 2020)

4.1.8 Overview

In Table 2 all the benefits of SUDS are provided in a brief overview including a description and provisioning details.

Table 2: SUDS benefit types, descriptions and provisioning details. Source: ((Ashley, et al., 2015); (Ballard, et al., 2015))

Benefit category	**Description**	**Aspects of the SUDS design that provide the benefit**
Surface temperature	Thermal comfort	Green and blue spaces, green roofs
Surface runoff	Reduced flows and volume to treat in combined systems	Interception and further runoff volume reduction
Air quality	Reduced damage to health from improved air quality	Air particulate filtering via vegetation (e.g., trees and green roofs)
Noise reduction	Reduced noise in urban areas	Green roofs absorb sound
Health and well-being	Physical, emotional and mental health benefits	See air quality and building temperature, recreation, crime reduction, reduced flood risk
Biodiversity	Sites of ecological value	Habitat creation and enhancement, connecting habitats
Economic benefits	Property value, heating and cooling energy, lifespan	Greenery, insulation layer, protection layer

4.2 Blue roofs

Apart from green roofs, there is another way of retaining stormwater. Blue roofs are non-vegetated systems able to retain an abundance of water. The technology uses weirs at the roof drain inlets to a temporary pond and slowly release rainwater (Shafique & Luo, 2019). Light-coloured material is used to reduce the surface temperature. Blue roofs help reduce rainfall runoff during small storm events for a shorter time (Shafique, Lee, & Kim, 2016). Furthermore, blue roofs are less costly than green roofs (Shafique, Lee, & Kim, 2016).

4.3 Conventional roofs

Traditionally speaking communities exposed to natural hazards have been relying on grey infrastructures (Jones, Hole, & Zavaleta, 2012). Concrete or other long-lasting materials are applied in these infrastructures, including drainage systems for storm water management. This comes with enormous benefits such as clean water, sanitation, etc.

However, grey infrastructures affect social and ecological components of the urban system. ´Grey infrastructures provide an important means of adapting to biophysical challenges including hazards and climate-driven extreme events, but are often costly to install and maintain, have long-term effects on ecosystems, tend to have low flexibility, and when they fail can generate catastrophic impacts on social and economic domains of urban social-ecological-technological systems’ (Kabisch, Korn, Stadler, & Bonn, 2017).

4.4 White roofs

White roofs are conventional roofs that are painted white such that they get a high albedo and reflect incoming solar radiation. The advantage of white roofs, in contrast to blue and green roofs, is that the roof is not required to be constructed flat. As mentioned before, green roofs have a cooling effect. However, the cooling effect of a white roof should not be underestimated. 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 (Solcerova, Ven, Wang, Rijsdijk, & Giesen, 2017). However, the water in the substrate of green roofs plays an important role in the cooling effect of the vegetation on the air. White roofs cool the air above them, but they do not provide all other advantages that green roofs provide, such as an increased insulation capacity, a higher aesthetic value and the contribution to the urban ecosystem.

4.5 Blue-green roofs

As 59% of land area in the Netherlands is vulnerable to floods (Planbureau voor de Leefomgeving, 2021), the city of Amsterdam needs systems to protect its city. As of January 2014, the Amsterdam Rainproof Program has kicked off. The RESILIO project is part of the program. They investigate and construct blue-green roofs, which combine all advantages of blue and green roofs. In their design, the blue layer is situated underneath the green vegetation layer and consists of plastic crates where excess rainwater can be stored. To protect the roof from leakage a water- and root-proof layer is situated underneath the blue layer. Furthermore, it is required to strengthen the roof with an extra cement layer, and water- and root-proof bitumen. Through capillary fibre cylinders, the vegetation can extract water from the blue layer during hot and dry periods. Moreover, when extreme precipitation events are expected water in the blue layer can be drained using a smart valve created by MetroPolder (MetroPolder, 2021). The smart valve system is also able to respond to dry periods where the valve system will be closed.

The system is illustrated in Figure 6 to give a clear overview of the layers in the structure. During extreme precipitation events, blue-green roofs manage water retention better because the water level in the blue layer can be regulated. The system can drain water, e.g. when heavy precipitation is expected. Furthermore, blue-green roofs can store water to irrigate the vegetation during hot and dry periods (RESILIO, 2021). It is important to optimise the valve system that regulates the water level. During hot and dry periods a high water level is desired to water the vegetation and to increase evaporative cooling. On the other hand, a low water level is desired when extreme precipitation events are expected. Hence, optimisation in forecasting local precipitation events is required to ensure the system functions to the best of its potential.

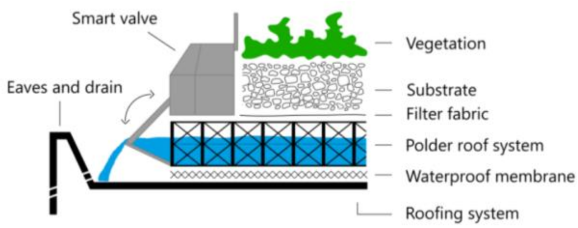

Figure 6: Blue-green roof concept showing the layers. Source: (RESILIO, 2021).

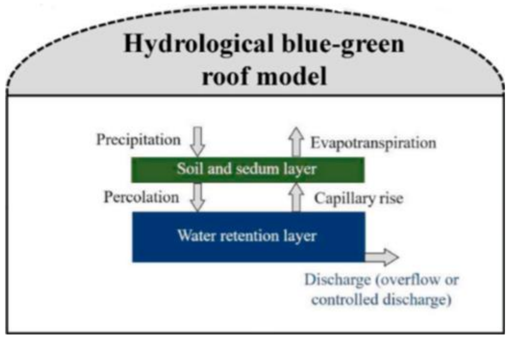

Figure 7: Hydrological system blue-green roof. Source: (RESILIO, 2021).

The system can be seen as a two-layered bucket model that involves hydrological fluxes, namely precipitation, evapotranspiration, capillary rise, percolation, controlled discharge and overflow Figure 7. The blue layer is connected with the green layer through capillary rise and percolation. The former occurs when the green layer is not saturated and the blue layer has water, whereas the latter occurs when the green layer is becomes saturated during precipitation.

The load of the relatively thin blue-green 'Polderdak' version PD85 is approximately 88 kg/m^2 (Metropolder, 2022). As mentioned in chapter 3.3 Water storage, the roofs at 't Bölke can sustain 200 kg/m^2 of fixed loads. Solar panels are most likely installed on top of the vegetation layer. However, this will not be a problem whatsoever since a load of solar panels is at most 20 kg/m^2.

Construction costs of the blue-green roof retention box (PD85), including the smart valve, filter fabric and waterproof membrane, are €40,-/m^2. Accordingly, the substrate layer including vegetation is estimated at around €50,-/m^2. Annual maintenance costs are roughly 1,-/m^2, depending on several factors. The payback period is heavily dependent on factors like the aimed water retention and solar panels (MetroPolder, 2021). Over time (blue-)green roofs are profitable. First of all, from construction on property values increase between 2% and 5% due to extensive green roofing (Bianchini & Hewage, 2012). Secondly, green roofs offer isolation which saves cooling and heating energy. The annual cooling energy savings vary between €0.40/m^2 and €1.50/m^2. In addition, the annual heating energy savings result in €2.30/m^2 (Atriensis, 2021). Thirdly, the expected lifespan of green roofs is much higher. Conventional roofs have an expected lifespan of 20 years (Evans, 2008). In contrast to green roofs, this is extremely low. The expected lifespan of green roofs varies from 40 to 55 years ((Acks, 2006), (Clark, Adriaens, & Talbot, 2008), (Kosareo & Ries, 2007), (Saiz, Kennedy, Bass, & Pressnail, 2006)). The cost process of re-roofing a conventional roof varies from €75/m^2 to €130/m^2 (Dakdekker-Weetjes, 2021), depending on several factors. Ultimately, the payback period of green roofs in combination with solar panels is surprisingly low (Kessling, Cohen, & Jasso, 2017). The payback period of just solar panels or green roofs is 13 and 73 years, respectively. However, in combination, the payback period is still 13 years. In conclusion, one could make a high amount of economical savings using green roofs. Further research is necessary to investigate these economical savings and produce an overview.

4.5 Roof type selection

As mentioned in 'chapter 4.1 Green roofs', green roofs decrease indoor temperatures and heat stress on hot summer days, provide extra insulation in winter, etc. However, the water storage capacity of green roofs during extreme precipitation events is limited, especially when the soil is already saturated ((Huang, et al., 2020); (Lee, Lee, & Han, 2015); (Viavattene & Ellis, 2013); (Yao, et al., 2020); (Zhang, Lin, Zhang, & Ge, 2021)). Hence this thesis investigates the hydrological benefits of combining green and blue roofs in the form of green roofs including a water retention layer, as depicted in Figure 6.

5. EPA SWMM model

For this research, the EPA Storm Water Management Model (SWMM, version 5.1.015) was selected as the modelling platform for investigating the hydrological performance during extremely dry and wet periods of both the blue-green roof and the conventional plot. In the following subchapters the model structure, input data, and parameter estimation are described, respectively.

5.1 Model structure

The blue-green roof is modelled as a sub-catchment that is 100% covered by the LID type 'bio-retention cell', which represents the blue-green roof. To make a closed network a junction, an outlet, and a conduit are added. Another sub-catchment is implemented to make a comparison with a conventional roof. This sub-catchment is 100% covered by the LID type 'permeable pavement'. Both sub-catchments are connected to a rain gage. In the design of 't Bölke, there are seven rooftops available for vegetation coverage, which adds up to 1326 m^2 (Maarseveen, 2021). The shape of the conduit is set on circular and the maximum depth of the conduit is set at 0.12 m (Busker, et al., 2022). The width of the overland flow path is assumed to be the average width of the roof, which is 15 m. Moreover, the slope of the blue-green roof is set at 0% to minimise runoff (Metropolder, 2022), while the slope of the conventional roof is set at 0.5%. Additionally, the bottom layer of the roof should be waterproof, so the percentage of impervious areas for both roofs is set at 100%. Ultimately, it is assumed that there is no depression storage for the blue-green roof. However, for the conventional roof, the depression storage depth is set at 1 mm. In Appendix B a clear overview of the model characteristics and the model structure are provided.

5.2 Input data

To investigate the performance of the blue-green roof model in comparison with the conventional roof several periods were modelled. These periods include: an extremely dry year in 1959; an extreme 1-hour precipitation event of 70 mm; an extreme two-day precipitation event of 160 mm; and an extremely wet summer in 2011. Monitored rainfall data is gathered from the KNMI weather station in Enschede (KNMI, 2022). Appendix C represents the monitored rainfall data for each event.

The daily minimal temperature, maximal temperature and average wind speed are also gathered from the KNMI website (KNMI, 2022), and are implemented in the model as an external climate file. Appendix C represents the monitored temperature data for each event. However, the data from the weather station in Twente was used because the station in Enschede does not provide data on temperature and wind. The evaporation rates are computed from the temperatures: 'the Hargreaves method is used to compute daily potential evaporation rates from the daily air temperature record contained in the external climate file specified on the temperature page of the dialogue' (EPA SWMM, 2015). The method also uses the site's latitude, which is approximately 52° (Mapsofworld, 2022). The formula for this method is provided in Eq. (*1*).

$$\mathrm{PET} = 0.0023 * \mathrm{R_a} * (\mathrm{T_{max}} - \mathrm{T_{min}})^{0.5} * (\mathrm{T_{mean}} + 17.8) \tag{1}$$

Where PET (mm/day) = potential evapotranspiration; R_a = mean extra-terrestrial radiation in mm/day which is function of latitude; T_{max} = maximum daily air temperature in °C; T_{min} = minimum daily air temperature in °C; T_{mean} = average daily air temperature in °C.

5.3 Parameter estimation

As mentioned in chapter 5.1 Model structure, there are two LID controls in the model for the two sub-catchments. The parameter values for both controls are estimated from literature or defaults. Firstly, the parameter values for the conventional roof are described; thereafter, the parameter values for the blue-green roof.

The conventional roof in the model functions as a 'reference' roof. Cipolla et al. investigated the hydrological efficiency of green roofs in comparison with conventional roofs. In this model, the same parameter values for the conventional roof are used. In Table 3 the parameter values are provided.

Table 3: Parameter values reference roof SWMM. Source: (Cipolla, Maglionico, & Stojkov, 2016).

Layer	Parameter	Values
Surface	Berm height	3 mm
	Vegetation volume fraction	0
	Surface roughness	0.02
	Surface slope	0.5%
Pavement	Thickness	100 mm
	Void ratio	0.4
	Impervious surface fraction	0
	Permeability	3000 mm/hr
	Clogging factor	0
Storage	Thickness	25 mm
	Void ratio	0.5
Drain	Flow coefficient	0.15
	Flow exponent	1.6
	Offset	3 mm

For the blue-green roof, the parameter values were estimated using multiple literature resources. First of all, the Storm Water Management Model user's manual version 5.1 (EPA SWMM, 2015) was used to estimate the vegetation volume fraction and the suction head. Secondly, for this research, it is assumed that the model uses the parameter values from 'Polderdak' version PD85 (Metropolder, 2022). As Ska-pa B.V. does not have to design a system that stores a massive amount of water, this version will be sufficient. Thirdly, Optigrün is a roof greenery company (Optigrün, 2022). The blue-green water retention system in this thesis is one that Optigrün uses. An expert interview with a green roof professional from Optigrün was carried out to obtain reasonable inputs for the parameter values of the soil. In Appendix D an overview of information gathered from Optigrün is provided. In addition, several types of research on modelling (blue-)green roofs were used to estimate the leftover parameter values. In Table 4 the parameter values are provided.

Table 4: Parameter values blue-green roof SWMM.

Layer	Parameter	Values	Source
Surface	Berm height	3 mm	(Cipolla, Maglionico, & Stojkov, 2016)
	Vegetation volume fraction	0.15	(EPA SWMM, 2015)
	Surface roughness	0.19	(Iffland, et al., 2021)
	Surface slope	0%	(Metropolder, 2022)
Soil	Thickness	60 mm	(Vlijm, 2022)
	Porosity	0.65	(Optigrün, 2022)
	Field capacity	0.35	(Optigrün, 2022)
	Wilting point	0.1	(Iffland, et al., 2021)
	Conductivity	36 mm/hr	(Optigrün, 2022)
	Conductivity slope	10	(Limos, et al., 2018)
	Suction head	88.9 mm (3.5 in.)	(EPA SWMM, 2015)
Storage	Thickness	75 mm	(Metropolder, 2022)
	Void ratio	1-(71/75) = 0.05	(Metropolder, 2022)
Drain	Flow coefficient	2	(Cipolla, Maglionico, & Stojkov, 2016)
	Flow exponent	2.1	(Cipolla, Maglionico, & Stojkov, 2016)
	Offset	0 or 145 mm	Assumed

6. Results

In this chapter results from the four modelled periods are outlined. These include: an extremely dry year in 1959; an extreme 1-hour precipitation event of 70 mm; an extreme two-day precipitation event of 160 mm; and an extremely wet summer in 2011, respectively. For the 1-hour and two-day precipitation events, it is assumed that the precipitation falls evenly over the time period (Appendix C) since the periods are short.

In every event, the 'offset height' is of high importance. This parameter value is the height of the drain line above the bottom of a storage layer (in mm) and is only applicable for the blue-green roof. The highest offset possible is 145 mm, as this is the height of the storage layer (plus the soil layer). The lowest offset possible is 0 mm, as it is unnecessary to prevent runoff from solid material because of the protective layer between the soil and storage layers. An offset height of 0 mm basically means there is not a smart valve system included. For the long periods, the offset height of 0 mm was neglected as this resulted in unrealistic results. The results are mainly focused on stored water and runoff coefficient.

6.1 Extreme dry year

For this event, the maximum offset height is taken into account. In Figure 8 the runoff for the blue-green roof compared to the conventional roof for offset height 145 mm is depicted. Runoff is determined in cubic meters per second (CMS).

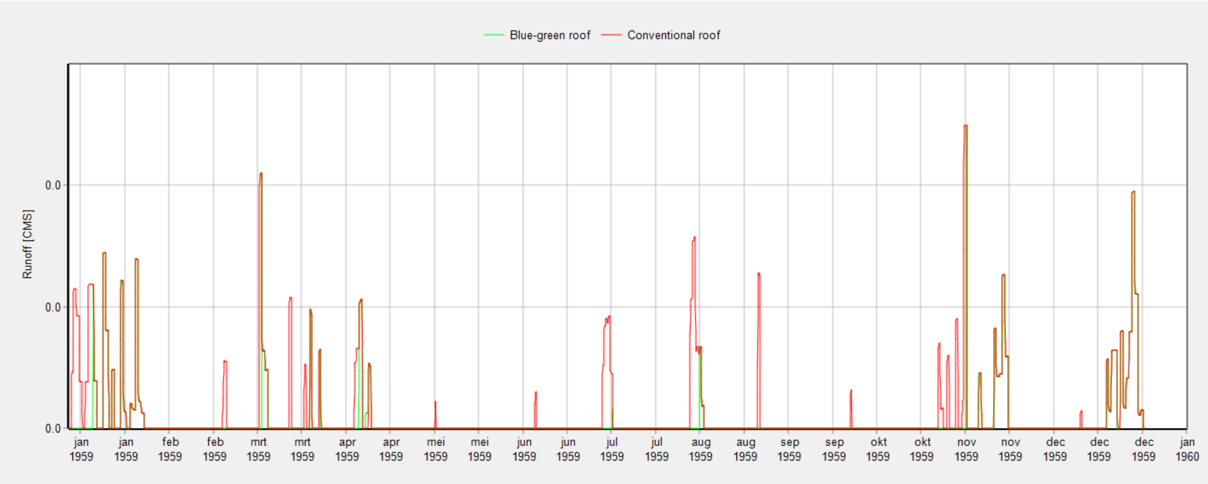

Figure 8: Runoff extreme dry year 1959, 145 offset.

Additionally, in Table 5 the performance of the blue-green roof compared to the conventional roof during an extremely dry year is provided for offset height 145 mm. The tables include the total evaporation, total runoff (through drain and/or overflow), stored water, and ultimately the water retention rate.

Table 5: Roof performance extreme dry year 1959, 145 mm offset.

Type	Total runon (mm)	Total evaporation (mm)	Total runoff (mm)	Stored water (mm)	Runoff coefficient (%)
Blue-green roof	478.00	290.24	150.79	36.97	31.55
Conventional roof	478.00	188.75	288.34	0.92	60.32

6.2 Extreme 1-hour precipitation event

For this event, the maximum and minimum offset heights are taken into account. In Figure 9 the runoff for the blue-green roof compared to the conventional roof for offset height 0 and 145 mm are depicted, respectively. Runoff is determined in cubic meters per second (CMS).

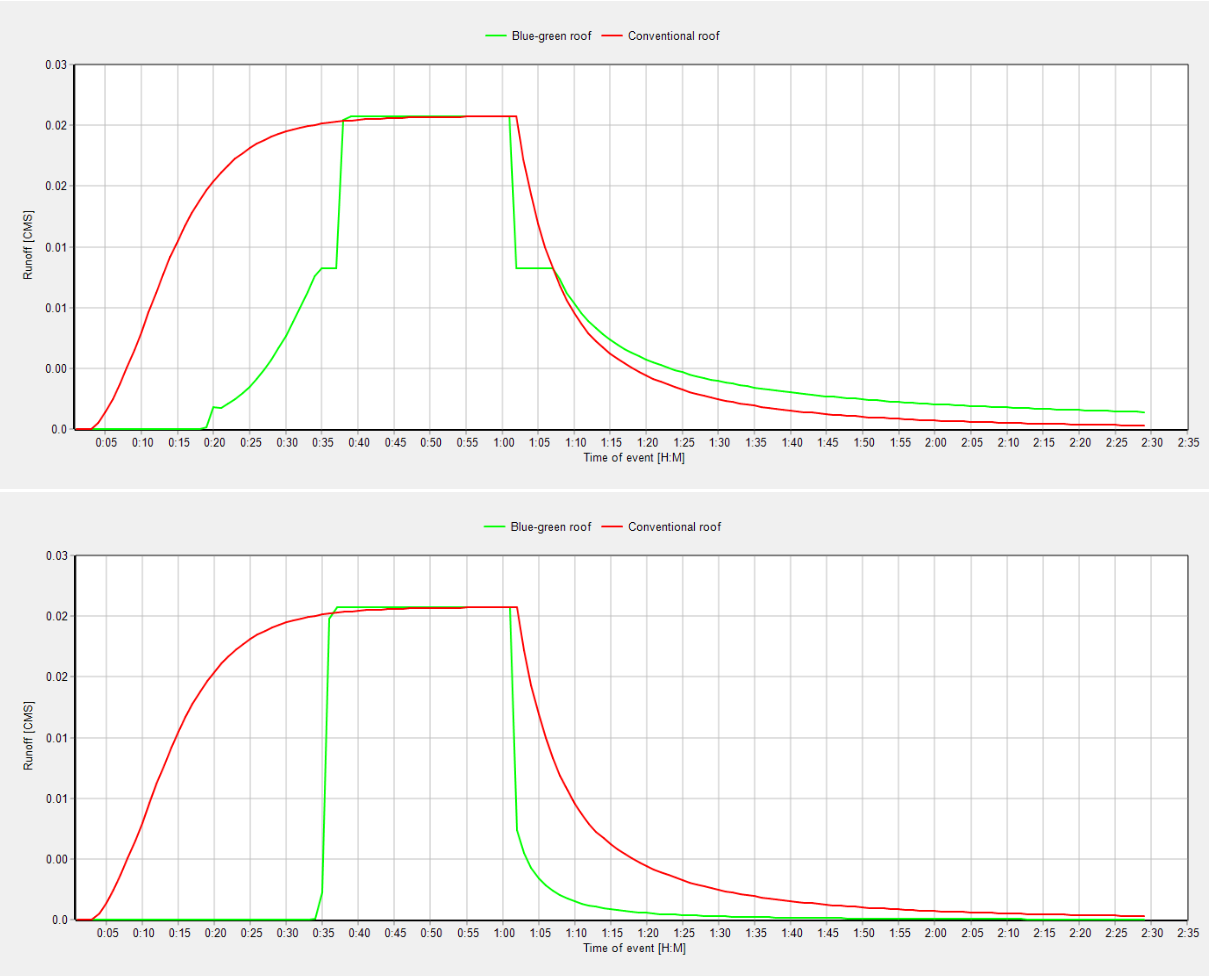

Figure 9: Runoff 1-hour precipitation event 0 and 145 mm offset, respectively.

Additionally, in Table 6 the performance of the blue-green roof compared to the conventional roof during an extreme 1-hour precipitation event of 70 mm is provided for offset height 0 and 145 mm, respectively. The tables include the total evaporation, total runoff (through drain and/or overflow), stored water, and ultimately the water retention rate.

Table 6: Roof performance 1-hour precipitation event 0 and 145 mm offset.

Type	Total runon (mm)	Total evaporation (mm)	Total runoff (mm)	Stored water (mm)	Runoff coefficient (%)
Blue-green roof (0)	70.00	0.29	50.35	19.45	71.93
Blue-green roof (145)	70.00	0.29	32.52	37.19	46.46
Conventional roof	70.00	0.37	67.71	1.93	96.73

6.3 Extreme two-days precipitation event

For this event, the maximum and minimum offset heights are taken into account. In Figure 10 the runoff for the blue-green roof compared to the conventional roof for offset height 0 and 145 mm are depicted, respectively. Runoff is determined in cubic meters per second (CMS).

Figure 10: Runoff two-days precipitation event 0 and 145 mm offset, respectively.

Additionally, in Table 7 the performance of the blue-green roof compared to the conventional roof during an extreme two-days precipitation event of 160 mm is provided for offset height 0 and 145 mm. The tables include the total evaporation, total runoff (through drain and/or overflow), stored water, and ultimately the water retention rate.

Table 7: Roof performance two-days precipitation event 0 and 145 mm offset.

Type	Total runon (mm)	Total evaporation (mm)	Total runoff (mm)	Stored water (mm)	Runoff coefficient (%)
Blue-green roof (0)	160.00	0.00	141.00	19.00	88.13
Blue-green roof (145)	160.00	5.40	116.49	38.11	72.81
Conventional roof	160.00	7.00	149.75	3.25	93.59

6.4 Extreme wet summer

For this event, the maximum offset height is taken into account. In Figure 11 the runoff for the blue-green roof compared to the conventional roof for offset height 145 mm is depicted. Runoff is determined in cubic meters per second (CMS).

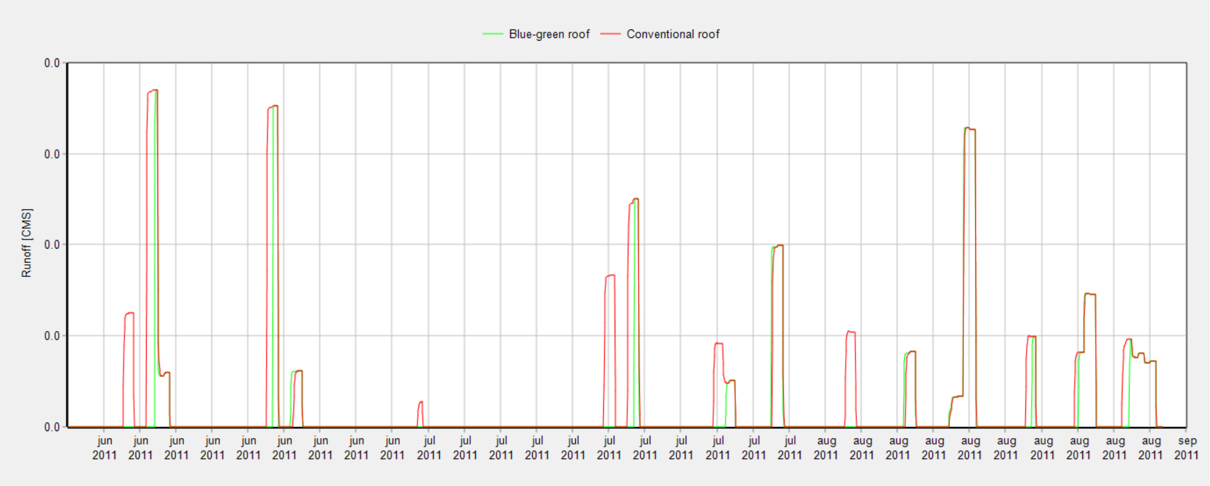

Figure 11: Runoff extreme wet summer 2011, 145 offset.

Additionally, in Table 8 the performance of the blue-green roof compared to the conventional roof during an extremely wet summer is provided for offset height 145 mm. The tables include the total evaporation, total runoff (through drain and/or overflow), stored water, and ultimately the water retention rate.

Table 8: Roof performance extreme wet summer 2011, 145 mm offset.

Type	Total runon (mm)	Total evaporation (mm)	Total runoff (mm)	Stored water (mm)	Runoff coefficient (%)
Blue-green roof	323.17	187.37	98.75	37.05	30.56
Conventional roof	323.17	153.9	169.27	0.00	52.38

7. Discussion

This thesis investigates the hydrological performance of blue-green roofs in comparison with conventional roofs. The results from both the literature and model research clearly indicate that blue-green roofs perform much better than conventional roofs. However, the outcomes are heavily influenced by limitations of this research which implies that blue-green roofs actually perform otherwise. As might be expected, blue-green roofs perform even better in practice because of their 'smart' functions. This chapter elaborates on the outcomes and limitations of this research.

Firstly, blue-green roofs are currently rarely implemented in constructions. This caused difficulties in literature studies regarding the performance of blue-green roofs in comparison with conventional and even common green roofs. There is qualitative information available on blue-green roofs. However, additional quantitative information is required to compare the systems' performance to this research. Furthermore, additional information is necessary to create a detailed financial cost overview, including the payback period which is of high importance to contractors.

Secondly, the modelling platform EPA SWMM has its limitations regarding the implementation of blue-green roofs. The program has LID control features including a green roof and bio-retention cell, while the blue-green roof feature is still missing. For this research, the bio-retention cell feature was used to represent the blue-green roof. However, some relevant parameter values regarding the 'smart' valve system of the blue-green roof were impossible to implement in the model. The model only provided parameter value input regarding the drain (valve) for offset height, open level and closed level. In reality, the system is rather dynamic and can act on forecasted weather. But, the open and closed levels can only be set to one value, so the model does not represent the blue-green roof well enough to get the desired results. Also, the model seemed to misread the offset height. The water storage layer in this research has a height of 85 mm. Logically the maximal offset height would also be at 85 mm. After lots of model running the maximal offset height that gave the most realistic results seemed to be 145 mm. This height is the storage layer plus the soil layer. Finally, only utilising the offset height parameter value of 145 mm was found to give the most realistic results by trial-and-error.

Thirdly, in the model, there is only one sub-catchment representing the roof while in reality, the design of 't Bölke includes seven smaller rooftops available for water storage systems. One might think this assumption does not impact the results but seven smaller rooftops mean six more valve systems. This could be interesting for further research. However, for this research utilising multiple sub-catchments in the model was too complicated to make a clear comparison between a blue-green and a conventional roof.

Last but not least, some parameter values are based on literature and/or theorems in combination with common sense. However, these values are established separately by individual studies. Studies combining blue-green roof characteristics (compared to conventional roof) with EPA SWMM parameter value inputs have not been conducted yet. These studies can help validate the parameter values used during this research.

8. Conclusion

This research focuses on assessing the hydrological performance of smart blue-green roofs compared to conventional roofs. The objective was to gain insight into the systems' performance by developing a model in the modelling platform EPA SWMM.

From literature research, it can be concluded that blue-green roofs possess all benefits that green roofs possess. The most important benefits are listed in an overview in Table 2. Additionally, blue-green roofs have a retention box underneath the vegetation layer. This 'blue' layer includes capillary fibre cylinders making it possible for the vegetation to extract water from the retention box during hot and dry periods. Furthermore, blue-green roofs include a smart valve system that can act on forecasted weather to optimally retain and release water during wet and dry periods. All these benefits are definitely interesting for contractors.

Parameter values were established using literature research and expert input to develop a model that represents the blue-green roof (and the conventional roof). Moreover, the model is made for four different periods. These periods include: an extremely dry year in 1959; an extreme 1-hour precipitation event of 70 mm; an extreme two-day precipitation event of 160 mm; and an extremely wet summer in 2011.

The model provides results for the comparison of blue-green roofs with conventional roofs. It can be concluded that:

1) during the extremely dry year the blue-green roof causes fewer and shorter runoff periods, which is of high importance during such a period. A lot of precipitation evaporates and some precipitation is stored in the retention box at the end of the simulation. Thus, the total runoff is almost half as much for the blue-green roof in comparison with a conventional roof during the extremely dry year.
2) during the extreme 1-hour precipitation event the 'green' characteristics already relieve the drainage systems to a high degree. With 0 offset (meaning without a smart valve system) the blue-green roof has a runoff coefficient of 72%, whereas the conventional roof has a runoff coefficient of 97%. With 145 offset (meaning with a closed smart valve system) the blue-green roof obviously performs even better with a runoff coefficient of just 46%.
3) during the extreme two-day precipitation event that the 'green' characteristics already relieve the drainage systems to some degree. With 0 offset the blue-green roof has a runoff coefficient of 88%, whereas the conventional roof has a runoff coefficient of 94%. With 145 offset the blue-green roof also performs way better with a runoff coefficient of just 73%.
4) during the extreme wet summer the blue-green roof cause fewer and shorter runoff periods, which relieves drainage systems. The blue-green roof allows about 20% more evaporation compared to the conventional roof and some precipitation is stored in the retention box at the end of the simulation. Thus, the total runoff is considerably lower for the blue-green roof compared to the conventional roof during the extremely wet summer.

Altogether, the model is a catalysator for the development of a model that represents all features the smart blue-green roof offers. Furthermore, this study is useful for further research on SUDS as the blue-green roof system is original and provides features that other SUDS like green roofs do not. In conclusion, this research indicates that smart blue-green roofs are definitely worth taking into account during the design phase of constructions, as they contribute to transforming urban areas into climate-proof and water-robust areas.

9. Recommendations

In this chapter, a set of recommendations for further research are formulated. These recommendations allow for a more accurate and realistic study that investigates the hydrological performance of blue-green roofs in comparison with conventional roofs.

First of all, this research was only focused on one complex' roof system. To prevent damage and flooding, especially important for the western part of the Netherlands, inner cities could include many smart blue-green roof systems in their buildings. Further research to what degree these systems relieve the cities' drainage system and to what extent this decreases the flood risk is recommended, as extreme weather conditions are a consequence of climate change.

Climate change also increases urban heat stress. Green areas reduce this stress. Further research is recommended on the influence of blue-green roofs on urban temperatures. This positively influences the well-being of the cities' residents and visitors, which enhances the cities' attractiveness.

Additionally, climate adaptation is required to pleasantly stay, live, and work in the city and surroundings. Green areas make the city more attractive. To what degree green areas make cities more attractive will be hard to investigate. However, it would still be interesting to perform further research on the attractiveness of green cities.

The modelling platform EPA SWMM has some limitations regarding modelling blue-green roofs. If one aims to perform a study on blue-green roofs in this platform it is recommended to EPA to further investigate their parameter input regarding offset height, open water level and closed water level. In reality, the blue-green roof system can dynamically act on forecasted weather, instead of just fixed input. One possibility is to introduce more detail in their parameter values connected to the LID control bio-retention cell, especially open and closed levels. The more evident possibility is to create a LID control specifically designed for blue-green roofs.

Currently, there is little quantitative information available on the financial effects of blue-green roofs. Further research on this is necessary to make a clear financial overview of the (potentially) economic benefits. Especially the payback period will be of high importance for companies like Ska-pa to sell their design product.

Ultimately, further research on other modelling platforms than EPA SWMM is required to make an extensive decision on which platform to use for blue-green roof studies. As mentioned before, the platform EPA SWMM has a few limitations regarding parameter values crucial for the novel system. This platform was chosen because of its open access, user-friendliness, and large user community support. Other stormwater management model platforms like Mike SHE and Hydrus-1D are closed access or too complex for such a short study. However, for further research without time or financial limitations, it is recommended to thoroughly investigate all available platforms.

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Appendix A

In Table 9 sources that helped build the model are provided.

Table 9: YouTube sources. Source: (YouTube, 2021).

Hassan Davani
EPA SWMM Part 1: General Concepts
EPA SWMM Part 2: Detention Basin Design I
EPA SWMM Part 3: Detention Basin Design II
EPA SWMM Part 4: Green Infrastructure
EPA SWMM Part 5: Water Quality Modeling
U.S. EPA
Introduction to EPA's Storm Water Management Model (SWMM)
Updates to EPA's Storm Water Management Model (SWMM)
Giswater
01.1 Adding a title and setting up the options
Robert Dickinson
Robert Dickinson playlist SWMM
PCSWMM
Introduction to SWMM Hydraulics

Appendix B

Model overview

In Figure 12 the model overview is illustrated. S1 represents the blue-green roof and S2 represents the conventional reference roof. RG1 represents the rain gage that is connected to a rainfall time series.

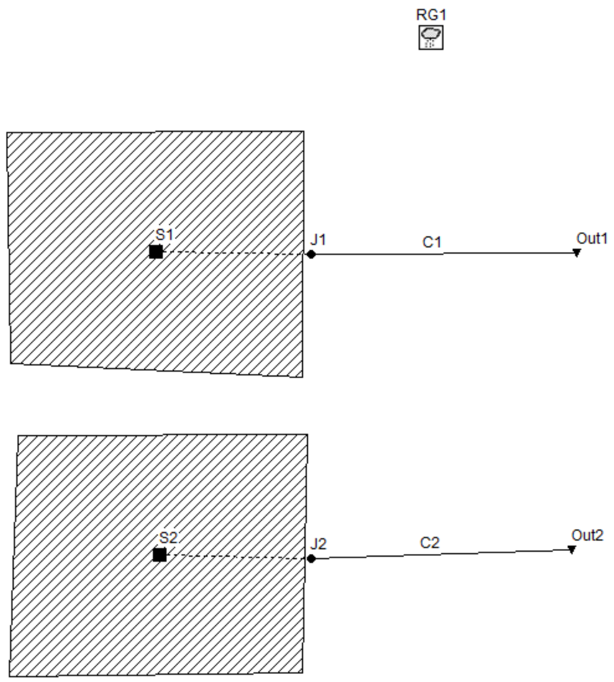

Figure 12: Model overview EPA SWMM.

Model characteristics

In Table 10 the simulation options used are provided. Moreover, in Table 11 the climatology editor input is provided. Ultimately, in Table 12 the hydrology and hydraulic parameter values are provided. One can note that multiple input values are missing in these tables. However, the ones missing are left on the program's default values.

Table 10: Simulation options SWMM model.

Simulation options	
General	
Process Models	Rainfall/Runoff Flow Routing
Infiltration Model	Green-Ampt
Routing Model	Dynamic Wave
Date	
9th August 1951 (for 1-hour simulation) 3rd August 1948 (for 24-hour simulation) 01/06/2011-31/08/2011 (for summer simulation) Whole year 1959 (for one-year simulation)	
Time steps	
Reporting Step	5 min (1-hour simulation) 1 hour (24-hour simulation) 1 day (summer and year simulation
Dynamic Wave	
Default values	

Table 11: Climatology options SWMM model.

Climatology Editor	
Temperature	
Source of Temperature Data	External Climate File
Evaporation	
Source of Evaporation Rates	Temperatures
Wind Speed	
Source of Wind speed data	Use Climate File Data
Snow Melt	
Latitude (degrees)	52

Table 12: Hydrology and Hydraulic options SWMM model.

Hydrology and Hydraulic parameter values	
Rain gage	
Rain format	VOLUME
Time interval	5 min (1-hour simulation) 1 hour (24-hour simulation) 1 day (summer and year simulation)
Sub-catchment 1	
Area	0.1326 ha
Width	15 m
% Slope	0
% Imperv	100
N-Imperv	0.01
Dstore-Imperv	0 mm
%Zero-Imperv	100
LID Control	100% Bio-retention cell (blue-green roof)
Sub-catchment 2	
Area	0.1326 ha
Width	15 m
% Slope	0.5
% Imperv	100
N-Imperv	0.011
Dstore-Imperv	1 mm
%Zero-Imperv	5
LID Control	100% Permeable pavement (conventional roof)
Junction 1&2	
Default values	
Conduit 1&2	
Max. Depth	0.12 m
Length	20 m
Roughness	0.01
Outfall 1&2	
Default values	

Appendix C

Rainfall and temperature data extreme 1-hour precipitation event

As mentioned in chapter 3.3 Water storage, the return period for precipitation events of 70 mm in one hour is once every 100 years. In this thesis, it is assumed that the precipitation falls evenly over the time period, as depicted in Figure 13.

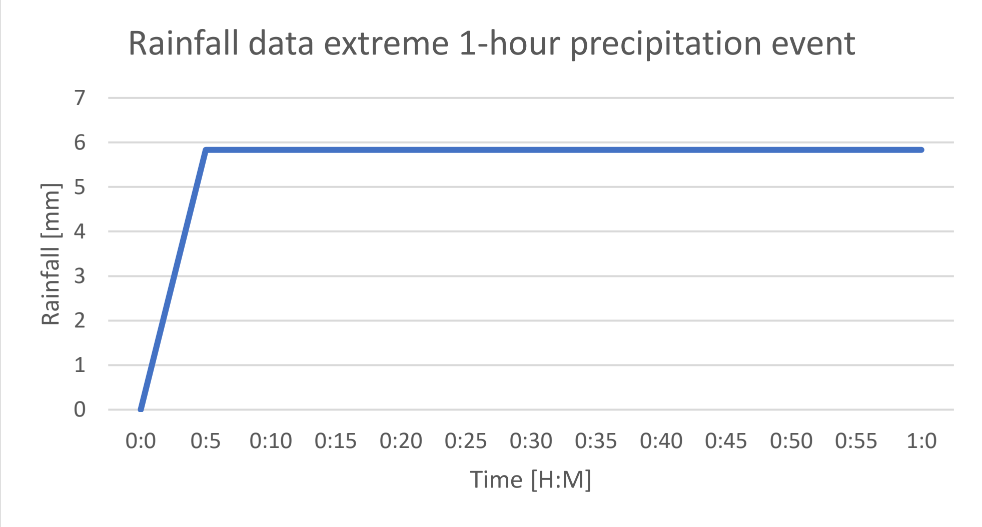

Figure 13: Rainfall data extreme 1-hour precipitation event. Source: (KNMI, 2022).

As it is most likely that the most precipitation falls in the summer, temperature and wind speed data are gathered for the 1st of August 2021 for this event (KNMI, 2022).

Rainfall and temperature data extreme two-days precipitation event

As mentioned in chapter 3.3 Water storage, the return period for precipitation events of 160 mm in two days is once every 1000 years. In this thesis, it is assumed that the precipitation falls evenly over the time period, as depicted in Figure 14.

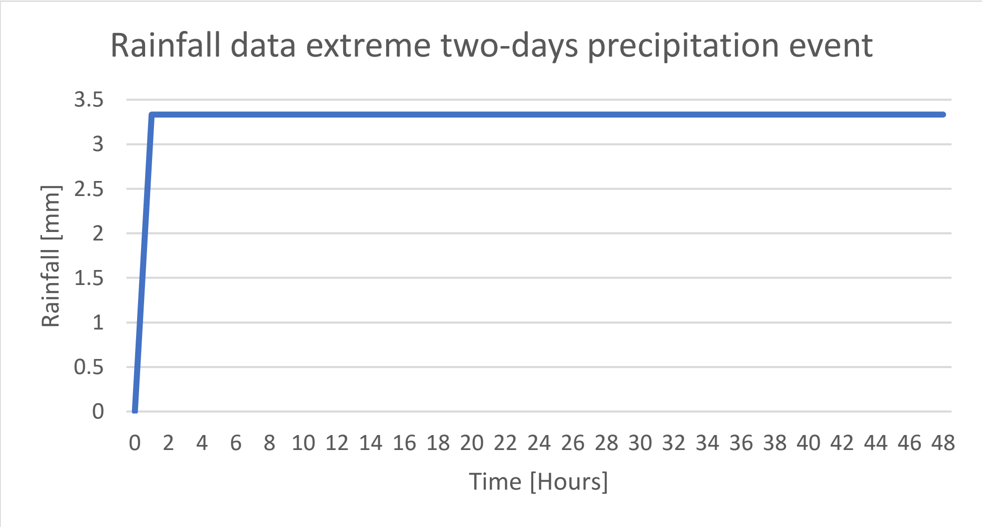

Figure 14: Rainfall data extreme two-days precipitation event. Source: (KNMI, 2022).

As it is most likely that the most precipitation falls in the summer, temperature and wind speed data is gathered for the 31st of July till 1st of August 2021 for this event (KNMI, 2022).

Rainfall and temperature data extreme wet summer

In Figure 15 and Figure 16 the rainfall and temperature data from the extreme wet summer in 2011 are provided, respectively.

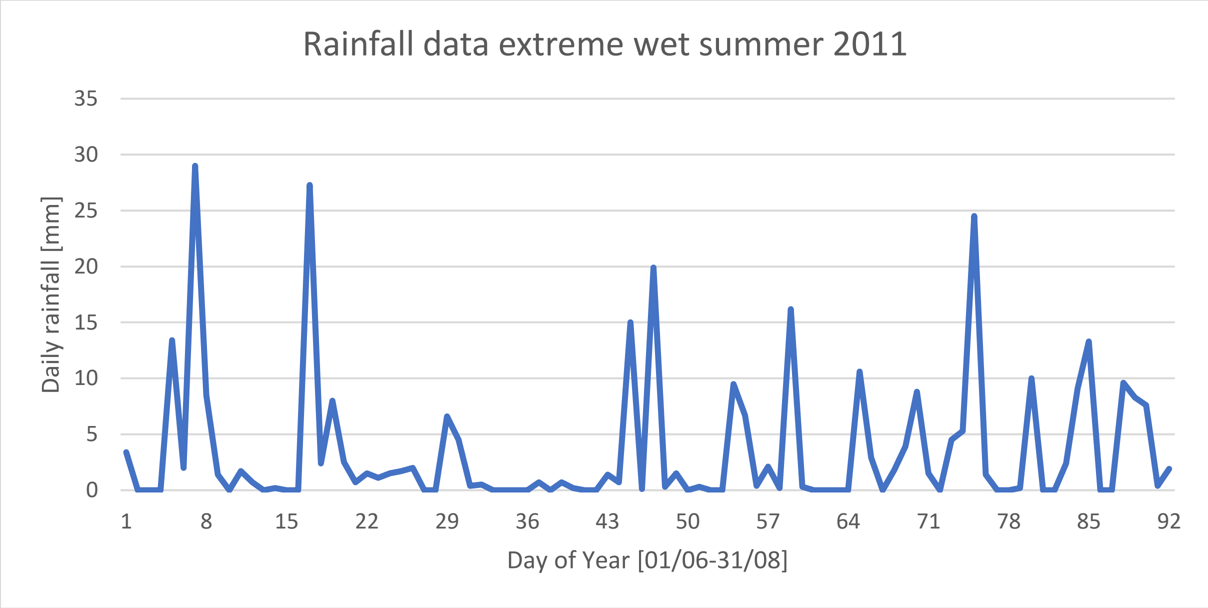

Figure 15: Rainfall data extreme wet summer 2011. Source: (KNMI, 2022).

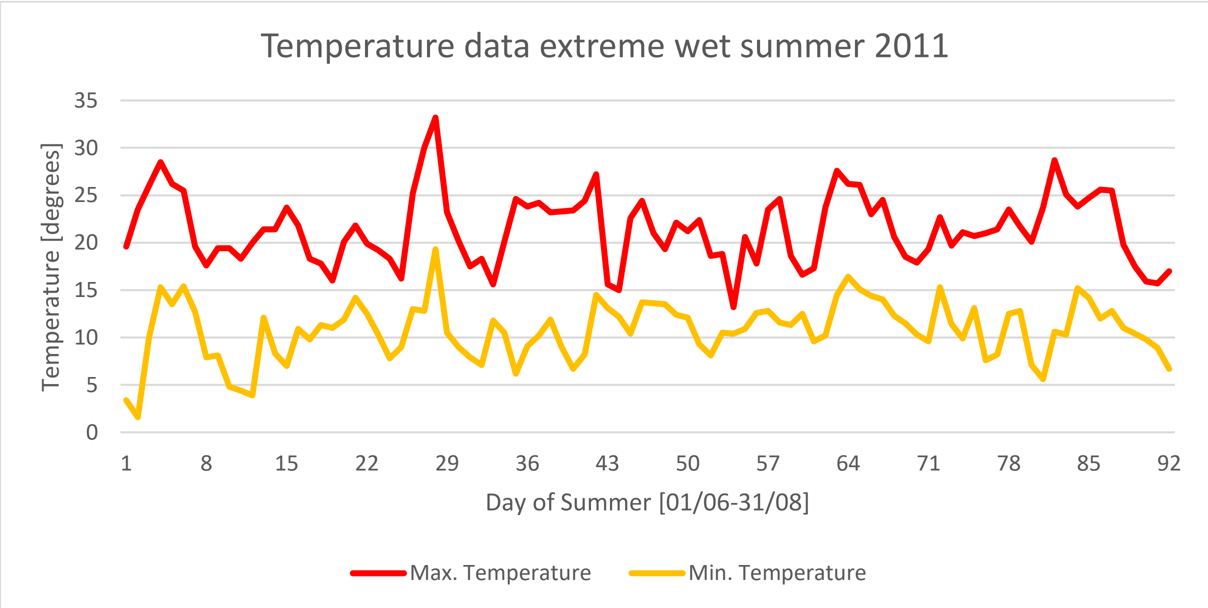

Figure 16: Temperature data extreme wet summer 2011. Source: (KNMI, 2022).

Rainfall and temperature data extreme dry year

In Figure 17 and Figure 18 the rainfall and temperature data from the extremely dry year in 1959 are provided, respectively.

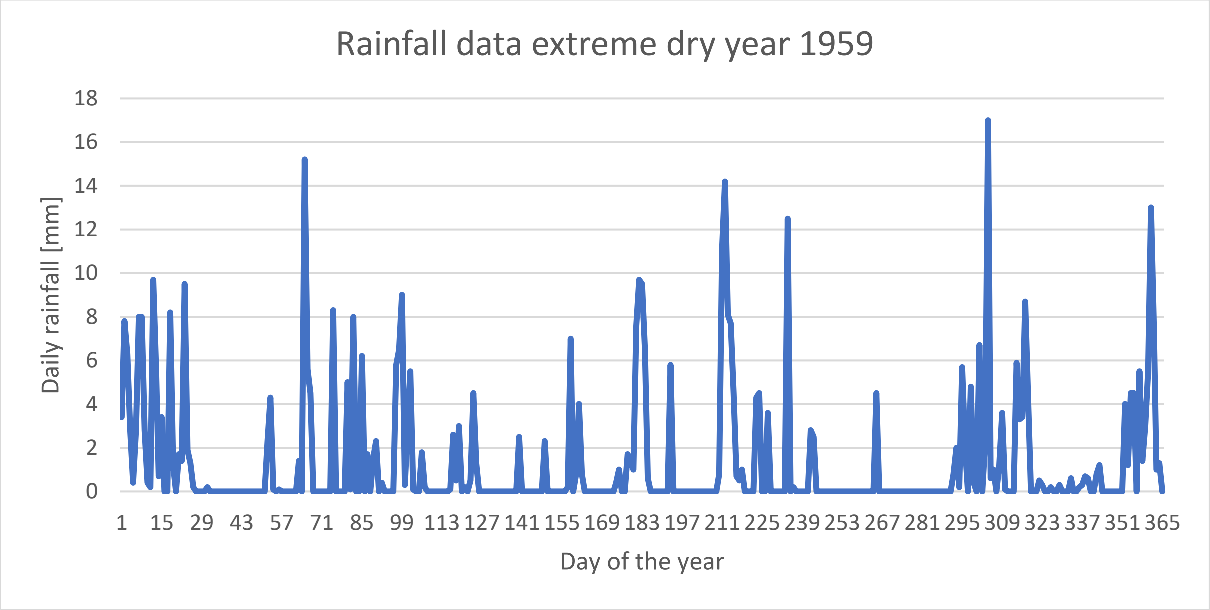

Figure 17: Rainfall data extreme dry year 1959. Source: (KNMI, 2022).

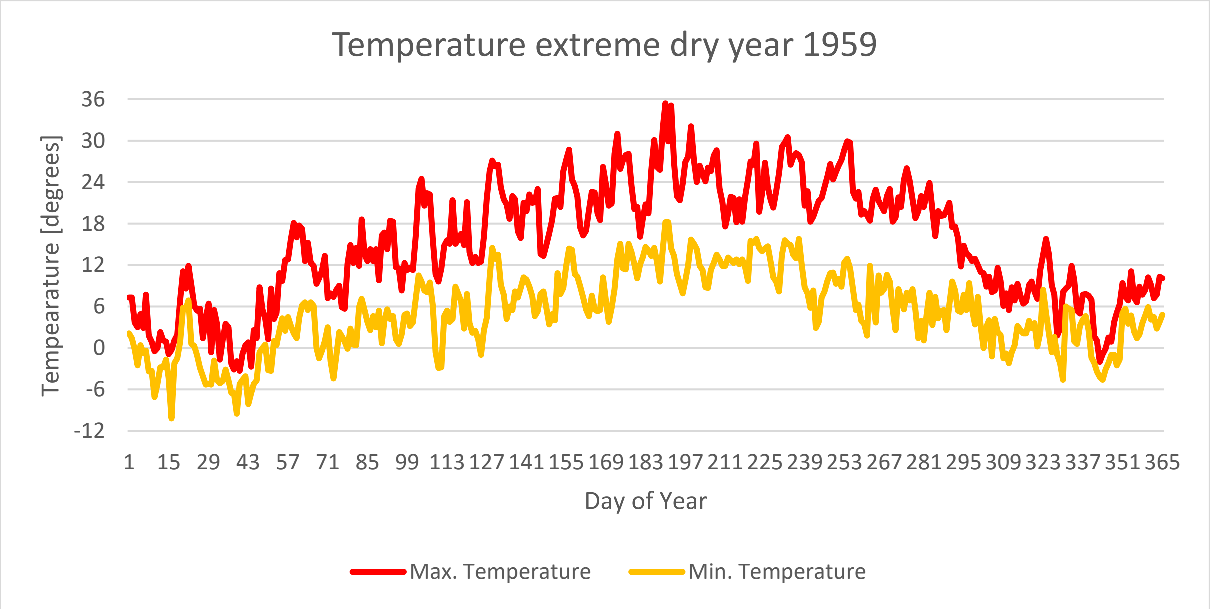

Figure 18: Temperature data extreme dry year 1959. Source: (KNMI, 2022).

Appendix D

Mail from Optigrün

Table 13: E-mail communication with Optigrün.

Mail from Optigrün
Het PD85 (Polderdak 85) systeem is een privatlabel naam voor ons Retentiedak systeem: https://www.optigruen.nl/systemen/retentiedak/drossel-intensief/ De 85 mm retentiebox in het PD85 systeem is onze WRB 85: https://www.optigruen.nl/producten/drainage-bufferlagen/wrb-85i/ Het substraat wat bij extensieve begroeiing (vaak Sedum en/of grassen kruiden) toegepast wordt is vaak een E- substraat https://www.optigruen.nl/producten/substraten/optigruen-substraat-e-s/ Bij Sedum heb je hiervan 6 cm nodig Bij grassen/kruiden heb je hiervan 12 cm nodig Als vegetatielaag veelal Sedum of als afwerking Sedum-grassen-kruiden https://www.optigruen.nl/producten/vegetatie-en-voeding/ Hopende je hiermee voldoende geholpen te hebben Henk Vlijm Directeur Benelux

Information blue-green roof Optigrün

In Table 14 all relevant information on the water retention box, soil, and vegetation is provided, respectively.

Table 14: Relevant information on blue-green roofs. Source: (Optigrün, 2022).

Water retention box (Optigrün, 2022)	
Thickness	85 mm
Weight	5,6 kg/m^2
Water storage	80 L/m^2
Void ratio	5%
Soil (Optigrün, 2022)	
Thickness	60 mm
Weight saturated	1140-1440 kg/m^3 (68,4-86,5 kg/m^2)
Field capacity	35 Vol% (0.35)
Conductivity	0,6 mm/min (36 mm/hr)
Porosity	60-70 vol.% (0.65)
Vegetation (Optigrün, 2022)	
Type	Sedum cuttings
Required quantity	50-80 g/m^2