FINAL REPORT – THE BUILDING-SCALE PERFORMANCE OF BLUE-GREEN ROOFS

Colophon

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Table of Contents

RESILIO is co-financed by the ERDF fund of the European Union through the Urban Innovative Actions program.

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Executive summary

This report presents the results for Work Package 6.3 of the RESILIO project on the building level performance of blue-green roofs. The report focuses on three key themes: the hydrological effectiveness of blue-green roofs under extreme conditions (research by Vrije Universiteit Amsterdam), indoor and outdoor heat stress reduction (research by Hogeschool van Amsterdam), and the effects on well-being (research by the GGD).

For the hydrological effectiveness, we estimated the hydrological performance of blue-green roofs under extreme weather conditions using a modelling study and observations from four RESILIO pilot roofs. Their hydrological effectiveness is determined based on three key performance indicators: (1) maximizing buffer capacity during rainfall events to decrease pluvial flood risk; (2) maximizing evapotranspiration and therefore evaporative cooling, to decrease heat stress; (3) minimize the amount of long-term drought events. The roofs are ‘smart’: their water level can be regulated using a smart valve which operates on meteorological forecast information. The combined results from the observation and the model analyzes shows that blue-green roofs allow very high rainfall capture ratios. They can store >90% of total precipitation, and 70-97% of extreme precipitation (>20 mm/h) when using precipitation forecasts. Moreover, evapotranspiration rates on blue-green roofs are around 50-70% of the potential evapotranspiration on hot summer days, which results in evaporative cooling. Traditional green roofs can only capture 12% of extreme rainfall, and only evaporate 30% of the potential evaporation on hot days. These performance values show-case the positive hydrological performance of blue-green roofs under these extreme conditions. Therefore, this study underscores the contribution blue-green roofs can make to reduce the impacts of future extreme weather events.

For indoor heat stress reduction, research has been conducted based on temperature measurements that have been carried out on ten different roofs. Four were RESILIO pilot roofs, four were reference roofs (black bitumen or gravel), and two were green roofs. The effect on indoor heat stress was determined by looking at the (1) the roof surface temperature, (2) inside temperature and (3) the effect on insulation properties. To research the impact on heat stress in summer and thermal benefits in winter temperatures have been measured above, on and under the roof surfaces, taking into account the influence of the different roof constructions and local conditions. The combined results from the contextual and statistical analyses shows how during cold periods, the surface temperature on blue-green roofs does not reach significant higher values than on conventional roofs. When comparing the surface temperature of blue-green roofs to more conventional sedum covered green roofs during warm periods, the measurements show that there is no substantial difference in substrate temperatures. However, the water storage underneath the substrate experienced much colder temperature during a day than all the other measured surfaces (gravel, bitumen, substrate with plants) which indicates that the additional water layer only present in blue-green roofs function can act as a temperature buffer. During cold periods the water crate layer is empty, showing that the stagnant air layer in the water crates was up to 3 °C warmer at night than other measured surfaces. The effect of the water crate layer was also measured inside the building. All indoor measurements showed a small but

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systematic effect of blue-green roofs on indoor temperatures. The actual effect on indoor heat stress reduction however could not be quantified due to the influence of external variables. Our results suggest that implementing blue-green roof might, at least partially, prevent the heat from entering during the day and offer a cooler environment at night.

For wellbeing, the goal was to study how people experience heat during summer in their home and if there are beneficial health effects associated with living under smart blue green roofs. We hypothesized that residents under smart blue-green roofs would have less heat related illnesses and would experience temperature at home as more pleasant compared to residents living under bitumen or sedum roofs. In total 237 addresses were selected from 9 different areas. The selected addresses had their apartment directly under the roof. Apartments with different kind of roof types were selected to make a comparison, including bitumen roofs (controls), sedum roofs, and smart blue green roofs. Out of these 237 addresses 122 were foreseen to have a smart blue-green roof at the beginning of the summer of 2021. In practice, due to changes in planning, this turned out to be only 19 addresses by the end of the summer of 2021. Unfortunately, due to a lack of respondents it was not possible the answer research questions regarding effects on wellbeing and smart blue green roofs.

1 Introduction

Green roofs in the urban environment are known to have wide-ranging societal benefits, ranging from increased biodiversity, mental health and recreational space to increased stormwater retention and heat stress reduction. Considering their multifunctional benefits, green roofs are popular measures to increase urban green, as high-density metropoles lack space for other forms of green infrastructure. Despite their benefits, the performance of green roofs is under strain due to the increasingly common hydrological extremes: long-term droughts, heat waves and extreme rainfall. Previous experience with green roofs showed a limited water buffer capacity during extreme precipitation events, particularly when the soil is already saturated (Huang et al., 2020; Lee et al., 2015; Viavattene and Ellis, 2013; Yao et al., 2020; Zhang et al., 2021). With regards to the other side of the extremes, many plant species do not survive long-term droughts without extra irrigational water supply. The increasingly erratic weather patterns of the future will only increase these pressures on existing green roof systems.

Over the last years, green roofs with an extra water retention layer underneath the plant layer have been piloted on multiple locations in the Netherlands. These blue-green roofs address above-mentioned challenges and will have an improved hydrological performance during extreme meteorological events. On these roofs, the blue layer is situated underneath the green soil layer and above the roof deck and is built with 85 mm deep plastic crates to create extra storage capacity for excess rainwater. Plants in the green layer can extract water from the blue layer through capillary fibre cylinders, which reduces the need for irrigation and increases the resilience of the plant layer during meteorological droughts (Cirkel et al., 2018). The municipality of Amsterdam is now testing these blue-green roofs in the RESILIO project (see Figure 1). The RESILIO project, an acronymn for ‘‘Resilience nEtwork of Smart Innovative cLImate-adapative rOoftops’, aims to investigate the key

Figure 1 A RESILIO blue-green roof implemented at the Benno Premselahuis (Amsterdam East). The green layer with a mix of different plant species is visible. The blue water retention layer is located underneath the substrate.

factors influencing the adoption of blue-green roofs and the effects of large-scale implementation. RESILIO uses an interdisciplinary approach with public and private stakeholders to realise approximatly 10.000 m^2 of blue-green roofs on mainly social rental properties, and engages 1500 citizens in the different pilot areas. An innovative aspect of the RESILIO blue-green roofs is the smart valve (The Smart Drop®) developed by the Dutch MetroPolder company (MetroPolder company, 2021). The smart valve allows a smart anticipatory release of water from the blue retention layer, and transforms a blue-green roof into an adaptive micro water management system. The smart valve is connected to weather forecast information to respond to extreme precipitation forecasts or droughts. For example, water can be released from the blue layer when an extreme precipitation event is forecast, creating the necessary buffer capacity to store the peak of the precipitation event. This can thus lower pluvial flood risk. Conversely, when a dry or hot period is forecast, the valve can be closed in advance to keep the water level as high as possible in an attempt to prevent vegetation drying. This therefore potentially increases the health and growth rate of the plants.

Blue-green roofs have wide-ranging other benefits beyond hydrological, namely on heat reduction and health. It is more and more known that green roofs greatly reduce the proportion of solar radiation that reaches the roof structure beneath as well as offering additional insulation value due to evapotranspiration by the vegetative layer (Pastore et al, 2017; Castleton et al, 2010). However, more recent research suggests that the availability of a water in the substrate plays an important role in a higher actual evapotranspiration rate, which improves the cooling effect of the roof (Aboelata, 2021; Solcerova et al, 2017) and potentially improves the thermal comfort in the indoor environment (Cirkel et al, 2018; Razzaghmanesh et al, 2015). Research specifically focusing on blue-green roofs potential in reducing heat stress is limited and research about potential insulation effects of the additional water crate layer in blue-green roofs is lacking.

Exposure to extreme heat can lead to adverse health outcomes. Heat related illness include headache, concentration loss, fatigue, sleeping problems, breathing problems or even heart failure (RIVM, 2013). In addition to morbidity, heat waves can cause increases in overall mortality. Some people are more vulnerable to heat than others. For children and elderly, chronically ill and people who are overweight heat is especially a health risk. People spend most time indoors. Therefore, indoor temperatures are important for heat related illness. Blue-green roofs are expected to lower indoor temperatures, especially in houses directly under the roof, which may have a beneficial impact on health.

This deliverable (O6.3.1) aims to conduct a building-level impact assessment of blue-green roofs, considering 3 main impact categories: (1) hydrological impacts, for example roof runoff reduction and evapotranspiration (ET), (2) heat stress impacts, such as indoor temperature reductions and (3) health impacts. First, the hydrological performance under extreme conditions will be outlined (Chapter 3). This performance is derived from water level observations on the pilot roofs, as well as a modelling study supporting these observations. Second, results from measurements on the roof and in the houses directly under the roof will show the effect on indoor and outdoor temperature reductions (Chapter 4). These observations indicate the potential reduction of heat stress and energy consumption. Finally, questionnaires from the Municipal Health Services (GGD) aimed at analysing the perceived health benefits of blue-green roofs for residents are discussed in Chapter 5. Note that due to delays in the implementation of the roofs, and the consequential difficulties in obtaining survey results, Chapter 5 is limited to a description of methodology and a qualitative discussion. The overall conclusions of these different studies will be given in Chapter 6.

Results from this deliverable will feed into other deliverables in Work Package 6 (WP6). The building-scale performance found here will be up-scaled to estimations of heat stress and flood risk reduction on a city-scale (O6.4.1). Furthermore, the environmental and health benefits will be monetized and compared to the costs of blue-green roofs in a societal cost-benefit analysis (O6.5.1).

2 The RESILIO pilot roofs

This paragraph outlines the main characteristics of RESILIO blue-green roofs, such as their area, the different layers and their main properties. Subsequently, the location of the RESILIO pilot roofs are shown and the operation of the smart valve will be explained.

2.1 Location and properties of the RESILIO roofs

The 10 RESILIO pilot roofs are located in different parts of the city, and their surface areas range from 410 to 1721 m^2 (Figure 2). The roofs are built mainly on social rental properties and together will form approximately 10.000 m^2 of blue-green roof surface in the city. The vegetated and substrate layers, referred to as the green layer, consists of a mix of different vegetation types and 6 cm of substrate. This substrate layer consists of expanded shale, expanded clay, lava, pumice, crushed brick, Porlith, and/or green waste compost. The blue layer consists of water retention boxes (see Figure 3, right side for an example) and is situated underneath the green soil layer and above the roof deck. They typically consist of 85 mm deep plastic crates to create extra storage capacity (71l/m^2) for excess rainwater. The water retention boxes are topped with a filter fabric. The original bitumen roof deck needs to be strengthen with isolating cement and waterproof and root-resistant bitumen. This reinforced roof deck is topped with another water and root proof layer to prevent leakages from the water retention layer (Figure 3, left side; RESILIO, 2020).

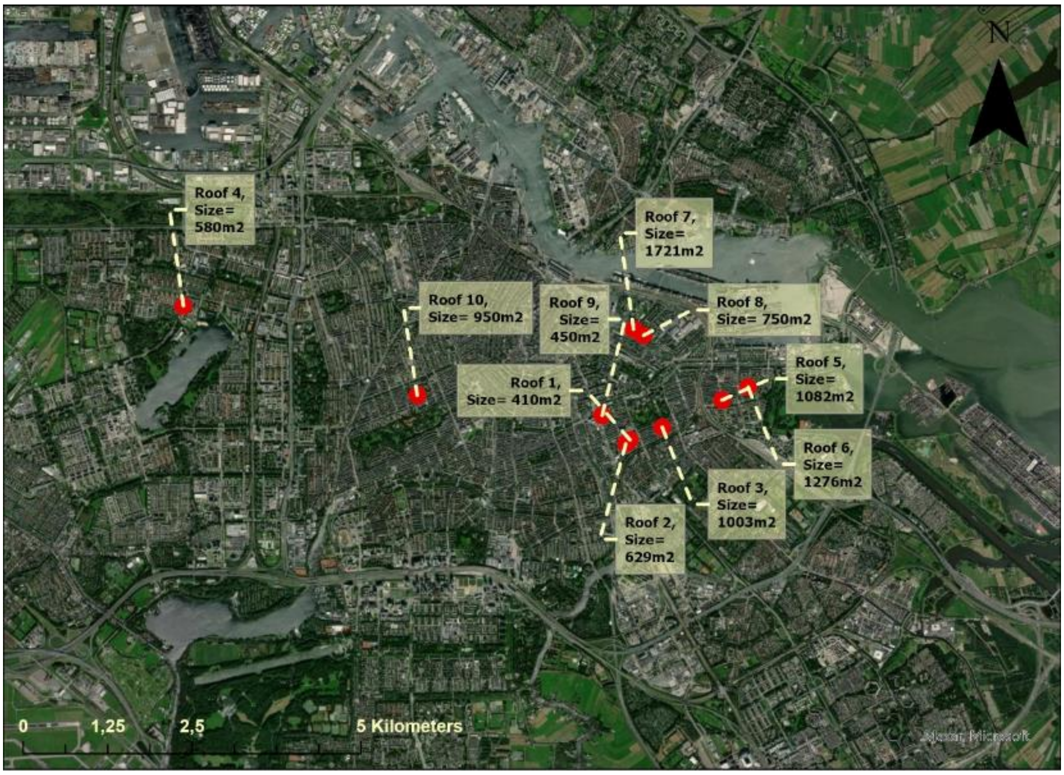

Figure 2 The location of the different roofs, including their sizes, as implemented in the project (see Appendix 1 for the roof's properties). Note that the displayed roof sizes are initial estimates and should be used with caution.

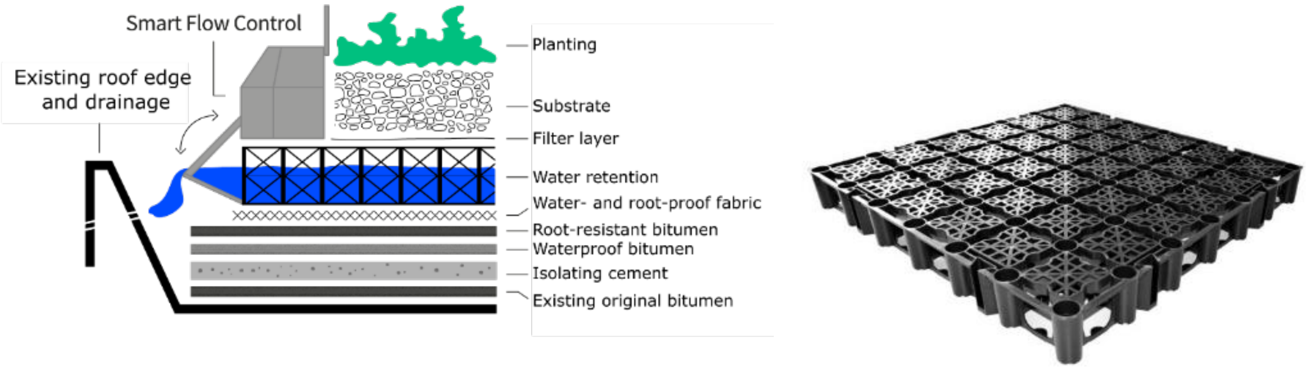

Figure 3 The different layers of a blue-green roof (left; RESILIO, 2020) and an example of a water retention box provided by the company Optigrun (right; Optigrün, 2021). Note that a variety of different suppliers are used for these retention boxes.

2.2 The Smart Drop®

An innovative feature of RESILIO blue-green roofs is The Smart Drop® (hereafter called the smart valve, Figure 4), developed by the Dutch Metropolder company (Metropolder Company, 2021). These valves allow for an automatic controlled drainage of water, based on either weather forecasts or observed weather conditions. Their width is 12 cm and they function on different operational modes, depending on the season (Table 1). In summer, the default configuration is closed to maximize water availability. The valve opens if the 36 hour precipitation forecast exceeds the current capacity of the blue layer, to increase rainfall buffer capacity. It closes again when the desired capacity has been reached. In winter, there is less need to store rainwater, as water demand by the plants is lower and extreme rainstorms causing floods do not occur. The valve is therefore open on default (Table 1). It will close if considerable precipitation is measured on the roof (>5 mm in the last 6 hours), to still ensure some water availability for the plants. For both seasons, the valve is programmed for an emergency release of water in case observed temperature drops below 2°C to avoid freezing. Ice can potentially damage the blue-green construction due to expansion.

The valve uses weather forecasts from MeteoServer (METEOSERVER, 2021). The data from Meteoserver contains weather forecasts from six different weather models, including high-resolution forecasts from The Royal Netherlands Meteorological Institute (KNMI). These include also forecasts from European Centre for Medium-Range Weather Forecasts (ECMWF), which are used in the modelling study outlined later.

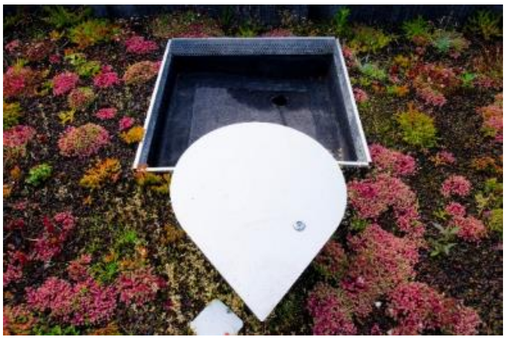

Figure 4 A smart valve as implemented on one of the RESILIO pilot roofs.

Table 1 The different operational configurations of The Smart Drop® in the summer and winter season (derived from Myers, 2020).

MetroPolder current operation rules	
Winter (starting from October 1st)	**Summer** (starting from March 1st)
Valve default=**open**	Valve default=**closed**
Valve **closes** when: - *>=5 mm of rain is measured in the last 6 hours.*	Valve **opens** when: *- 36 hours precipitation forecasts exceeds the amount of free storage in the system* *- Measured temperatures drop below 2°C to avoid freezing of water.*
Valve **opens** again when: - *< 5 mm of rain is measured in the last 6 hours.* - *Measured temperatures drop below 2°C to avoid freezing of water.*	Valve **closes** again when: *- The required amount of water has been drained.*

3 Hydrological effectiveness during extreme events

This chapter is written by the Vrije Universiteit Amsterdam

Take home messages

1. *Using weather forecasts to operate the smart valve, blue-green roofs can potentially* ***reduce runoff*** *during extreme rainfall events (>20mm/h) with* ***70%-97%****.*
2. *Blue-green roofs have the potential to provide* ***twice the amount of evaporation*** *during hot summer days as green roofs (****70%*** *vs 30% of PET). This underscores their* ***higher rate of cooling****.*

Note*: results presented in this Chapter, and parts of the previous chapters, are published as a peer-reviewed scientific article: Busker, T., de Moel, H., Haer, T., Schmeits, M., van den Hurk, B., Myers, K., Cirkel, D.G., Aerts, J., 2022. Blue-green roofs with forecast-based operation to reduce the impact of weather extremes. J. Environ. Manage. 301, 113750. https://doi.org/10.1016/J.JENVMAN.2021.113750. We acknowledge all authors for their contributions to this report.*

3.1 Introduction

Weather extremes such as heat waves and extreme rainfall will become more extreme and frequent in the coming decades (IPCC, 2021). For urban areas, where space for adaptation measures is limited, this poses a challenge on how to reduce the impacts of these extreme events. It is widely accepted that green infrastructure (e.g. parks, green roofs, etc.) are effective adaptation measures to reduce the impacts of these extremes in urban environments. They decrease pluvial flood risk by boosting storage capacity, infiltration and evapotranspiration, resulting in less surface runoff (World Wildlife Fund (WWF), 2016). Green infrastructure also decreases heat stress due to more evaporative cooling, shadow and (sometimes) a higher albedo. Blue-green roofs might outperform green roofs on evaporation rate and water storage capacity, also during these extreme events. The roofs have three main objectives from a hydrological perspective (defined in Busker et al., 2022):

1. Maximize buffer capacity during rainfall events to decrease pluvial flood risk;
2. Maximize ET and therefore evaporative cooling, to decrease heat stress;
3. Minimize the amount of long-term drought events (28-days <10 mm of water in the green layer);

These different objectives are conflicting: objective 1 requires a low water level to maximize buffer capacity, while objective 2-3 require a high water level to maximize ET and minimize the impact of long-term meteorological droughts. The smart valve regulates the water level on the RESILIO roofs (see paragraph 3.2). To maximize retention capacity during

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rainfall the valve should be on a ‘always open’ configuration, and close whenever rainfall is measured on the roof. Although this strategy would maximize water retention during rainfall, it minimizes overall water storage. This would result in a lack of water for the plant layer, especially during summer periods when lack of rainfall might occur. On the other hand, an ‘always closed’ configuration maximizes water supply for the plants and consequently increases evapotranspiration (ET). Although this configuration will boost evaporative cooling, it can lead to considerable overflow during rainfall events due to a lack of capacity in the blue layer. Hence, this configuration is also undesired. The optimal configuration of the smart valve therefore lies somewhere in between an ‘always open’ or ‘always closed’ configuration, and depends upon changing weather conditions. This is why precipitation forecasts can be used to optimize the operation of the smart valve. When anticipating on precipitation forecasts, the smart valve is always closed, except for the cases when predicted precipitation exceeds the current capacity of the blue layer. In these cases the smart valve can open a priori to create the necessary capacity to buffer incoming rainfall. This forecast-based drainage could allow for both a high buffer capacity during rainfall, and high overall water levels to boost ET and increase drought resilience of the plant layer. A perfect forecast system would therefore allow full utilization of the storage capacity for precipitation, while keeping the water level at an overall maximum at times when it is not raining.

3.1.1 Research aim

Despite improvements in precipitation intensity forecasts, forecasting local extreme precipitation events is still very challenging, even with non-hydrostatic numerical weather prediction (NWP) models (Manola et al., 2018). Furthermore, forecast accuracy generally decreases for higher-intensity events, such as the convective summer precipitation that occurs frequently in the Netherlands and have a very limited spatial extent (Imhoff et al., 2020). These uncertainties could limit the added value of anticipating on precipitation forecasts for very local applications such as blue-green roofs. Due to these uncertainties it is not yet known what the added value of precipitation forecast information is, and which forecast triggers should be used to optimize overall roof performance.

Therefore, we calculated and show-case the so-called “hydrological performance” of forecast-based blue-green roofs as observed on four RESILIO pilot roofs. This will give a general idea of the performance of these roofs when operating on precipitation forecasts. We compare the observed hydrological performance to the performance results found using our hydrological model to increase our confidence in the performance estimates. The final aim of this research is to assess the hydrological performance of blue-green roofs under extreme weather conditions, and to estimate the added value of using precipitation forecasts in their operation.

3.2 Methods and data

First, hydrological performance indicators will be defined that are used to measure the performance of blue-green roofs. Subsequently, the pre-processing method for the observations will be discussed and we will explain how the performance indicators are calculated from these observations. Last, the model for analyzing the performance of hydrological blue-green roofs will be outlined. This includes an explanation of the use of ECWMF meteorological forecasts in the model.

3.2.1 Hydrological performance indicators

Three different performance indicators have been used in the RESILIO project to test the hydrological performance of blue-green roofs, reflecting their most important objectives of (1) maximizing buffer capacity, (2) maximizing evapotranspiration, and (3) minimizing long-term drought events:

$$Performance_{\mathrm{buffer}} = \frac{Total\,rainfall\ captured\ (mm)}{Total\,rainfall\ (mm)} * 100 \tag{1}$$

$$Performance_{\mathrm{ET}} = \frac{ETa\ (mm)}{PET\ (mm)} * 100 \tag{2}$$

$$Performance_{\mathrm{droughts}} = (1 - \frac{\#\ drought\ events}{\#\ years\ analyzed}) * 100 \tag{3}$$

Performance$_{\mathrm{BUFFER}}$ (Eq. 1) yields the percentage of all precipitation that the blue-green roof captures. Every deviation below 100 denotes the occurrence of unwanted overflow. Performance$_{\mathrm{ET}}$ (Eq. 2) expresses the amount of actual evapotranspiration (Eta) relative to potential evapotranspiration (PET) and is therefore an indicator of water stress and evaporative cooling. Performance$_{\mathrm{DROUGHTS}}$ (Eq. 3) minimises the number of cases in which water is depleted from the green layer over a long period. This green layer drought is defined as a 28-day period with <10 mm of water in the green layer. This threshold is critical: once it is exceeded, a sedum plant with a substrate depth of 6 cm requires additional irrigation to continue growing and to stay green (Van Woert et al., 2005). Inevitably, a trade-off exists between the performance indicator of Eq. 1 on the one hand and those of Eq. 2 and Eq. 3 on the other: for buffer capacity to be optimised, the blue layer needs to be as empty as possible, but a full green layer is optimal for cooling and drought resistance. False heavy rainfall alarms may drain blue-layer water unnecessarily and lower the performance indicators measured by Eq. 2 and Eq. 3. Conversely, overly conservative draining may cause insufficient rainwater storage capacity during extreme events and result in otherwise preventable overflow.

3.2.2 The observations on RESILIO pilot roofs

The observations on the four RESILIO pilot roofs are analyzed to determine their performance for Performance$_{\mathrm{BUFFER}}$, Performance$_{\mathrm{ET}}$, Performance$_{\mathrm{DROUGHTS}}$ (eq. 1., 2., 3.). Observation data of water levels, precipitation, air temperature, water temperature and the position of the

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smart valve is collected by MetroPolder company. Water level, temperature and precipitation data are used to derive the performance estimates.

The measurements took place on four different roofs: Benno Premselahuis (Figure 2, Roof 9), Tweede Oosterparkstraat / Sparrenweg (Figure 2, Roof 1), Derde Oosterparkstraat (Figure 2, Roof 2) and Ite Boeremastraat (Figure 2, Roof 10). Most roofs contain multiple compartments with independent water levels and a smart valve (Table 2). Sensors in each of these compartments measures temperature, precipitation and water level. Only the Tweede Oosterparkstraat/Sparrenweg roof has one single compartment. The Benno Premselahuis roof consists of four different compartment, with in total five smart valves, as one compartment has two smart valves. The Ite Boeremastraat roof consists of two compartments.

Table 2 An overview of the properties of the different RESILIO roofs for which observations are available.

Roof Name	Roof # (see Appendix 1)	Amount of compartments	Amount of smart valves	Total size of compartments[a]
Tweede Oosterparkstraat/Sparrenweg	Roof 1	1	1	316m2
Derde Oosterparkstraat	Roof 2	2	2	465m2
Benno Premselahuis	Roof 9	4	5	380m2
Ite Boeremanstraat	Roof 10	2	2	327m2
Standardized model roof	-	1	1	500m^2

[a] The total size is smaller than the roof size shown in Appendix A, as space is used for the construction at the roof edges which cannot be used for water retention.

3.2.2.1 Pre-processing water level data

The observed water level data required pre-processing before use to remove errors and noise. Negative water levels have been deleted. Additionally, water level increases of more than 15 mm/10 minutes are removed: more than 15mm/10 minutes of rainfall is never observed by the rain gages and therefore these abrupt water level increases will be caused by water level measurement errors. For one of the compartments on Benno Premselahuis (high compartment, southern smart drop; black line Figure 9) and for the Tweede Oosterparkstraat roof (blue line, Figure 10), water levels above 65 mm were removed. These water levels represent measurement errors, as they structurally deviated significantly from the trend observed at the time steps before and after the measurement.

The roof on the Ite Boeremastraat consists of an inner compartment, which is surrounded by an outer compartment. The outer compartment's water levels are influenced by the discharge/overflow from the inner compartment and are therefore not used. For the Benno Premselahuis roof we only used the two main compartments (240 and 124 m^2) as they are representative for normal RESILIO roofs. The other two compartments are small and covered with different materials than the normal RESILIO roofs (e.g. solar panels, and white pebbles instead of vegetation). The roof in Tweede Oosterparkstraat consists of only one compartment, which is used in the analysis. The Derde Oosterparkstraat roof consists of two different compartments, each with a smart valve. One of the compartments showed a continuous record of very low water levels, and was therefore omitted from the analysis.

3.2.2.2 Deriving performance indicators from observations

Performance indicators are derived for all compartments, using these pre-processed water level, temperature and precipitation time series. We only used the buffer and ET performance indicator ($\text{performance}_{\text{BUFFER}}$ and $\text{Performance}_{\text{ET}}$), because the time period is too short for estimating the occurrence of long-term droughts ($\text{Performance}_{\text{DROUGHTS}}$). Some steps were necessary to calculate these two indicators from the observations:

a) **Estimation of $\text{performance}_{\text{BUFFER}}$ (i.e. overflow) from water level observations:** An estimation of amount of overflow is necessary to estimate the rainfall capture ratio. Overflow occurs if the amount of rainfall at a time step exceeds the capacity of the blue layer at the previous time step. Although the maximum capacity of the roofs is 71 mm, overflow is assumed to occur for water levels exceeding 60 mm. This is due to two reasons. First, water levels of one of the compartments (Benno Premselahuis, low compartment, blue line Figure 9) showed to have a clear maximum at around 63 mm. Secondly, for another compartment in the Benno Premselahuis observations beyond 65 mm showed abundant errors and therefore had to be omitted. All the other compartments (and the roofs in the Oosterparkstraat) very rarely showed water levels beyond 60 mm, and were therefore not influenced by this threshold.

b) **Estimation of $\text{performance}_{\text{ET}}$ from water level observations:** No direct ET measurements are available from the MetroPolder data. Therefore, the ET performance was estimated directly from the water level data. The study by Cirkel et al. (2018) showed that ET is similar to PET for water levels exceeding 10 mm. For lower water levels, ET decreases linearly from PET. As measurements of PET were not available on the roofs, we estimated the ET performance directly from the water level. For water levels >10 mm, it is always 100%, but for lower water levels the indicator has been set to 10 times the water level. For example, a water level of 6 mm yields a ET performance of 60% for that time step.

The mean of the ET and buffer performance over all time steps return the final performance per individual compartment, and a (time-weighted) average for each compartment yields the final performance per roof.

3.2.3 The modelling study

This section describes the blue-green roof modelling study, as published by Busker et al. (2022). Results from this study complement the observations at the RESILIO pilot roofs. The observations cover a period of only several months, and are therefore too short to represent hydrological extremes. This modelling study covers longer period (2013-2019) and models many more (virtual) blue-green roofs. Therefore, this modelling study is used to strengthen confidence and robustness of the observed hydrological performance on the RESILIO pilot roofs.

3.2.3.1 General model setup

Figure 5 shows the overall approach of this research of the modelling study on blue-green roofs. After pre-processing, historical ECMWF forecasts are used as an input for the hydrological model that simulates the hydrological flows of a blue-green roof. Different forecast-based drainage strategies (see Table 3) are developed to trigger opening of the smart valve and to drain water from the blue layer based on ensemble precipitation forecasts. These different strategies were compared using the different hydrological performance indicators (see section 4.2.1). They are also compared to other roof configurations, such as a traditional green roof and a blue-green roof without a valve.

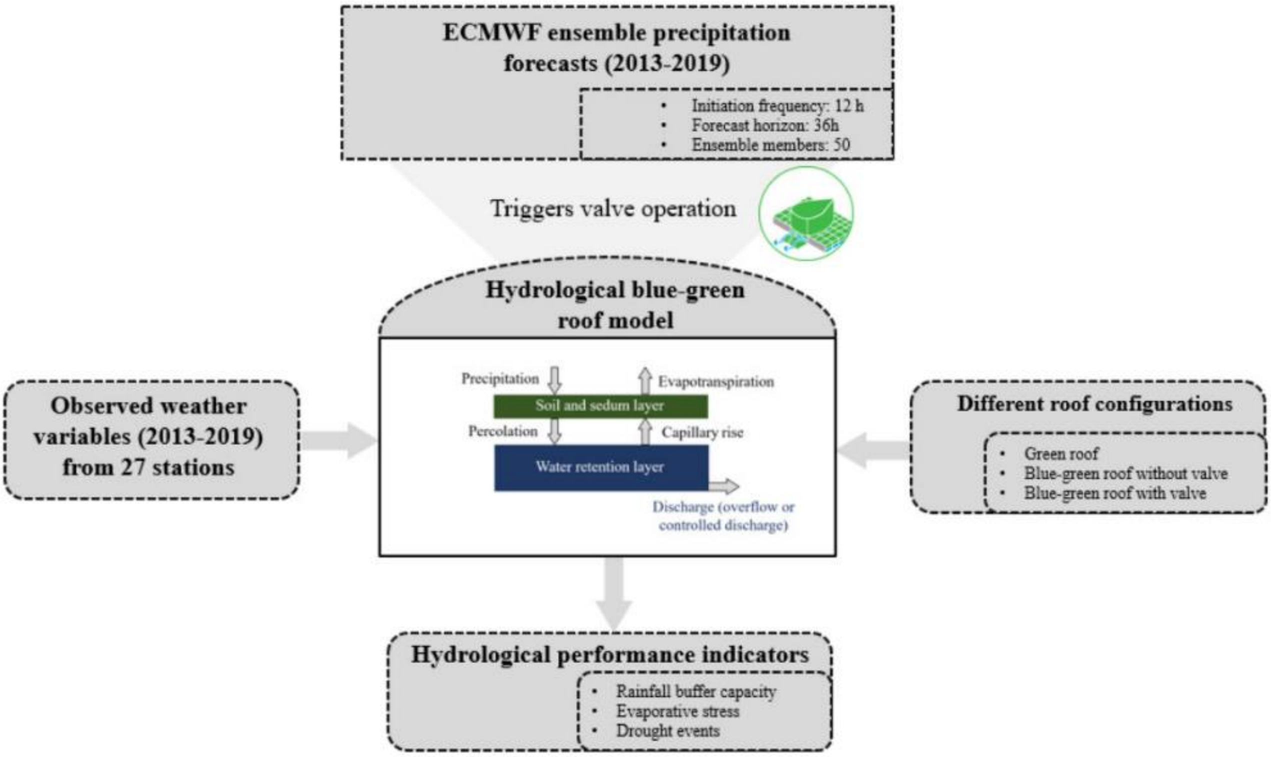

Figure 5 Framework of the research methodology, including inputs to the hydrological model and the three performance indicators used in the evaluation.

The hydrological model ran with weather data from 27 automatic weather stations in the Netherlands for which continuous data was available over seven years (2013-2019, Figure 6, KNMI, 2020). We sampled all 27 locations to increase the statistical robustness of the output

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of the model, which is especially important for extreme rainfall (>20 mm/h) events with a low return period. Six out of 27 stations did not record any extreme events, and the stations with extreme rainfall recorded 1-5 events each. The meteorological data cover hourly precipitation observations and daily meteorological variables. The latter, namely global radiation, mean windspeed, mean, minimum and maximum temperature, and minimum and maximum relative humidity, were used for the evaporation module of the hydrological model. The hourly precipitation observations were used as input to the blue-green roof in the hydrological model on every 10-min time step. They are also used to generate a perfect forecast in the 'perfect_forecast' drainage strategy (see Table 3).

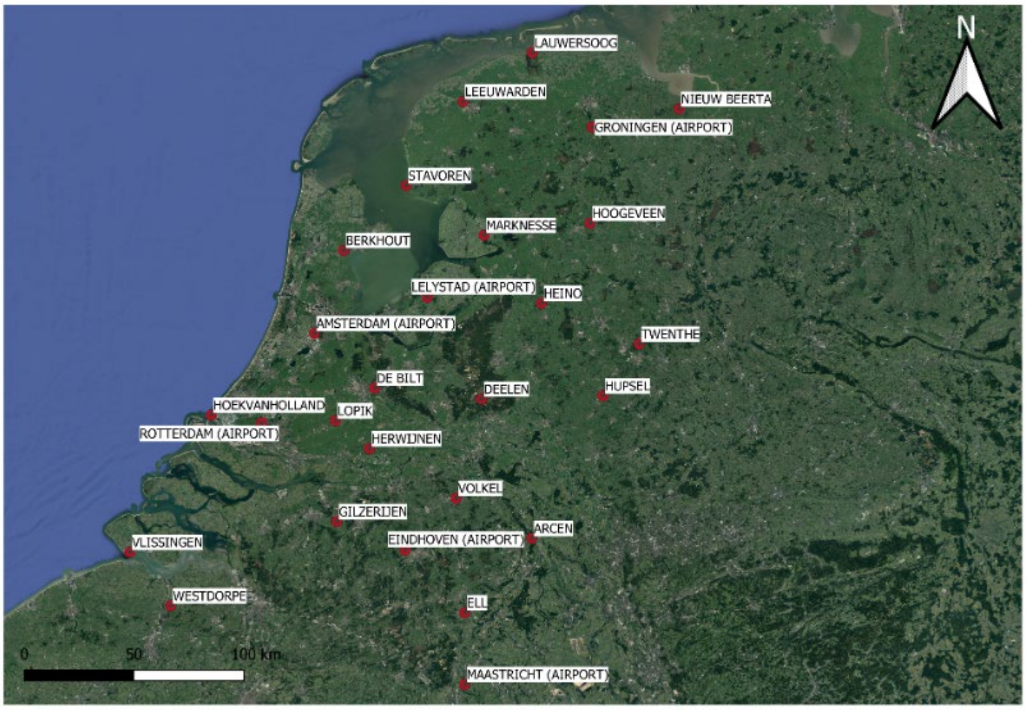

Figure 6 The 27 KNMI weather stations whose data are used as sources of inputs for the hydrological blue-green roof model for the 2013-2019 period.

3.2.3.2 Processes in the hydrological model

Together with co-authors (Busker et al., 2022), we developed a hydrological model simulating forecast-based operation of a blue-green roof. This model is based on the conventional recharge model presented by Ireson & Butler (2013) and the blue-green roof model that was developed by Cirkel et al. (2018). For an individual blue-green roof, it simulates the main hydrological fluxes, namely precipitation, evapotranspiration, capillary rise, percolation, controlled discharge and overflow (see Figure 7) at 10-minute time steps. We modelled virtual roofs with the same properties (e.g. water capacity and vegetation type, size, amount of smart valves) as the RESILIO pilot roofs. This includes a green layer consisting of 60-mm substrate with sedum vegetation. The water storage capacity of this green layer is 12 mm on average (20% of the 60 mm substrate; Metropolder Company, 2021). Below this layer, a blue layer with a capacity of 71 mm is present (Metropolder Company, 2021). The blue and green layers are connected such that the green layer can access water from the blue layer through capillary rise when the substrate is not saturated. Overflow to the city drainage system occurs without any intervention when the capacity of the blue layer (71 mm) is exceeded during rainfall (Figure 7, red line in the blue layer). To regulate storage in the blue layer, the smart valve, with a width of 12 cm, can regulate outflow based on forecasts. We simulated discharge through the valve using the Poleni equation (Indlekofer and Rouve, 1975).

We estimate daily potential evapotranspiration (PET) and actual evapotranspiration (ETa) using the Penman-Monteith equation (Allen et al., 1998; Monteith and Unsworth, 2013; Penman, 1948). The necessary meteorological input variables are retrieved from the daily observations of the selected KNMI weather stations. Eta is estimated based on the water content of the green layer and the PET value. Following Cirkel et al. (2018), we assume that ETa is equal to PET when the amount of water in the green layer exceeds 10 mm (Figure 7, red line in the green layer). For lower water contents, ETa decreases linearly with water content. As the green layer only begins to dry if the blue layer is empty, ETa only decreases relative to PET if the blue layer is empty and ETa from the green layer exceeds precipitation.

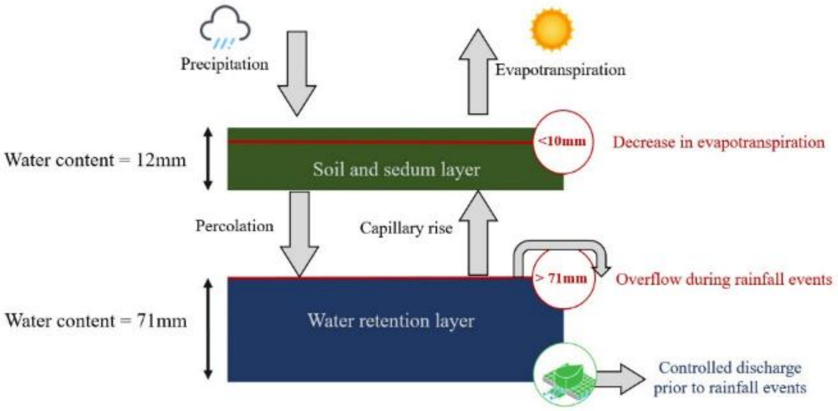

Figure 7 The configuration of blue-green roofs in the hydrological model. The red lines show the water content thresholds for which exceedance produces undesired outcomes (overflow for the blue layer, reduced ETa for the green layer).

3.2.3.3 The use of ECMWF forecast on blue-green roofs

The developed hydrological blue-green roof model described above uses precipitation forecasts to close and open the smart valve. Whenever the predicted precipitation exceeds the capacity of the blue layer, the valve opens to drain water in advance of the rainfall event. In this study, we use forecasts from the ECMWF. As shown by Haiden et al. (2019) the ECMWF outperforms other deterministic and ensemble global-scale forecast models (the Japan Meteorological Agency, UK Met Office, and the United States National Centers for Environmental Prediction) based on 500 Hectopascal (hPa) geopotential, 850 hPa temperature and total precipitation estimates.

Decision-support systems for blue-green roofs could either use single deterministic forecasts, or an array of many different forecasts: a so-called forecast ensemble. The ECMWF ensemble precipitation forecasts consists of a 50-member ensemble. The ensembles are created using different perturbations in initial conditions, forecast model equations, surface parameters and lateral boundary conditions (Frogner et al., 2019). These ensemble forecasts provide probabilities that a certain rainfall intensity will be exceeded, and therefore reflect forecast uncertainties. Uncertainty is most commonly expressed using Cumulative Distribution Functions (CDF) (see Figure 8, right). CDFs indicate the probability that the observed value will be higher than the forecast, also called the Probability of Exceedance (P). These reflect different percentiles of the statistical ensemble distribution. For example, the amount of rain forecast by the 60th percentile of the distribution is equal to the amount of rain with P=0.4; there is a 40% chance that more than X mm will fall, and a 60% chance that less than X mm will fall. For the extreme precipitation event in July 2014, the 99th percentile of ECMWF indicated 37 mm of rain between 6-12am (Figure 8). This basically means that the extreme of the 50 ensemble members forecasts 37 mm of rain. The median, or 50th percentile indicates that half of the ensemble members are above a certain amount of rain (approximately 25 mm as shown in Figure 8 for this example). Blue-green roofs could utilize these ensemble information, instead of always opting for the control (or median) forecasted values. For example, if capturing rainfall is a priority, high percentiles from precipitation forecasts could be used to drain water from the blue layer. However, this will likely overestimate actual rainfall and therefore lead to decreased water availability, and reduced ET from the plant layer.

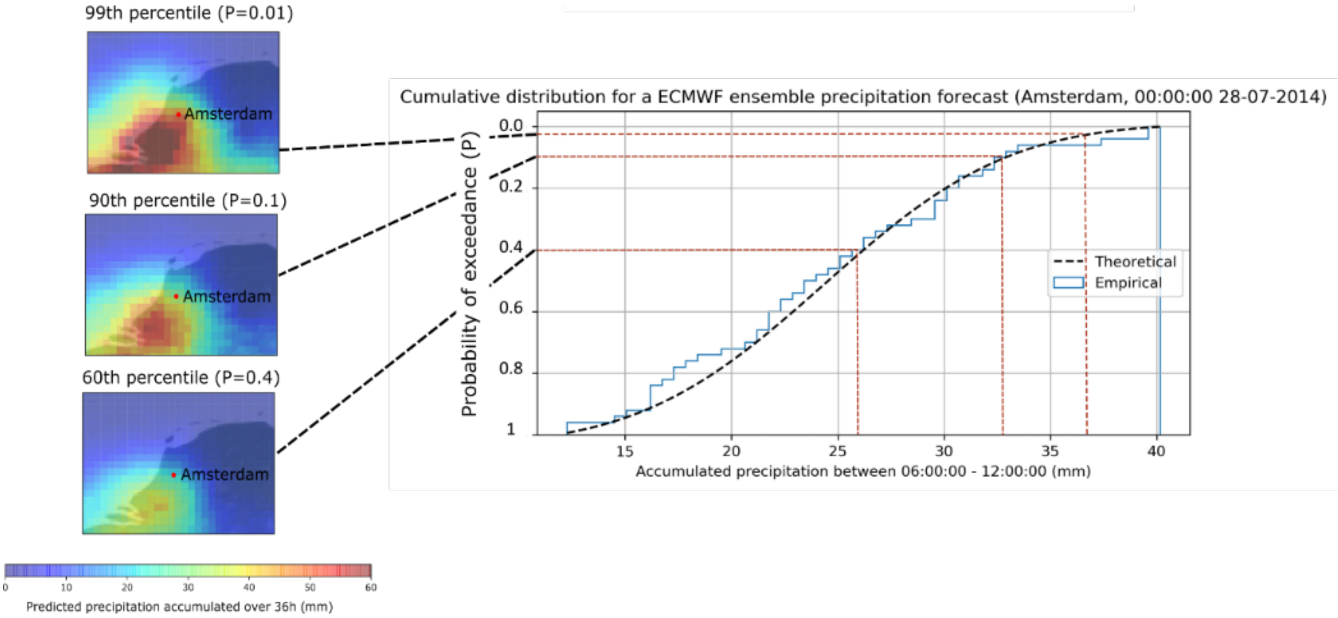

Figure 8 Right: An ensemble distribution, visualized as a CDF, for a ECMWF precipitation forecast for Amsterdam on 28 July 2014, derived from 51 ensemble members with a 6h lead time. Left: Maps visualizing the ECMWF precipitation forecast for 28 July 2014, using different percentiles (i.e. probabilities) of the distribution as visualized on the right.

In the hydrological model, the valve operates based on these ensemble forecasts, with 50 ensemble members available for each six-hour forecast accumulation period in the 36-hour forecast horizon. We chose a 36-hour forecast horizon to ensure that there is always enough time to drain the blue layer: ECMWF forecasts are issued every 12h, and it can take 24 hours to drain a complete blue layer of 500 m^2 through the 12 cm wide valve. We used six different percentile variations: the 30th, 60th, 90th and the 99th percentile as well as increasing and decreasing percentiles with lead time (Table 3, and Figure 8 for the illustration). The following strategy names were adopted: ‘per_30’, ‘per_60’, ‘per_90’, ‘per_99’, ‘per_increasing’ and ‘per_decreasing’. The valve opens, that is, controlled drainage starts, when the total precipitation amount indicated by these percentiles over the 36-hour forecast horizon exceeds the current capacity of the blue layer. However, the valve never opens at moments that it is already raining.

We compared this forecast-based roof operation with several benchmarks: a perfect forecast based on ‘future’ observations (‘perfect_forecast’), a blue-green roof without any drainage (‘BG_bucket’) and a traditional green roof without a blue layer (‘green_roof’; Table 3). An overview of these different strategies, including the strategy names, is given in Table 3.

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Table 3 An overview of the different strategies assessed in this study, including the forecast-based drainage strategies.

	Strategy description		Strategy name
No drainage	Traditional green roof		Green_roof
	Blue-green roof without drainage		BG_bucket
Forecast-based drainage	Trigger to open valve: Precipitation forecast exceeds blue layer capacity (i.e., overflow is predicted), according to:	ECMWF's X^{th} percentile	Per_X
		ECMWF's X^{th} percentile and decrease percentile with lead time: - 0-12h: 90th percentile - 12-24h: 60th percentile - 24-36h: 30th percentile	Per_decreasing
		ECMWF's X^{th} percentile and increase percentile with lead time: - 0-12h: 30th percentile - 12-24h: 60th percentile - 24-36h: 90th percentile	Per_increasing
		A perfect forecast: observed precipitation for the next 36h	Perfect_forecast

3.3 Results

In the following section, we will outline the performance indicators as observed on the RESILIO pilot roofs. Subsequently, we will show the results from the hydrological modelling study of Busker et al. (2022) for a standardized model roof with an area of 500 m^2 and one smart valve. Afterwards, the roof area and amount of valves will be tailored to best represent the different RESILIO pilot roofs. This allows for a comparison between the modelled and observed performance indicators.

3.3.1 Hydrological performance from observations

We first show the time series of water level observations from three of the pilot roofs: Benno Premselahuis, Tweede Oosterparkstraat and Derde Oosterparkstraat. Afterwards, the performance indicators are calculated from these observations, and compared to the modelled blue-green roof performance.

3.3.1.1 Observational timeseries – Benno Premselahuis

The Benno Premselahuis roof has two main compartments of 364 m^2 in total. The time series in Figure 9 show the water level dynamics in these two compartments. The water level clearly shows the effect of the different valve configurations in summer and winter. Water levels in winter (starting October 1st) are on average lower than in summer (starting March 1st), as the valve is open on default in winter and only closes if precipitation is measured. Two out of three sensors recorded data from May 2020 to July 2021 in the same compartment (high compartment, red and black line in Figure 9). However, they didn't record exactly the same water levels. The southern smart valve of this compartment (black line, Figure 9) structurally recorded higher water levels than the northern smart valve of that same compartment (red line, Figure 9). This can potentially be explained by the considerable roof slope at the base of this compartment, which pushes the water up on the south side. Data for the other compartment (low compartment, blue line Figure 9) is shown from March 2021, as the measurements prior to that contained many unfixable errors.

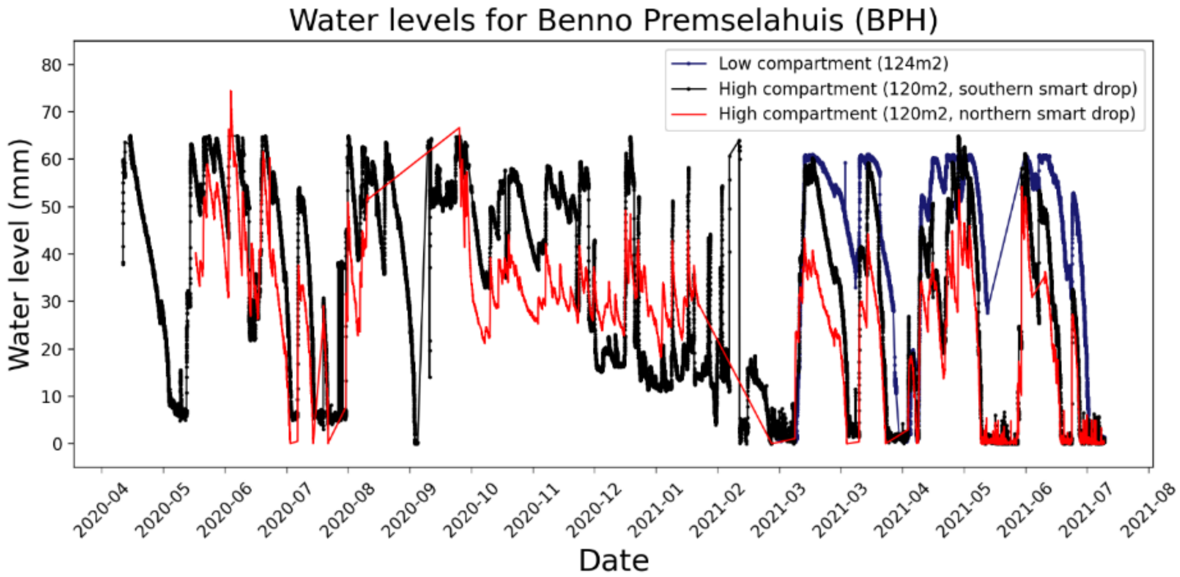

Figure 9 Time series of observed water levels for the RESILIO roof at Benno Premselahuis.

3.3.1.2 Observational timeseries - Tweede and Derde Oosterparkstraat

The water levels for the two roofs in the Oosterparkstraat are shown in Figure 10. As shown, both roofs have consistently low water levels, not exceeding 50 mm and rarely exceeding 40 mm. This can be explained by low rainfall amounts in this part of the city, false alarms in the forecast unnecessarily opening the valve, or a very high evaporation demand due to growing vegetation and/or hot weather conditions. The time series from the two roofs show a very similar pattern, which is logical given their proximity and therefore similar meteorological conditions. Both time series cover a period of only 6 months, which is shorter than the observations from the Benno Premselahuis.

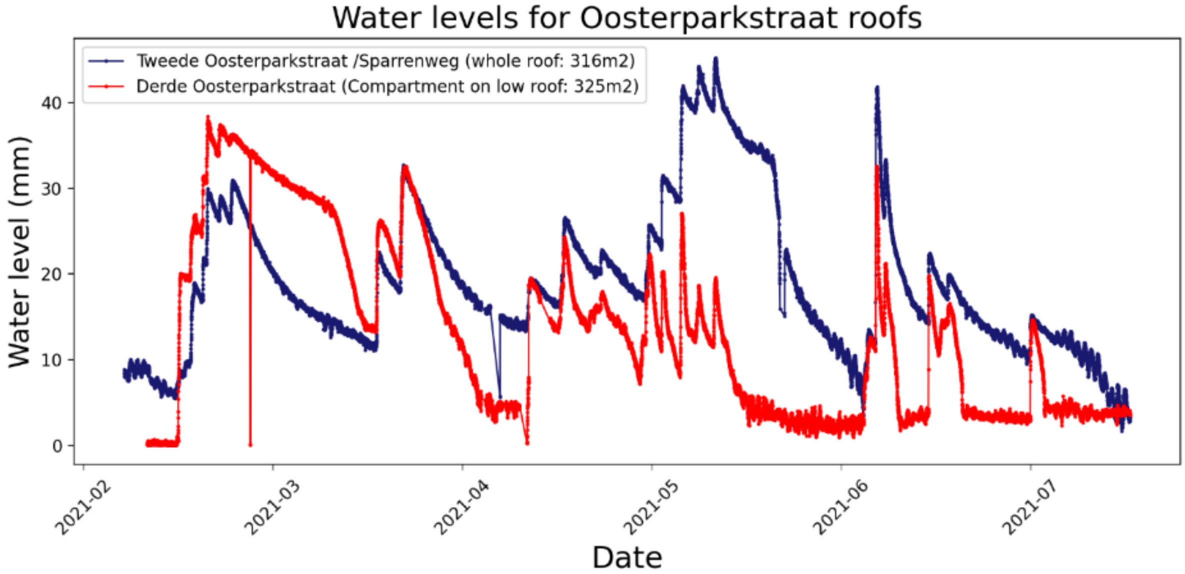

Figure 10 Time series of observed water levels for the RESILIO roof at the Tweede Oosterparkstraat and Derde Oosterparkstraat.

3.3.1.3 Observed performance indicators

We extracted hydrological performance indicators from these observations on the considered RESILIO pilot roofs. We calculated the performance of ET relative to PET ($\text{Performance}_{\text{ET}}$, %) and the relative amount of rainfall capture ($\text{Performance}_{\text{BUFFER}}$), using the methodology described in section 4.2.1 and 4.2.2. We also calculated these performance indicators for summer heat events, and extreme rainfall events specifically. We define rainfall peaks as precipitation in excess of 20 mm in one hour. The extreme event is then defined as the peak itself plus the rainfall at the time steps before and after the peak for which continuous rainfall is observed. The summer heat events only represent time steps for which the observed temperature is above 25℃.

The ET performance average over all roofs is 84%, meaning that the total amount of ET relative to PET is 84% (Figure 11). This indicates that the roofs have an overall high water availability and therefore high evaporation rates. Evaporative demand is higher on hot summer days (T>25 ℃) than on normal days. Therefore, the ET performance is reduced to 51 % on these warm periods. The roof on the Derde Oosterparkstraat shows a significantly lower ET performance than the rest of the roofs (Figure 11). The large spread of performance values among the different roofs can be explained by the large spatial variation in rainfall; if multiple precipitation events miss a roof before/during a hot and dry period, this can cause a large reduction in ET performance during these hot days.

The rainfall capture performance is high among all roofs: on average 90% for all rainfall and 95% for extreme rainfall (>20mm/h) (Figure 11). This indicates that the RESILIO roofs often have enough capacity to capture (almost) the whole rainfall event. Two roofs (Tweede and Derde Oosterparkstraat) even captured all rainfall events completely (Figure 11). The

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extreme rainfall performance is always >90%, indicating that very large shares of extreme rainfall can be stored on the roof. This only considers rainfall events of >20mm/h, and therefore these large capture ratios will translate to a reduction in pluvial flood risk. It should be noted that relatively few observations (only 4h in total) are present for these extreme rainfalls (see table 4). To increase the robustness of our estimates, we therefore additionally conducted a modelling study with more of these extremes.

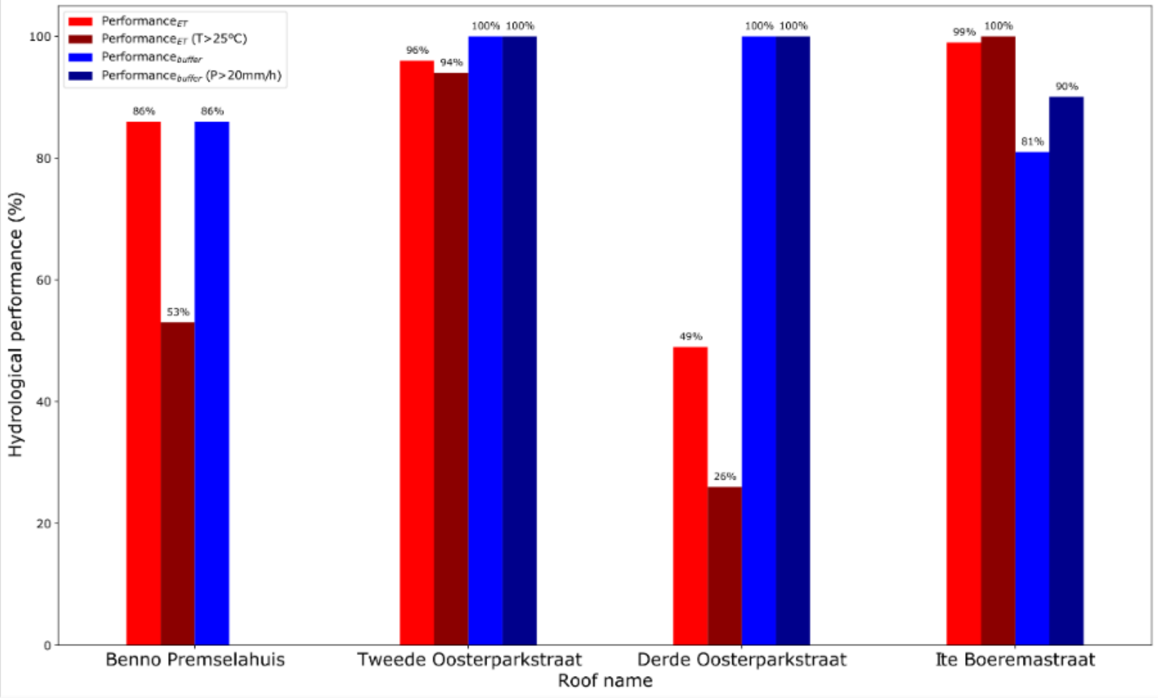

Figure 11 The hydrological performance indicators (%) as calculated from the observations on the 4 RESILIO pilot roofs considered in this report.

3.3.2 Hydrological performance from the modelling study

The observed performance indicators (4.3.1) are derived from observations during a limited number of months. To increase the statistical robustness of these estimates, we developed a hydrological model. This model runs on 27 different locations between 2013-2019 and therefore captures many more extreme events (45 in total). Below we will outline the results from this modelling study for a standardized sedum roof of 500 m^2 with one smart valve that uses ECWMF ensemble forecasts to trigger controlled discharge. We compare this blue-green roof to a normal green roof (‘green_roof’) and a blue-green roof without any controlled discharge (‘BG_bucket’).

3.3.2.1 General hydrological performance

The performance indicators for the standardized model roof of 500m^2 are depicted in boxplots and representing the distribution of accumulated values over the seven years under observation (Figure 12). Without the blue layer, the green layer would only store approximately 30% of the total precipitation (leftmost blue box in Figure 12), with the other 70% being uncontrolled overflow. When the blue layer is added without any controlled drainage (‘BG_bucket’), the capture ratio increases to approximately 50%. The addition of the smart control improves performance considerably, with values in excess of 90% under most strategies. The use of high percentiles from the forecast ensemble (90th or 99th percentile) sees performance approach values that are close to 100%. This means that almost all rainfall is captured, and overflow does (almost) not occur during rainfall. This translates to a reduction of pressure on the drainage system during rainfall.

In terms of ET performance, it is evident that blue-green roofs evaporate considerably more than green roofs (Figure 12). There is, however, little variation between the strategies: performance is always above 80% of PET when ECMWF forecasts are used, even for the higher percentiles. Only when the highest percentile (99th percentile) is used, ET performance drops by approximately 5 percentage points. Lastly, the mean performance of the green roof during meteorological drought events is only 17%, which increases to almost 80% for the blue-green configuration. The added value of using the blue layer as an irrigation source through capillary rise is thus evident. However, the drought indicator varies significantly between the 27 locations, as reflected by the wide confidence intervals of the green boxes. There is less uncertainty for buffer capacity performance; almost all stations showed a similar amount of overflow relative to total precipitation.

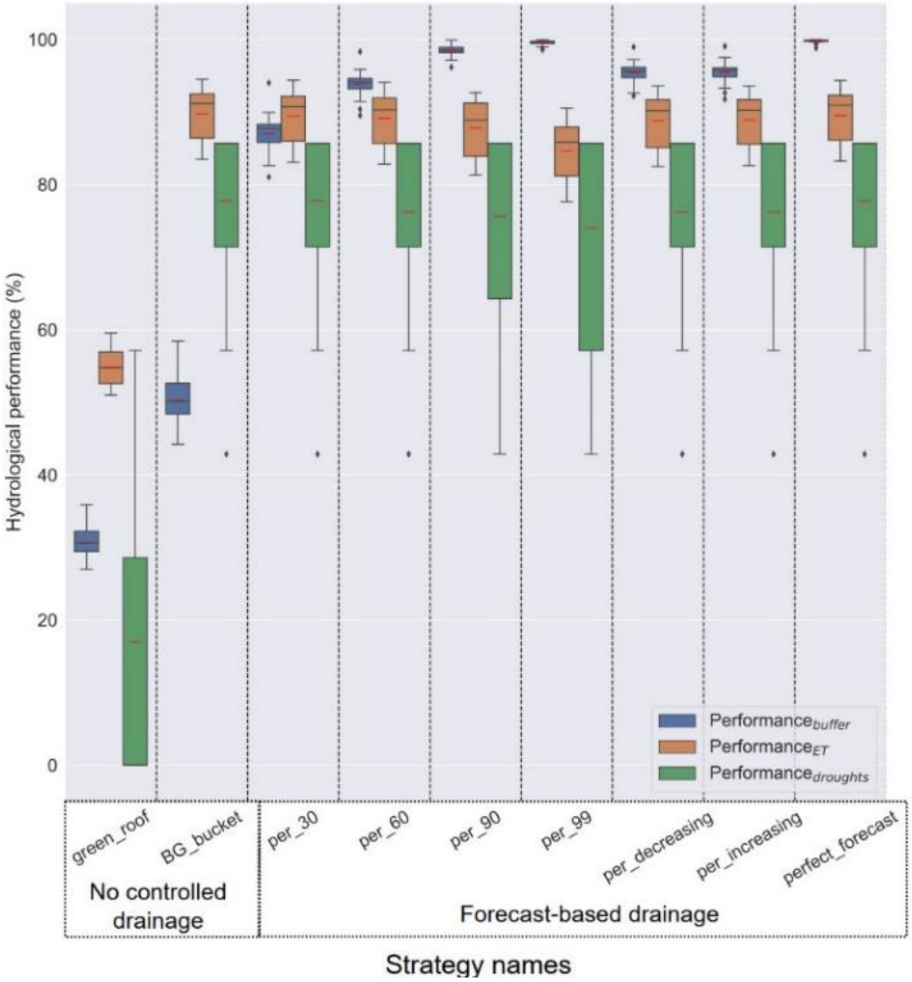

Figure 12 The overall hydrological performance of the standardized model roof, expressed as the three performance indicators for different early-drainage strategies. The boxplots represent the distributions of the performance indicators as calculated from all 27 simulated roofs. The mean values for the 27 roofs are indicated by the horizontal red lines.

3.3.2.2 Extreme hydrological performance

To test the performance of the standardized model roof in specific extreme events, we filtered the time series to include only observations of extreme precipitation (P>20mm/h) and summer heat events (T>25 °C). Our results indicate that the blue-green roofs perform much better than green roofs for both wet and hot extremes (Figure 13).

Summer heat events

The average ET performance of the standardized model roof is lower for each strategy when the model is applied only to summer heat events (Figure 13, left cf Figure 12). This stands to reason because summers are dryer than winters, and evaporative demand of the plants is also higher in summer. Consequently, average ET effectiveness is only 74%, even when controlled drainage is not allowed (the ‘BG_bucket’ configuration). The use of higher percentiles, that is, allowing more roof drainage, results in less evaporation, with an ET decrease towards 64% for the 99th percentile. However, the drop in ET at the 90th percentile is limited, and it is only 4.5 percent points lower than under the ‘BG_bucket’ configuration (Figure 13, left).

Extreme rainfall events

The ‘BG_bucket’ configuration already exhibits comparatively high effectiveness in storing rainfall, with a mean capture ratio of 59% (Figure 13, right). This performance increases to >83% if the 90th and 99th percentiles are used. Some rainfall events simply exceed the capacity of the blue layer (71 mm). For this reason, performance is less than 100% (but still 99%) even with perfect forecasts (‘perfect_strategy’ configuration). A precipitation event on 28 July 2014 of 131 mm in 4 hours was recorded at the Deelen station (see Figure 6 for the location), which was only captured for 30% (using the 90th percentile) due to an underestimation in the ECMWF forecast. The ‘per_increasing’ strategy yields better performance than its ‘per_decreasing’ counterpart. The most likely explanation is that the ‘per_increasing’ strategy triggers drainage for extreme events with long lead times if those events are only forecast by a small number of ensemble members. Notably, this more frequent drainage with uncertain, relatively long lead times does not result in considerably less evaporation than the other strategies (Figure 13, left). Overall, using high (90-99th) percentiles from the ECMWF ensemble precipitation forecast results in very high capture ratios, even during extreme events.

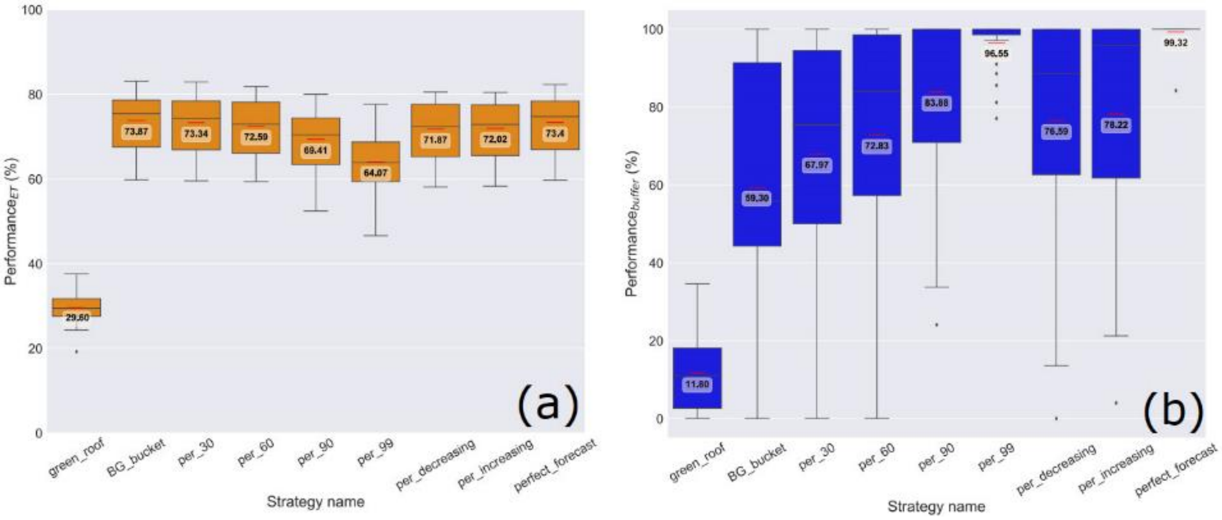

Figure 13 Boxplots from the standardized model roof that represent the distributions of the indicators of the performance of the 27 roofs in providing evaporative cooling during summer heat events with T > 25℃ (Panel a) and buffer capacity during extreme rainfall events with P > 20 mm/h (Panel b). The numbers indicate the mean values of the performance indicators, which are represented by the red horizontal lines.

3.3.3 A comparison between the model and observations

The modelled hydrological performance indicators (4.3.2) are compared to the observations (4.3.1) on the four RESILIO pilot roofs. The observation time-series are relatively short, and there is significant variance in the observations for the different roofs. However, the observational and modelled performance indicators (using ECMWF 60th percentile, 'per_60 strategy) show good similarities for all roofs (Table 4).

The average capture ratio ($\text{Performance}_{\text{BUFFER}}$) from the RESILIO pilot roofs is 92%, which underscores the high capture ratio of 94% as indicated by the model. We find very high capture ratios of on average 97% for extreme rainfall (>20mm/h) in the observations. It is worth noting that these cover only four hours of extreme rainfall events, making this estimate uncertain. The modelled performance, based on longer time-series, still shows high performance of 73% (Table 4).

The ET performance from the model and observations is very similar, respectively 89% and 83%. Also during warm days (T>25°C) the ET shows similar performance between the average observations and the modelled results. However, the spread between observations across roofs is large. The following can explain the differences between modelled and observed results for each roof:

1. The period of these hot summer temperatures in the observations (1445h), compared to the model results (32083h) is relatively short. This makes the observed ET performance uncertain. This is especially true for the Ita Boeremastraat, which has only 23 hours of observations;

2. The different weather forecasts that are used. On the RESILIO pilot roofs, a combination of different weather forecasts are used from Meteoserver (METEOSERVER, 2021), while forecasts from the ECWMF are used in the modelling study. The higher ET performance from the modelling study could be an indication that the ECMWF forecasts are more accurate (with less false alarms) than the forecasts from METEOSERVER. However, the timespan of the observations is too short to derive any conclusions about this;

3. The difference in vegetation between the model (Sedum plants) and the RESILIO pilot roofs (mostly grasses, shurbs and herbs, see e.g. Figure 1).These latter vegetation types have a higher water demand and more evaporation, which could decrease water availability on hot days.

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Table 4 A comparison between the observed and modelled performance indicators ($Performance_{ET}$ and $Performance_{buffer}$). The performance values shown are the (time-weighted) average performance over all compartments, and the average performance over all 27 weather stations, for the observations and model results respectively. Time covered (h) values show the total time for which data was available to estimate the performance.

Roof Name	$Performance_{ET}$ *[time covered (h)]*		$Performance_{ET}$ **for T>25℃** *[time covered (h)]*		$Performance_{buffer}$ **(%)***[time covered (h)]*		$Performance_{buffer}$ $(> 20mm/h)$ **(%)***[time covered (h)]*	
	Modelled	Observed	Modelled	Observed	Modelled	Observed	Modelled	Observed
Benno Premselahuis	**89.11%** [1656288h]	**86%** [1545h]	**72.56%** [32083h]	**53%** [456h]	**94.01%** [186288h]	**86%** [2223h]	**72.91%** [45h]	**-**
Tweede Oosterparkstraat	**89.12%** [1656288h]	**96%** [742h]	**72.59%** [32083h]	**94%** [289h]	**93.88%** [186288h]	**100%** [305h]	**72.82%** [45h]	**100%** [1h]
Derde Oosterparkstraat	**89.12%** [1656288h]	**49%** [1300h]	**72.58%** [32083h]	**26%** [678h]	**93.91%** [186288h]	**100%** [605h]	**72.86%** [45h]	**100%** [1h]
Ite Boeremastraat	**89.11%** [1656288h]	**99%** [573h]	**72.57%** [32083h]	**100%** [23h]	**93.98%** [186288h]	**81%** [194h]	**72.9%** [45h]	**90.04%** [2h]
Average	**89%**	**83%**	**73%**	**68%**	**94%**	**92%**	**73%**	**97%**

The performance values show much larger variability between the roofs for the observations than from the modelling study. This is expected due to the much larger time coverage of the modelling results. The advantage of the model is that it covers seven years of simulation on 27 different locations in the Netherlands, which greatly increases the robustness of the estimated performance indicators. Interesting to note is that the different roofs show very minor differences among their modelled performance, despite their different sizes and amount of smart valves. This suggests that roof size, and number of smart valves, have only a very minor influence on the total hydrological performance.

3.4 Discussion and conclusion

This section provides a discussion on the results presented in this chapter. We discuss potential considerations to improve the operation of blue-green roofs further, and give recommendations for future steps in research and development.

3.4.1 Improving meteorological forecasts on blue-green roofs

The RESILIO roofs apply precipitation forecast to operate the smart valve, a process which is also represented in the model study performed here on blue-green roofs. The RESILIO roofs use weather forecasts from MeteoServer (METEOSERVER, 2021), which are weather forecasts from six different weather models, including high-resolution KNMI forecasts and ECMWF forecasts. In the modelling study, we used only predictions from the ECWMF model. Potentially, this leads to small differences between the observation and model results. Especially during very local extreme rainfall events, the ECMWF model likely gives an underestimation of rainfall due to the relatively coarse 18 km resolution (Hewson and Pillosu, 2020). However, using ECMWF forecast allows for scaling up the analyzes, as ECMWF is generally seen as the most accurate global-scale weather model (Haiden et al., 2019). Moreover, we show in this study that the performance of blue-green roofs is already high when using ECMWF forecasts, and higher resolution data is expected to provide only marginal improvements to the performance. To combine scalability and resolution, further research could take advance of the EcPoint forecast which are under development by ECMWF (Hewson and Pillosu, 2020). These EcPoint forecasts, as well as higher resolution forecasts from KNMI, probably better represent local extreme precipitation than ECMWF forecasts.

The modelling study showed the advantage of using ensemble precipitation forecasts. The percentile considered can be changed, based on the objectives of the considered roof. If buffering rainfall is a priority over providing evaporative cooling, high percentiles of the ensemble distribution (i.e. more extreme forecast values) could be used. This is preferable for a roof in a flood-prone area, especially when there is a relatively low need for evaporative cooling, and drought-resistant plant types are used (e.g. Sedum). Using these higher percentiles, 70-97% of extreme precipitation can be captured (Figure 13). Moreover, these ensemble forecasts provide uncertainty information which can be used to improve forecast-based drainage further.

3.4.2 Improving observations of extreme events

The observations on the four RESILIO roofs used here cover a period of only six months for the Oosterparkstraat roofs, and 14 months on Benno Premselahuis. This period is too short to capture enough extreme weather events: the observations now include only four extreme precipitation events. The model results are robust, but they should be checked and validated using longer observational time series. Therefore, it is important to continue and expand the monitoring efforts on blue-green roofs. This will increase our understanding about their dynamics, and especially their performance under extreme conditions. Therefore, we encourage blue-green roof companies like MetroPolder to expand its measurements for the attainment of multiyear ground truth data.

3.4.3 Summary of findings

Blue-green roofs are effective adaptation measures to reduce the impact of extreme weather events. Recent observations on RESILIO pilot roofs show that a minimum of 81% of precipitation is captured, with the average capture ratio at 90%. For extreme rainfall events

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(>20mm/h), the capture ratio is 95%. However, the measurement period on the RESILIO roofs is short. To increase our confidence in the observed performance, we developed a hydrological model which ran on 27 different locations over the 2013-2019 period. This modelling study further strengthens the observations. It confirms that blue-green roofs can capture significant shares of rainfall (>90%), even for extreme events (70-97%), when operating on ECWMF ensemble precipitation forecasts. These capture ratios are much higher than for blue-green roofs without forecast-based drainage (around 50%). For traditional green roofs, we found capture ratios of only 12% and 30% for extreme rainfall (>20mm/h) and all rainfall, respectively. These numbers underscore the significant benefits of the blue layer with respect to buffering rainfall, and therefore its contribution to reduce pluvial flood risk.

The RESILIO pilot roofs moreover showed high evaporation rates compared to potential evaporation (on average 86%). The model results confirm the high evaporation rates compared to traditional green roofs (>80% vs. 55% of PET) due to the extra water availability and capillary rises. These evaporation rates are also evident on hot summer days (around 70% of PET), although evaporation decreases slightly with the considered percentile of the ECMWF ensemble forecasts.

Future studies should assess how uncertainty information from ensemble forecasts can be used further, and how precipitation forecasts can be translated to water level forecasts by including evaporation predictions. In project deliverable O6.4.1, the roof-scale performance found here is translated to city-scale impacts on heat stress and flood risk reduction.

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4 Indoor and outdoor heat stress reduction

This chapter is written by the Hogeschool van Amsterdam

Take home messages:

1. The temperature of the roof surface on the blue-green roofs is cooler than conventional roofs during summer. The temperature of the vegetation layers of (blue-)green roofs is similar.
2. The water crate layer has lower maximum temperatures than the other measured surfaces and less diurnal fluctuation through both cold and heat waves, indicating that the additional water layer only present in blue-green roofs function as a temperature buffer.
3. All indoor measurements showed small, but systematic influence of a dampening effect of blue-green roofs on indoor temperature.
4. Blue-green roofs contribute to extra insulation properties of the roofs.

***Note:** Due to limitations during the research, the results presented in this chapter are based on limited amount of roofs, influenced by external factors.*

4.1 Introduction

Within the Resilio project, the Hogeschool van Amsterdam has researched the cooling and insulation effect of blue-green roofs on the indoor temperature. The project was an unique opportunity where newly installed blue-green roofs could be compared with reference and green roofs located nearby. This gave insight in the thermal behavior of different types of roofs. In this field study we examined the impact on surface temperatures, indoor temperature and insulative properties of blue-green, green, and conventional gravel/bitumen roofs in the city of Amsterdam.

Roofs have received increased attention in mitigating the consequences of climate change in urban areas. This resulted in a variety of roof systems designed as part of integration in the built environment (Andenæs et al, 2018). It is more and more known that green roofs greatly reduce the proportion of solar radiation that reaches the roof structure beneath as well as offering additional insulation value due to evapotranspiration by the vegetative layer (Pastore et al, 2017; Castleton et al, 2010). However, more recent research suggests that the availability of a water in the substrate plays an important role in a higher actual evapotranspiration rate, which improves the cooling effect of the roof (Aboelata, 2021; Solcerova et al, 2017) and potentially improves the thermal comfort in the indoor environment (Cirkel et al, 2018; Razzaghmanesh et al, 2015).

Blue-green roofs have been mostly studied from the perspective of a higher water capture ratio (Busker et al, 2022, van Hamel, 2021) where the benefits of the extra water crate layers are often related to the potential of reducing pluvial flood risk or storm management (Shafique et al, 2016). Research specifically focusing on blue-green roofs potential in reducing heat stress is limited and research about potential insulation effects of the additional water crate layer in blue-green roofs is lacking.

4.1.1 Research objective

The aim of this research is to provide a better understanding of the effects of blue-green roofs on the inside temperature. To this end, the thermal flows through roofs were investigated by measuring the temperature in- and outside the building, both in the summer and winter. To assess the effect of the blue-green roofs, various questions have been defined focusing on the effect on (1) roof surface temperature, (2) inside temperature and (3) insulation properties:

1. **What is the thermal effect of blue-green roofs compared to non-vegetated roofs on the roof surface temperature?**
   a. What are the differences between surface temperature of reference roofs, substrate temperature of blue-green roofs and green roofs?
   b. What is the temperature inside the water crate layer compared to other measured outdoor surfaces?
2. **What is the thermal effect of blue-green roofs compared to non-vegetated roofs on the indoor temperature?**
   a. What are the differences in absolute temperature measured under a blue-green roof and under reference roofs?
   b. How does the indoor diurnal temperature fluctuation differ at locations with and without blue-green roofs?
3. **What is the effect of blue-green layer on insulation properties of the roofs?**

To answer the research questions, temperature measurements have been carried out above, on, and underneath roof surfaces of newly constructed blue-green roofs in Amsterdam, NL. The study was not conducted as a controlled lab-experiment but measurements were done as field studies. We relied on an environment with changing meteorological conditions, with a relatively cold and wet summer, and a high variability between measurement locations characteristics. Despite the same measurement methods for the different roofs, the resulting data set was influenced by external factors resulting in a lower quality than originally anticipated. There were delays in construction of the roofs and after delivery some of the roofs were without vegetation for a large part of the measurement period. Further, the measurements of water levels in some of the retention crates were still being calibrated or with measurement errors, resulting in unknown amount of water availability. During the analysis, these different conditions are taken into account.

4.2 Methods and data

The thermal impact of blue green roofs on building scale has been examined based on four newly installed RESILIO blue-green roofs, four reference roofs (black bitumen or gray gravel) and two conventional sedum covered green roofs. All roofs were in the vicinity of each other in order to have the same general meteorological conditions.

The measured temperatures at the blue-green roofs were put into perspective by comparing them with measurements at reference roofs with similar construction characteristics. Two already existing extensive green roofs have been included in the study in order to compare the well-established vegetation with the newly planted vegetation on blue-green roofs as

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well as the effect of the water crate layer. See also section 4.2.2.3 which presents the details of the different roofs. All the measurements were done in 2021 during both winter and summer conditions. Each roof was equipped with several sensors measuring the temperature above the roof surface, at the roof surface, and also inside the building. All these measurements allowed us to understand the temperature exchange between the indoor environment, the roof, and the air above.

4.2.1 Measurement Locations

The measurements took place at 10 roofs, all located in the east of Amsterdam, the Netherlands. None of the roofs stand in the shade of nearby buildings or trees. All buildings have 4-5 floors and are between 10-15 m tall. All roofs are within 5 km radius from each other and should not experience significant differences in weather patterns. However, local factors such as construction of the roof and roof elements (such as chimneys), the presence of water and plants, as well as the indoor context might have had an influence on the measured values.

The measurement locations and their naming can be found in Figure 14 and Table 5. The different neighborhoods of Amsterdam in which the roofs are located are Oosterparkbuurt, Indische Buurt and Oostelijke Eilanden.

Table 5 Overview of the different roofs where temperature measurements have been carried out. The roofs are labelled in the following way: Neighborhood, followed by an abbreviation of type of the roof, and – as some neighborhoods have multiple of roofs of the same type – a number of the roof . The newly constructed blue-green roofs have the abbreviation BG, the reference roofs R, and the green roofs G.

Roof Name	*Roof number in Resilio project (see appendix)*	Total roof size	Roof size suitable for blue-green
Oosterparkbuurt_BG_1	Roof 1 (BG)	410	410
Oosterparkbuurt_BG_2	Roof 2 (BG)	997	629
IndischeBuurt_BG_1	Roof 7 (BG)	1286	1276
OostelijkeEilanden_BG_1	Roof 8 (BG)	1746	1721
	Roofs not part of Resilio project:		
Oosterparkbuurt_G_1	Roof 12 (G)	62	n.a.
IndischeBuurt_G_1	Roof 13 (G)	62	n.a.
Oosterparkbuurt_R_1	Roof 14 (R-gravel)	288	n.a.
Oosterparkbuurt_R_2	Roof 15 (R-gravel)	129	n.a.
IndischeBuurt_R_1	Roof 16 (R-gravel)	179	n.a.
Oosterparkbuurt_R_3	Roof 17 (R-bitumen)	188	n.a.

Figure 14 The location of the different roofs, including their sizes, where temperature measurements have been carried out.

4.2.2 Measurement characteristics

4.2.2.1 Measurement periods

Figure 15 shows the timeline of the measurements at the roofs. The data were collected in 2021 and cover both winter and summer period. Although the data collection was continuous, in the analysis we predominantly looked at data from several distinct time periods that best represent the winter and summer situation. Occasionally, the entire summer or winter period was analyzed to get a more robust result. These cases are then specifically mentioned in the analysis.

Due to lack of official cold- and heatwaves in 2021, thresholds to define the warm and cold periods were set based on expert knowledge. Based on the gathered data, the following thresholds have been set and will be further used for analysis (Table 6). For a period to be considered as “warm” the average 24-hour air temperature measured above all blue-green

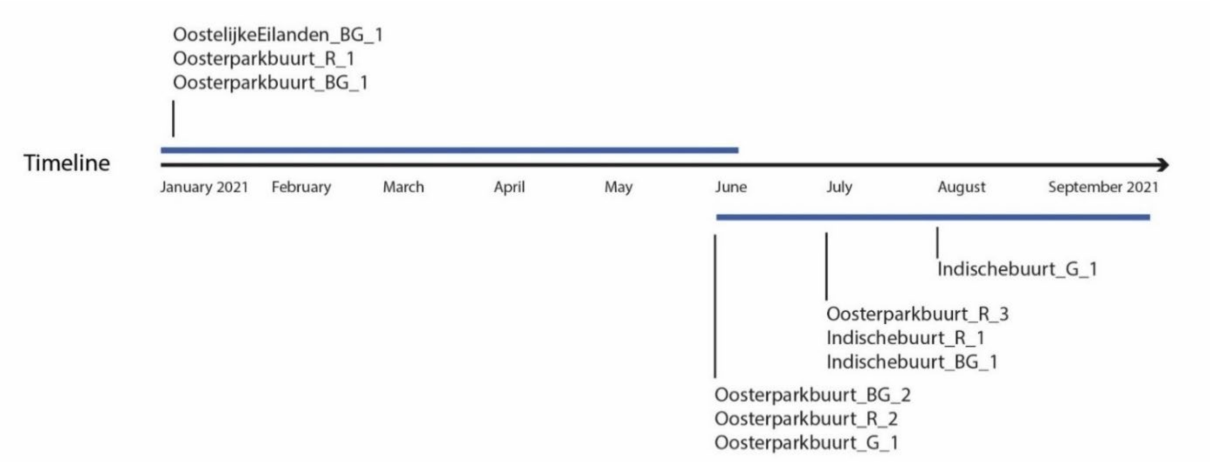

Figure 15 Timeline of the period where measurements have been carried

and green roofs had to be at least 20 °C for 5 consecutive days. For the cold period, the average air temperature should not exceed 0 °C for at least 5 consecutive days. Last defining factor was a sufficient data availability for both the indoor and outdoor temperatures as well as sufficient data for various types of roofs.

The above mentioned requirements, resulted in one suitable cold period and three warm periods, presented in Table 6. The cold period started on the 7th of February 2021 and persisted for 7 days with the minimum air temperature reaching -8.5 °C and average temperature of -2.8°C. The first warm period started on the 4th of June 2021, and persisted for 13 days with a maximum of 33.0 °C and an average temperature of 20.2 °C . The second warm period started the 16th of July 2021, and persisted for 12 days with maximum temperatures of 32.5 °C and an average of 20.4 °C. The third warm period started the 6th of September 2021, and lasted for 5 days with a maximum of 33.0 °C and an average temperature of 21.3 °C.

Table 6 The minimum, maximum and average values temperature values based on air temperatures measured above the green and blue-green roof(s).

Period	(Blue-)green roofs used to estimate the air temperature	Measurement Period	Threshold (°C)	Minimum Temperature (°C)	Maximum Temperature (°C)	Average Temperature (°C)
Cold	Oosterparkbuurt_BG_1 & OostelijkeEilanden_BG_1	07/02/2021 - 14/02/2021	Max. 5.0 (5 days)	-8.5	2	-2.8
Warm	Oosterparkbuurt_BG_1	04/06/2021 - 16/06/2021	Avg. 20.0 (5 days)	11.5	33.0	20.2
Warm	Oosterparkbuurt_G_1	16/07/2021 - 27/07/2021	Avg. 20.0 (5 days)	14.5	32.5	20.4
Warm	Oosterparkbuurt_BG_2 Indischebuurt_BG_1 Indischebuurt_G_1	06/09/2021 - 10/09/2021	Avg. 20.0 (5 days)	12.0	33.0	21.3

To better understand the weather conditions during the measurement periods, the Royal Netherlands Meteorological Institute (KNMI) records of temperature, wind and radiation measurements from the Schiphol station have been used as a reference for the air temperature measured on the roofs (daggegevens.knmi.nl). This station is located at ca. 13 kilometers from the measurement locations. As seen in Figure 16, during the cold period, the weather was transitioning from cloudy conditions with very low incoming radiation and high windspeeds (7 February) to more sunny and calm conditions at the end of the week (14 February). The warm periods were sunny days, defined by high incoming radiation values, with relatively low to average wind speeds.

There is a noticeable difference between the air temperature measured at Schiphol and on the roofs within this research. A small difference is to be expected due to effects of the city on air temperature (Steeneveld et al., 2011). These generally warmer city temperatures are visible on the winter measurements (Figure 16a). However, the difference for summer is higher than expected. This is probably due to the placement of the temperature sensors near the surface of the roof and often on a vertical construction on top of the roof (e.g. a wall of a chimney), causing extra infrared radiation coming from the stone surface (see also section 4.2.2.2). When comparing the air temperature on the blue-green roofs in summer (Figure 16b) with the radiation measurements from KNMI (Figure 3d), a pattern appears suggesting that the heating of the building surfaces due to reflected sun radiation is what causes the high temperature differences between our measurement sites with high building density and the measurement station at Schiphol, located at a rural open environment.

Because the measurement methods for the different roofs used in this study are the same, the quantitative results can be cross compared. However, as can be seen in the timeline, the measurements periods of the different roofs do differ with different meteorological situations. Therefore, the results of various measurement periods cannot be directly cross compared without taking into account the contextual analysis. In order to compare the results, the contextual analysis draws the background of the statistical analysis.

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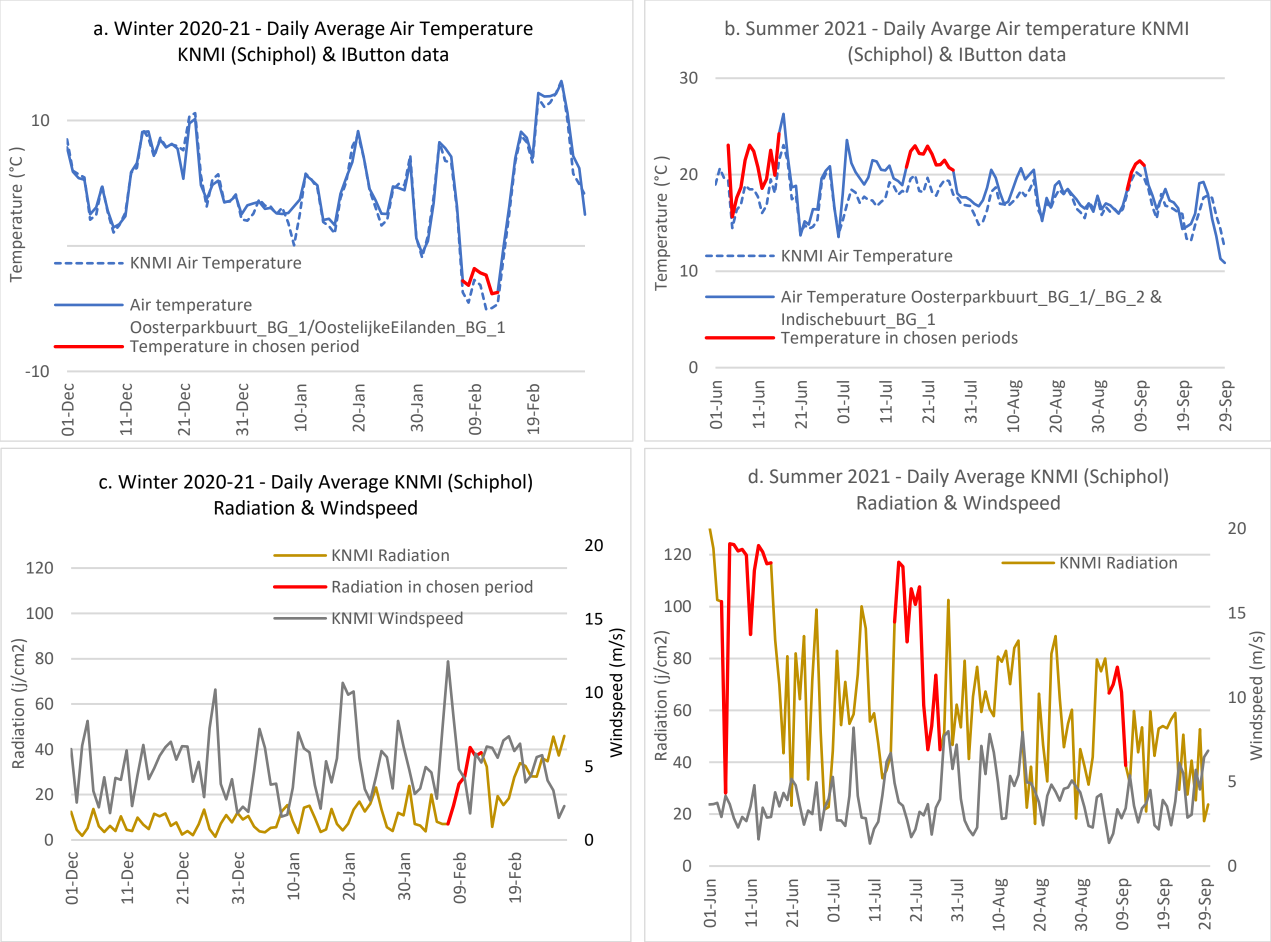

Figure 16 Graphs with data from the KNMI weather station, located at Schiphol Airport, and temperature measurements from the field study. In graphs a and b, the air temperature from the station and field study is represented. In graphs c and d, the radiation and windspeed from the weather station are presented. The periods that are analyzed in this research are highlighted with red.

4.2.2.2 *Temperature sensors and their placing*

The temperature was measured with Thermochron iButton temperature loggers (Thermocron iButton, 2015) (see Figure 17). These small sensors measure temperature at an user-set interval. For the Resilio project, they have been set to a 10 minute interval. The iButtons are capable of capturing temperatures between -30 and 85 °C with an accuracy of 0.5 °C. At each site, the temperatures have been measured above the roof, on the roof surface or in the substrate, and inside the building as shown in Figure 18. Outside, the air temperature was measured by placing an iButton at approximately 50 cm above the roof on a vertical construction on top of the roof (e.g. a wall of a chimney). The iButtons have been placed on the northside, to limit the direct influence of sun radiation. The surface temperature of the different roofs has been measured either on top of the surface or in the substrate, depending on the type of roof. The sensor was buried a few centimeters under the surface in the gravel or in the substrate in case of a (blue-)green roof. For surface measurements of the bitumen roofs, the iButton was directly placed on the surface of the roof in a shaded area. In case of blue-green roofs, the temperature was also measured in the water crate layer. Two types of temperatures were measured inside the building. The temperature of the ceiling was measured by placing the logger directly on the ceiling and the indoor air temperature measurement was taken ~10 cm under the ceiling.

Figure 17 Thermochron iButton, Maxim Integrated Products (2015)

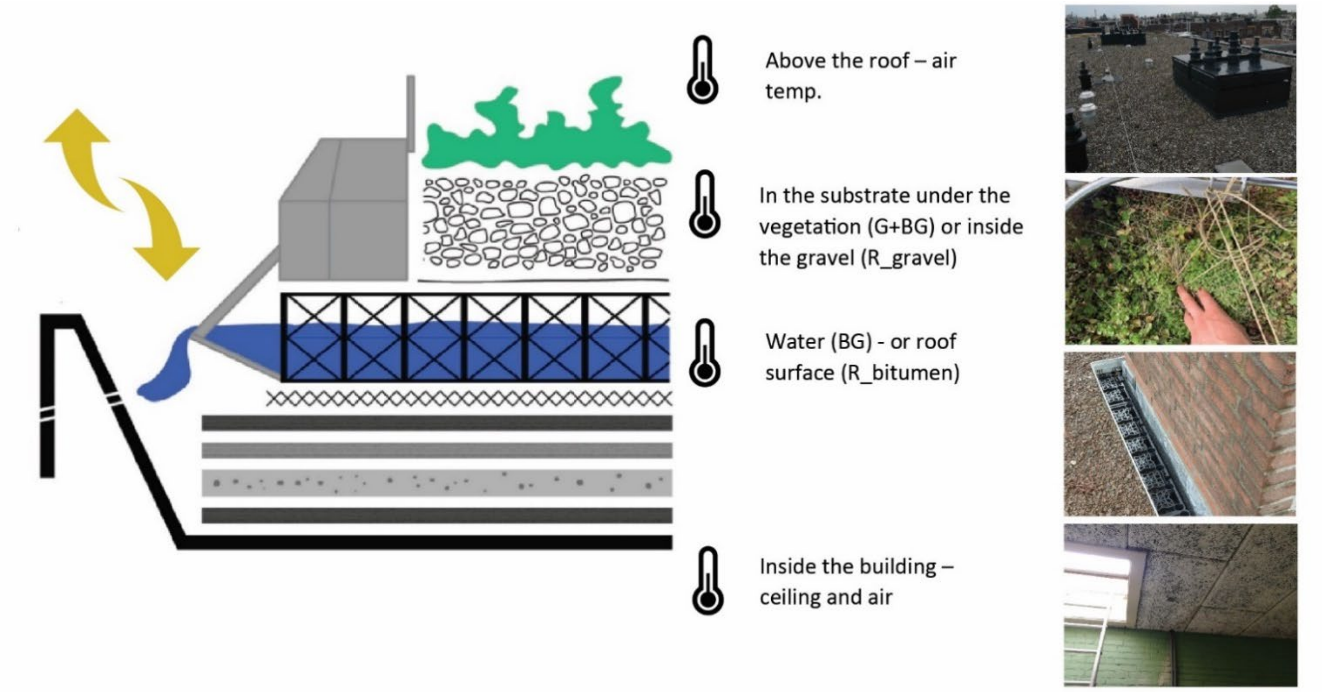

Figure 18 Overview of the placed measurement devices at the research site. Please note that the placement of the devices depended on the type of roof.

4.2.2.3 Roof structure

To understand how a blue green roof influences the temperature inside a building, it is necessary to look at the construction of such a roof in comparison to the reference roofs. In Figure 19 the different constructions are illustrated. The top layer of a blue-green roof is a green layer consisting of a substrate with vegetation. The substrate layer consists of expandable shale, expandable clay, lava, pumice, crushed brick, and/or green waste compost. This is very similar to a traditional green roof. The water crate layer in a blue-green roof consists of water retention boxes, plastic crates that are 85 mm deep which creates water storage capacity for rainwater. The system enables a capillary rise of water from the crates to the substrate above. The blue and green layers are connected and the plants growing on such roofs are supplied with water from the storage layer. This is the main difference between a blue-green and a green roof. Under the water crate layer, a water and root barrier prevent leakage and damage to the roof from plant roots. While installing the new blue-green layers on the bitumen roof deck, the original decks have been strengthened with an extra cement layer and waterproof and root-resistant bitumen. Under the (existing) bitumen layer lays the insulation layer of the roof. The reference roofs that are used in this research have either a bitumen or a gravel layer as a top layer. In case of a roof with gravel, there is a bitumen layer under the gravel.

Among the four different types of roof, insulation properties can vary per roof construction, which should be considered before drawing conclusions on the insulative benefit of green or blue-green roofs. Known insulation capacities of the insulation layer of the different roof locations are shown in Appendix E.

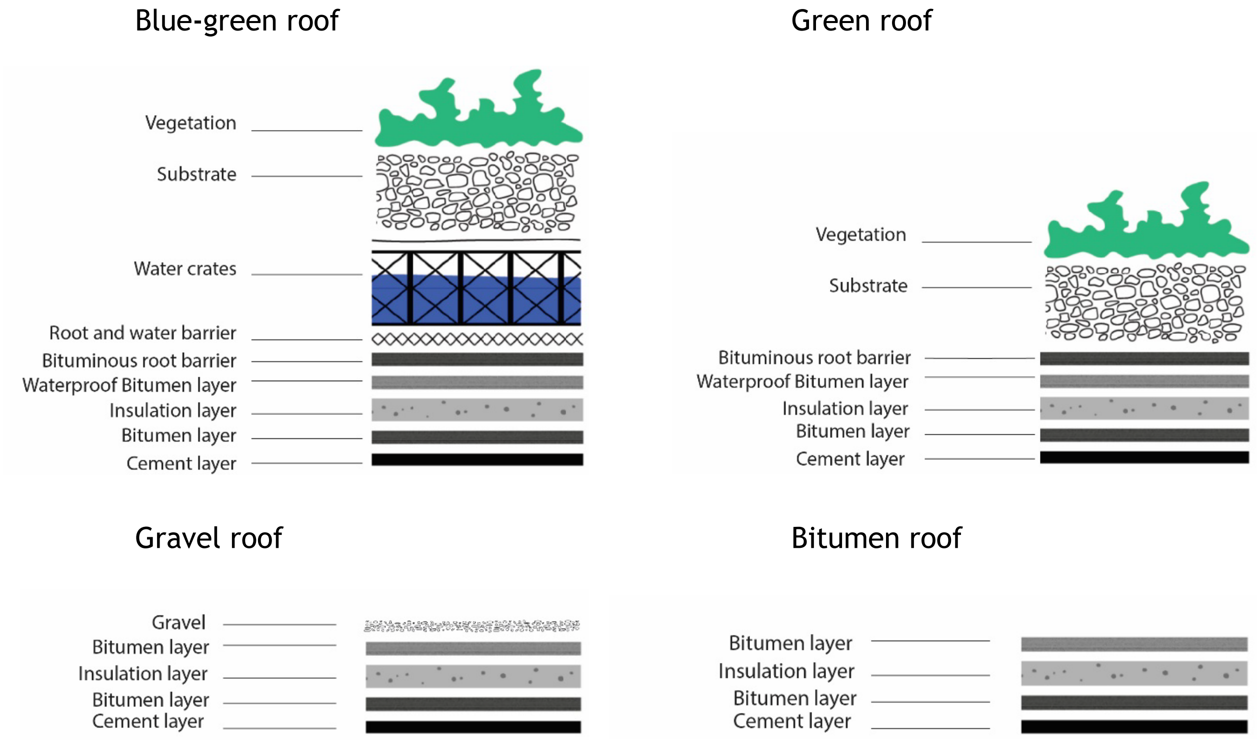

Figure 19 Overview of the roof structures for the different types of roofs. Please note that thickness and materials used for each layer can vary.

4.2.2.4 Water storage

An important design element of the blue-green roofs incorporated in this research is the water crate layer that facilitates a higher potential evaporation rate than conventional green roofs (Busker et al., 2022). In winter, the water crates are empty to avoid freezing and potential damage to the crates and the roofs self.

The summer of 2021 was a relatively wet summer with 268 mm of rain from 1 June to 31 Augustus measured at Schiphol, where a normal Dutch summer has 224 mm of rain (KNMI, 2021). During each chosen warm period there was little to no amount of rain, however, prior to each chosen warm period it has been raining with the exception of the last one (6 -10 September 2021), see Figure 20. Due to the combination of relatively wet summer and rainfall prior to the measurement periods it is expected that the plants on all locations were well watered and that the water availability for plants is similar at green roofs as at blue-green roofs.

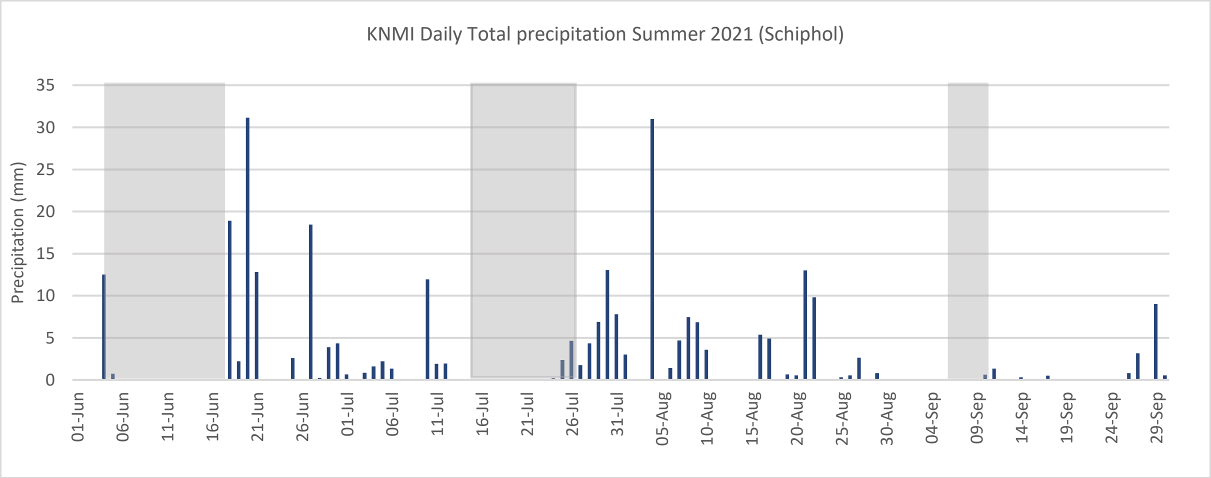

Figure 20 Time series of Daily KNMI Precipitation data. Grey boxes show the chosen warm periods.

4.2.2.5 Presence of plants

The green roofs and blue-green roofs have extensive vegetation of sedum and grasses. The full list of plant species can be found in Appendix B. Since the substrate of the blue-green roofs is maximum 6 cm thick, a mix of plants was used that is biodiverse and can withstand dry conditions. Due to construction works and spring or autumn planting, some blue-green roofs did not have (fully grown) plants yet during the measurement period: at the research locations Oosterparkbuurt_BG_1 and BG_2 vegetation layers were not yet planted. The research sites OostelijkeEilanden_BG_1, Oosterparkbuurt_G_1, Indischebuurt_G_1 had fully grown vegetation layers. At Indischebuurt_BG_1, full grown plants were present in the radius of 100 cm from the surface measurement location. On the rest of the roof, the plants were planted but not fully grown yet.

This high variation in maturity and presence of plants provided an opportunity to study the difference between the substrate temperatures of roofs with and without plants. However, the lack of established vegetation at the blue-green locations is expected to have an influence on the total evaporation rate of these roofs. For this reason, together with the uncertainty in the measurements of the water levels (section 4.2.2.4), the evaporation rates are not examined in this report. We acknowledge that the effect is present, and will briefly discuss this under section 4.3.2.3.

4.2.2.6 Indoor environment

As mentioned in section 4.2.2.2, indoor air temperature as well as the ceiling temperature was measured at each location. When measuring indoor environment, factors that influence the measured temperature should be considered. For example the presence of hatches and windows or the use of heating. These factors have been limited as much as possible by, for example, placing the iButtons out of direct sunlight and in hallways instead of in people's homes to limit the influence of heating habits of the tenants. Some of the measurement locations had windows in the hallway, such as skylights, while others did not. In Appendix C there is a list of photos of the measurement locations indoors.

4.2.3 Analysis of measured temperatures

To detect the possible effects of the blue-green roofs, measured data from all monitored roofs have been analyzed in various ways. First, time series plots have been made of all the measured temperatures on the roofs. The measurements were then analyzed based on hourly averages. Indoor temperatures were further studied based on the amplitude in diurnal variation (daily maximum minus daily minimum). The results of these analyses have been compared to each other to see the differences in performance of the roofs. To ensure a better readability of the report, detailed description of each method can be found in chapter 4.3 together with the results of the analysis.

4.2.3.1 Insulation computation

In addition to looking at the indoor and outdoor temperature differences between blue-green roofs and reference roofs, insulation properties of the investigated roofs have been investigated. A common way to assess the insulation is by looking at how much energy, in the form of heat, escapes the building during a winter night. The insulation value is expressed in so called U-values (W/m^2 K) which show the potential of the construction to transmit heat from a warm space to a cold space; in our case, from inside the building through the roof to the outside.

We computed the U-values for winter months based on the temperature-based method (TBM) that uses indoor and outdoor temperatures time series (Kim et al, 2018):

$$U = \frac{1}{R_s}\left[\frac{\sum_{i=1}^{n}(Ta_{in_i} - Ts_i)}{\sum_{i=1}^{n}(Ta_{in_i} - Ta_{out_i})}\right]$$

where, R_s is the inner ceiling surface total vertical heat transfer resistance and is set to 0.10 m^{2}K/W, as suggested in (ISO, 2017). Ta_{in}represents the indoor air temperature, Ts the indoor ceiling temperature, and Ta_{out} the outdoor air temperature. The subscript *i* represents each member of the data set.

U-values have only been estimated during winter night hours (00:00 – 06:00): during night hours to minimize the impact of irradiation by the sun (ISO, 2018), and only during winter because in summertime the radiation from the surroundings and the roof itself make it hard to estimate the heat flux and therefor the U-value. The threshold difference between the indoor and outdoor air temperature was set to >8.0°C. This threshold is lower than normal Dutch standards (15.0 °C, ISO, 2018), however, sufficiently above the bare minimum (5,0°C (Kramer-Segers, 2021).

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4.3 Results

Based on the analyses of the data set, some general observations can be drawn regarding the temperature differences between the blue-green roof, green roof and reference roofs:

1) The substrate temperature under the vegetation for (blue-)green roofs was on average 10°C cooler in summer compared to bitumen roofs and 5°C degrees colder than the temperature of the gravel roofs.
2) The temperature inside the water crate layer was during both warm and cold periods more stable than the temperature of the measured surfaces.
3) Average indoor temperatures showed that rooms under blue-green roofs were colder during summer and warmer in winter compared to reference roofs. Moreover, the measurement results show that inside temperatures under blue-green roofs are less sensitive to outside air temperature changes than temperatures under reference roofs.

In the following paragraphs, these found effects of the blue-green roofs are described and further evaluated. First, time series plots are presented that give a general overview of the behavior of the different parameters (section 4.3.1.). Secondly, the clear variety in the thermal behavior of the layers of the different types of roofs are shown and analyzed based on hourly averages in section 4.3.2. Thirdly, in section 4.3.3, the effect on the indoor environment under blue-green roofs is presented for both summer and winter, and the potential contribution of the blue-green layer to insulation properties of the roof is quantified.

4.3.1 General overview of measured time series plots

In this section we present the measured data without any additional analysis. The time series plots are exemplary of the thermal behavior of each measured layer of the roofs during both winter and summer, using the cold period in February 2021 and one of the warm periods in the summer of 2021. The general patterns are described and put into perspective of the meteorological situation.

4.3.1.1 Cold period

During the cold period in the winter of 2021, only one blue-green roof had been entirely finished, namely Oosterparkbuurt_BG_1 (see Figure 21). This location is used as an example to show the thermal behavior differences between a blue-green and reference roof.

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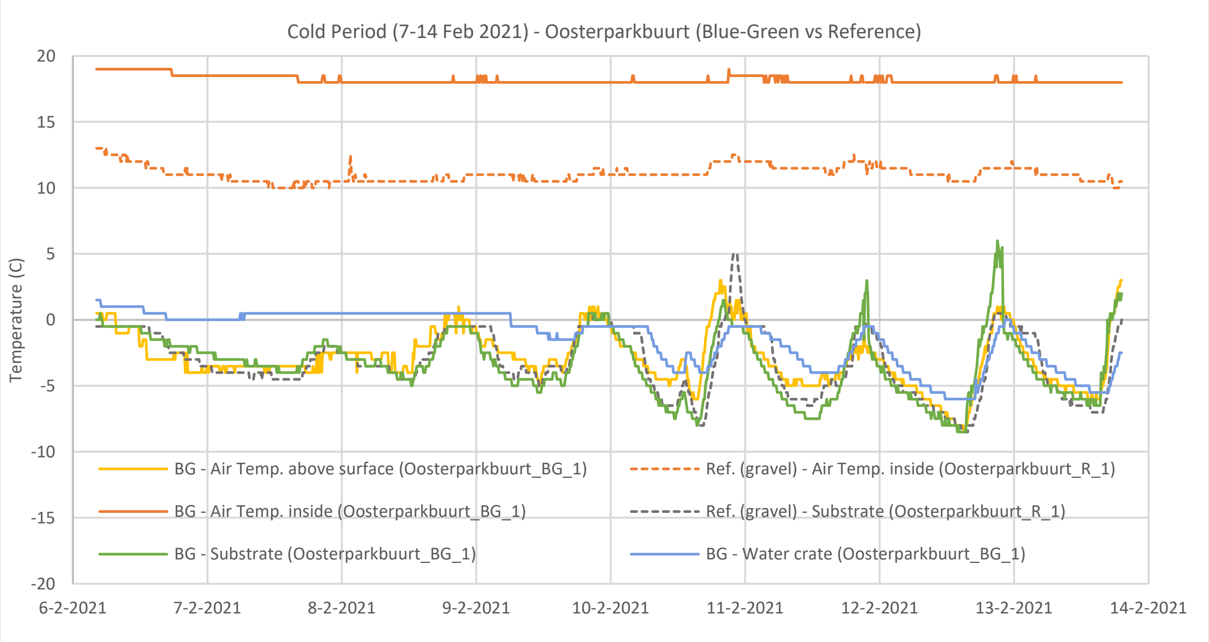

Figure 21 Time series of measured temperatures during the cold period in Oosterparkbuurt.

The substrate temperature varied from -8,5 °C to 5 °C for the blue-green roof and from -8,5 °C to 6 °C for the reference gravel roof. These temperatures are both similar to the air temperatures measured above the blue-green roof (Figure 21). When comparing the daily substrate temperatures of the two different roofs, no substantial differences were found as the differences were in the range of the measuring uncertainty. Figure 16 shows that at the beginning of the cold period, when there were cloudy conditions, the outside air, surface and substrate temperatures were more similar. The weather became more sunny and less windy in the second half of the measurement period. This caused peaks in the substrate temperature for both the blue-green roof substrate and the gravel at the reference roof.

Another measured variable was the temperature of the water crate layer. During this cold period, the sensor is in fact measuring an air temperature inside the water crates since the storage is empty to prevent frost damage. The results show that the temperatures measured in the water crates are most of the time higher than the temperatures of the blue-green roof substrate with the exception of the afternoon peaks in the substrate temperatures. The relatively stable temperature in the water crate layer suggests that empty crates on the blue-green roof function as an additional insulative buffer when it comes to heat transfer between inside and outside of the building. The indoor temperature under the blue-green roof show less fluctuations and higher absolute temperatures compared to the time-series of the indoor temperature under the reference roof.

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4.3.1.2 Warm period

The first week of the second warm period (15 – 27 July 2021) was chosen to demonstrate the general behavior of blue-green roofs compared to reference roofs (both gravel and bitumen) in summer. This specific period was chosen because of its very sunny conditions with low wind speeds (see Figure 16). During this period, there were two locations with blue-green roofs, at the Oosterparkbuurt and Indische Buurt. Measurements at Oosterparkbuurt are shown here to demonstrate the thermal behavior during a summer situation.

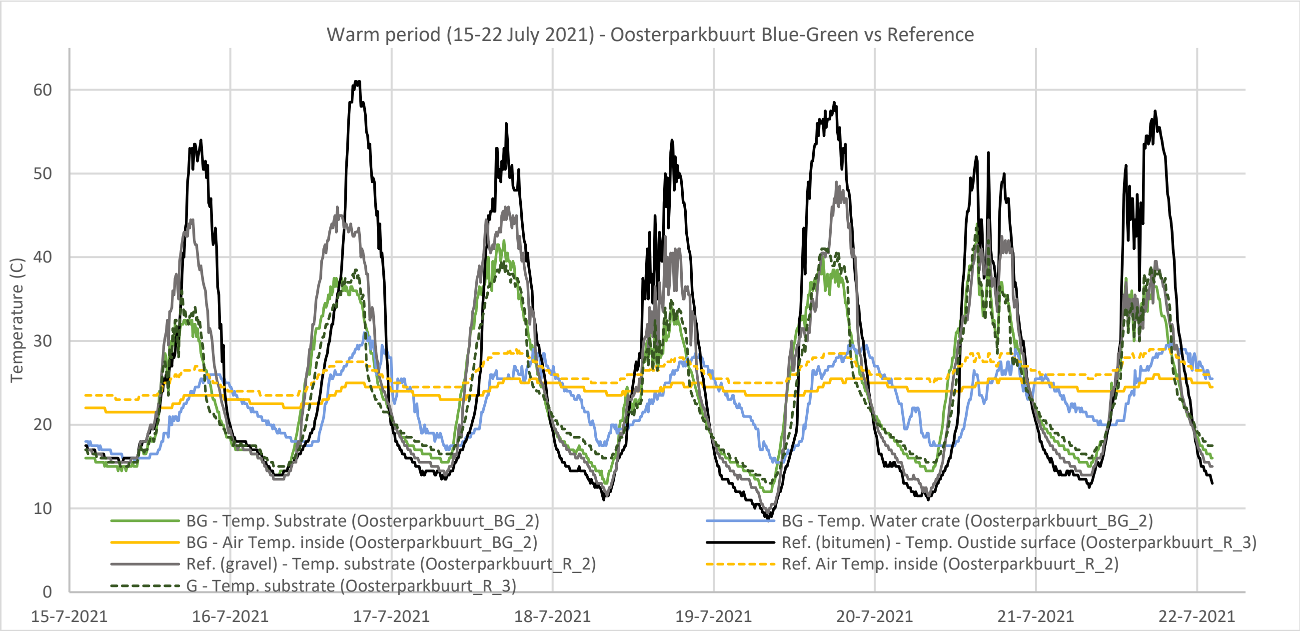

Figure 22 Time series of measured temperatures during the warm period in Oosterparkbuurt.

The difference between the temperatures measured at the blue-green roof and the reference roofs were more pronounced during summer than it was for winter. On warm sunny days, the measured surface temperature of the bitumen reference roof varied from 8.5 ˚C to 61 ˚C and of the gravel roof from 8.5 ˚C to 58 ˚C, whereas the temperature of the substrate of the blue-green roof showed much lower variation, from 12 ˚C to 44 ˚C (Figure 22). Additionally, the figure shows that substrate temperatures of blue-green roofs and green roofs is similar. The presence of no plants at the blue-green roof seems to have a limited influence on the temperature measurements.

Based on temperature measurements under the two different roofs, the indoor temperatures show a lower maximum temperature under the blue-green roof (26 ˚C) than under the reference roof with gravel (29 ˚C). Furthermore, it can be directly seen that the indoor temperature under the blue-green roofs (solid yellow line) has a lower fluctuation than the indoor temperature under the conventional roof (dashed yellow line). Also the timing of the air temperature peaks under a blue-green roof is slightly delayed compared to the peaks above the roof. Both of these findings could be the effect of the blue-green roof on higher insulation properties of blue-green roofs compared to conventional roofs.

Although these time series plots do provide useful insights, more (statistical) analyses needs to be done because of factors that can have an influence on the measured temperatures, especially for the measured indoor temperature. For that purpose hourly averages and the standard deviation have been calculated. The results are shown and explained in the following subsections.

4.3.2 Analysis of temperatures measured on the roof

To further analyze the general patterns seen in the time series plots, the outside measured temperatures have been averaged for each hour of the day for the chosen periods. Within the datasets, there were small variations between each 10-minute interval and also day-to-day differences as a result of varying meteorological conditions. Averaging the data per hour limits the influence of potential outliers on the final pattern. Considering the temperatures are measured every 10 minutes, there are 6 measurement values in each hour and for a 7-day measurement period, each point in the figure is an average of 42 values (6*7). For the cold period, around 1200 measurements and for the multiple warm periods together around 4350 measurements have been included.

4.3.2.1 Cold period

Figure 23 shows the hourly averages for the cold period for the substrate layer of a blue-green roof compared with a reference gravel roof. During the cold period, the blue-green substrate temperatures only show minor differences with the substrate of the gravel roofs and also the maximum temperatures are not significantly different. The blue-green roof substrate warms up slightly quicker and reaches its maximum temperature at around 12:00-13:00, whereas the substrate temperature of the reference roofs reaches its maximum at around 14:00-15:00.

When looking at the temperatures of the water crates (empty during winter) and the gravel of the reference roof, the differences are more evident. The daily temperatures fluctuate much less inside the water crates than the air and substrate temperatures, for both the water crate layer at the Oosterparkbuurt and Oostelijke Eilanden location. The night and morning temperatures in the water crates are 2-5 °C higher than the air temperatures and up to 3-6 °C higher than the substrate and gravel temperatures.

The averaged data show that all measured surface temperatures followed the general pattern of the air temperature, indicating that during a cold period the surface temperature of a roof is mostly determined by the outdoor temperature. This was not the case for the air temperature measured inside the water crate layer. The relatively stable temperatures suggest a buffering effect of the water crate layer potentially resulting in higher insulation value of the roof. The insulation efficiency is further studied in section 4.3.3.2.

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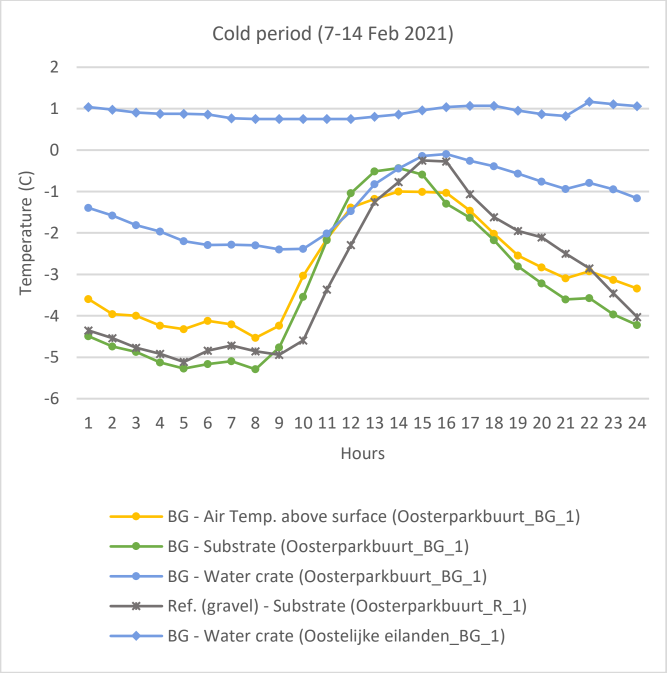

Figure 23 Graphs of the hourly temperature averages (over several days) during the cold period. The graph compares two roofs in Oosterparkbuurt. The water crate layer of the Oostelijke Eilanden has been included as it is the layer with the least influence of external factors as well to confirm the pattern of the water crate layer.

4.3.2.2 Warm periods

Figure 24 shows the hourly averages for all investigated warm periods for the substrate layers of all blue-green roofs compared with reference roofs. Results that are most noticeable are:

1) Maximum daytime surface temperatures for blue-green roofs are on average ~5.0˚C lower than for gravel roofs and even 10-18.0˚C for bitumen roofs.
2) The measured temperatures in the water crate layers show the lowest absolute maximum temperature from all the measured layers and the lowest diurnal fluctuation over the 24-hour period;
3) There is no substantial difference measured in substrate temperatures between green and blue-green roofs.

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These three results together show that temperatures above and on the roofs are lower for (blue-)green roofs compared to gravel and bitumen roofs. In the water crate layer temperatures are even lower, implying a cooling effect of blue-green roofs compared to all reference roofs. To investigate this in more detail each research site is discussed individually in the following paragraphs, followed by comparisons of these sites and a comparison of blue-green and green roofs.

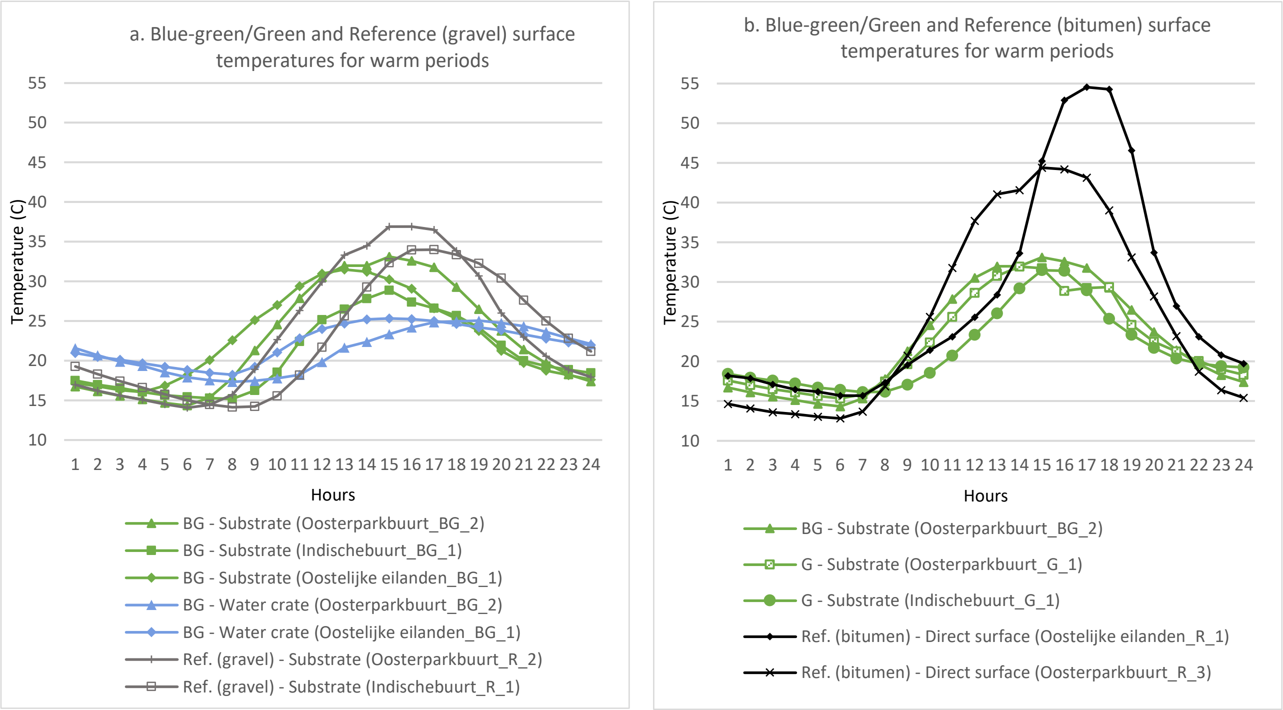

Figure 24 Graphs of the hourly averages of measured temperatures during the warm periods for all research locations.

Oosterparkbuurt locations

Presented data for the roofs located at Oosterparkbuurt are hourly averages of surface temperatures using measurements from all three chosen warm periods in 2021 and all types of measured roofs (see Figure 25). In general, there is a strong difference between the temperatures for the different types of surfaces during daytime, while at night the differences are less pronounced.

Black bitumen was the warmest surface measured during the day with maximum temperatures reaching 45 °C and lowest at night-time with temperatures of 13 °C. Gravel roofs reached second highest temperatures from all measured surfaces, 37 °C on average. The substrate measurements of (blue-)green roofs were similar and reached temperatures ~5°C and ~10 °C lower compared to the gravel and bitumen roofs, respectively. Nighttime surface temperatures of gravel roofs and (blue-)green roofs were similar and dropped down to around 14 ˚C; making these surfaces cooler during the day and warmer at night than black bitumen.

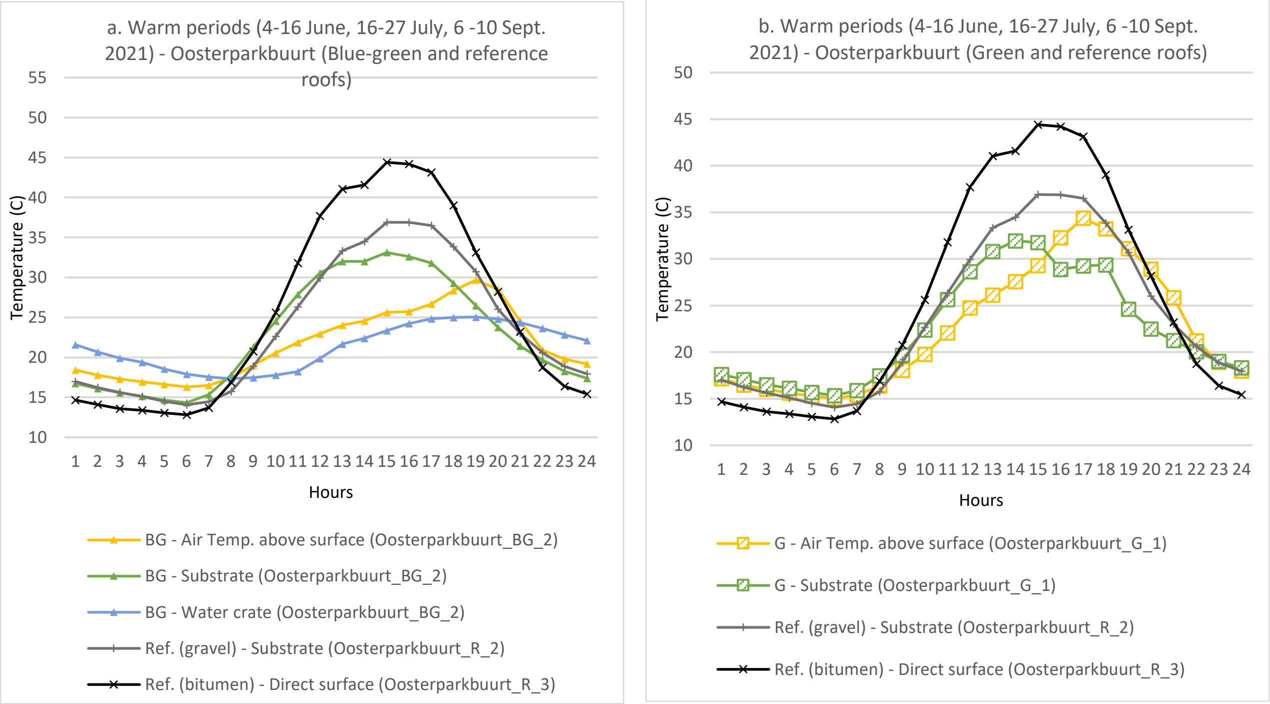

Figure 25 Graphs of the hourly averages of measured temperatures during the warm periods for the research locations within Oosterparkbuurt.

The temperature measured in the water crate layer was the most stable of all measured surface temperatures. The diurnal fluctuation was in fact only 8˚C, with daily maximum at ~25˚C and nighttime minimum at ~18˚C. This shows a similar buffering effect as was measured during winter months. In summer, the water crate layer can be both empty – if all water is discharged or used by the plants – or containing water. For cases when the water storage is full, this buffering capacity can be assigned to high heat capacity of water of water.

The air temperatures at 50 cm above the roof were also measured at all locations (see Figure 25). It is necessary to point out that from all measured temperatures, air temperatures can be easiest influenced by external factors such as solar radiation, wind, or various surfaces. Nonetheless, above the green roof, the temperature appeared 5 ˚C higher than above the blue-green roof. This is surprising as the substrate temperatures were almost equal. Possibly other surfaces (maintenance unit walls, chimneys, etc.) or local micrometeorological conditions had stronger influence on the measured air temperatures than the roof surface. For this reason, outdoor air temperature measurements will not compared to each other any further.

Indische Buurt and Oostelijke Eilanden locations

The temperature measurements in Indische Buurt and Oosterlijke Eilanden only represent one hot period (6-10 September 2021) due to a later than anticipated installation date. The measured substrate layers at the Indische Buurt (Figure 26a) and Oostelijke Eilanden (Figure 26b) locations show similar patterns to what has been already demonstrated in the data from Oosterparkbuurt. However, we see differences in the absolute temperatures between the three locations. For Indische buurt there is ~5.0°C difference between daily maximum substrate temperatures for gravel and blue-green roofs, similar to the Oosterpark location. However, the maximum substrate temperatures in Oostelijke Eilanden were almost 10.0 °C lower for blue-green roofs than for gravel roofs and even several degrees lower than the measured air temperature.

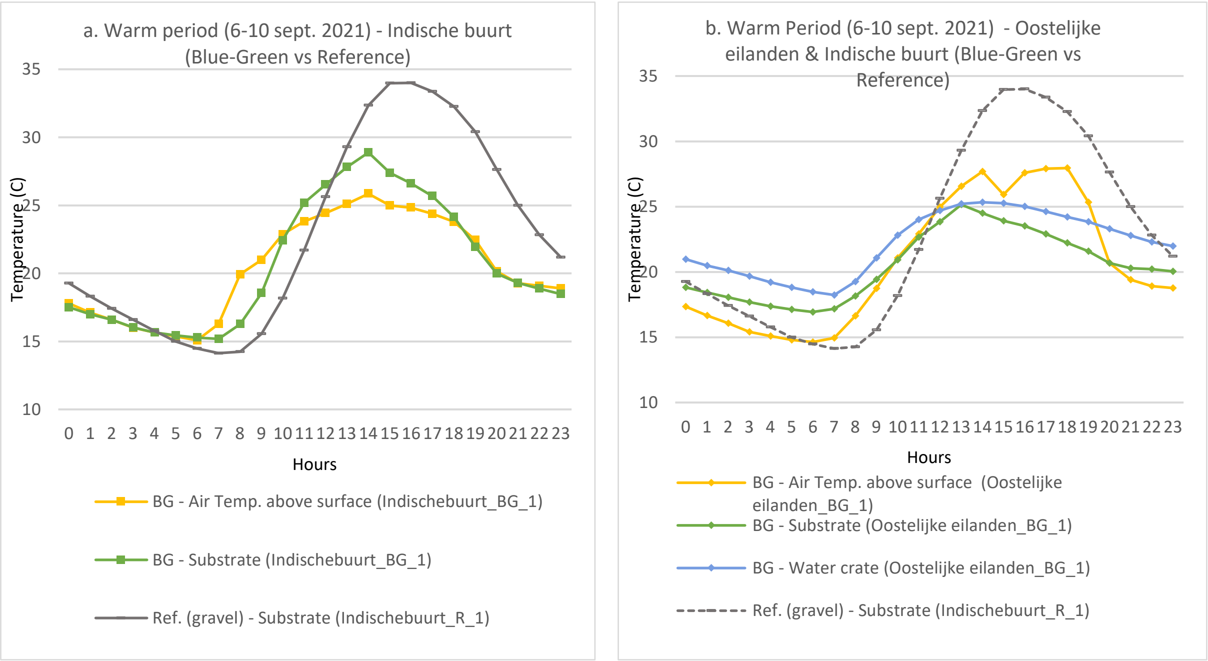

Figure 1 Graph of the hourly averages of measured temperatures during the warm period for the research locations in Indische Buurt (left) and locations in Indische Buurt compared with Oostelijke Eilanden (right).

Comparison of various locations

There are several general patterns seen across all the locations, e.g. the similar amplitudes of measured surface temperatures or the buffering effect of the water. Nonetheless, the various roofs start warming up at different times and therefore peak at different times. It is unclear if this difference is location driven (e.g. higher buildings in the surrounding and therefore later exposure to sunlight) or if it is an artifact of the roof type.

It appears that gravel roofs reach their maximum temperature later during the day; at 15:00-16:00 compared to 14:00 for blue-green roofs. For one of the bitumen roofs (Oostelijke eilanden) this is even later around 16:00 (see Figure 24b). This could be partially explained by higher thermal mass of gravel and bitumen roofs compared to (blue-) green. Since the water crate layer is less influenced by external factors, the delay in the temperature peak is easier to clarify. The maximum temperature within the water crates was reached at 19:00, 3-4 hours later compared to the other surfaces. This is caused by a combination of two factors: 1) the water crate layer is located bellow the substrate layer and is not exposed to direct solar radiation. The water will heat up as long as the surroundings are warmer. 2) water has high thermal mass which causes it to warm up slower than other used surfaces.

Comparison substrate temperatures of blue-green and green roofs

The substrate temperatures of blue-green roofs and green roofs do not differ significantly. Figure 24b shows the comparison of blue-green and green roof substrate temperature measured at the Oosterparkbuurt location together with an additional green roof in Indische Buurt. All three measured temperatures follow a similar pattern with daily maximum around 32 °C and nighttime minimum of 15 – 16 °C. This similarity is contradicting the quite varying circumstances at each roof. Since it has been raining prior to each chosen warm periods, the availability of water on (blue)-green roofs was comparable. We expect that in dry and warmer circumstances, a blue-green roof should imply higher soil evaporation rate compared to the green roofs. On the other hand, the plants at the green roofs were fully grown and established, while the vegetation at the blue-green roof at Oosterparkbuurt was not yet planted. It is possible that the two effects of lacking fully grown vegetation and a relatively wet summer negated each other and resulted in very small differences between blue-green and green roofs.

4.3.2.3 Conclusions and discussion of measured surface temperatures

Differences between surface and substrate temperatures

The effect of blue-green roofs on the substrate temperature is different for cold and warm periods. The average substrate temperature of blue-green roofs in winter are similar to the surface temperature of gravel. The differences between surface temperature of the gravel roof and the substrate temperature of blue-green roof is thus negligible. During warm periods, the results show that the average substrate temperature of blue-green roofs is lower and that the peak is reached much earlier on the day than for the surface temperatures for gravel and bitumen roofs. We see almost identical patterns of all parameters on all the roofs within the three neighborhoods (Oosterparkbuurt, Indische Buurt and Oostelijke Eilanden) in summer.

Differences found in the surface temperatures of (blue-)green roofs and reference roofs in summer show a cooling effect of (blue-)green roofs as it has been shown that the surface temperatures are consistently lower for (blue-)green roofs than for gravel and bitumen roofs. The observed trend can be partly explained by the physical properties of the various roof surfaces, for example its albedo, but also by a potential contribution of evapotranspiration to the cooling. As measuring these processes were out of the scope of this research, we base the assumptions about these effects only on the measured temperatures and literature review, see the following paragraphs.

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Lazzarin et al (2005) showed that evapotranspiration is responsible for 12% solar absorption when the substrate is dry and 25% when wet. This implies the importance of the capillary system from the water crate layer to the substrate as it can provide an ongoing water supply for evapotranspiration and therefore contribute to cooling of the roof. The study also found that evapotranspiration can provide an outgoing thermal energy flux from inside towards outside during summer. During our measurements, the cooling effect was visible for the vegetated and non-vegetated roofs which we assume had a more or less equal soil moisture because of the relatively wet summer, indicating the effect of evaporation. The presence of the water crate layer could as well benefit thermal conditions during winter (Johannessen et al, 2017) as the process of the outgoing energy flux will be limited because the substrate is not in direct contact with the roof construction.

The second variable influencing the surface temperature is the solar reflectivity (albedo) of plants and the substrate self. In general, higher albedo reduces temperature build up (solar absorption) and therefore lowers the maximum peak temperature during the day (Castleton et al, 2010; Lazzarin et al, 2005). Different research has shown that a green roof could have a 2.3 times higher reflectivity in summer than a conventional roof (bitumen or gravel); with the remark that this might be different for white gravels versus bitumen (Gaffin et al, 2005; Bretz et al, 1998). For winter, the effect of albedo seems limited because of lower solar radiation (Barozzi et al, 2016) and poorer plant conditions. The results presented in Figure 23 for the cold period showed that the maximum peak of measured substrate temperatures of blue-green roofs are similar to reference roofs.

Temperature inside the water crate layer

The comparison of blue-green roofs with reference roofs during both cold and warm periods showed a systematic buffering effect of the water crate layer. The temperature inside the water crate layer, both with and without water, stayed the most stable throughout the measurement periods compared to other outside surface measurements. One explanation for this buffering effect in summer is the higher thermal mass of water. Consequently, the roof has a higher total thermal mass and will take longer and more sun radiation to warm up, especially when more mass is added due to water in the crates (Schade et al, 2021; Castleton et al, 2010). However, this buffer capacity can also have negative consequences, as it results in higher temperatures during the night and hinders or delays the cooling down at night. The higher nighttime water temperatures might have negative consequences for indoor thermal comfort. Furthermore, after a heatwave, or a period with persistent heat, the buffering effect makes it harder for the roof to cool down which might lead to an undesired effect of persistent heat (van Hamel, 2021). Unfortunately, we were not able to study such periods, due to a relatively cold summer in 2021.

The buffering effect of the water crate layer is also visible in winter when the storage is empty. In fact, the constant temperatures found in the water crate layer were the only measured outdoor temperatures that did not follow the air temperature pattern. This suggest that even without the additional thermal mass of water, the empty crate layer provides some level of temperature buffering. Possibly the temperature buffer in the water crates is the predominate factor that distinguishes the thermal behavior of blue-green roofs from other types of roofs.

4.3.3 Analysis of indoor temperatures

In order to analyze the effect on the indoor environment under blue-green roofs, a standard deviation calculation has been performed. Additionally, the insulation values have been computed in order to investigate the potential contribution of the blue-green layer to insulation properties of the roof.

4.3.3.1 Indoor temperature variation

The time series plots (Figure 21 and 22) showed a large absolute difference for inside temperatures between reference and blue-green roofs at different locations. The average daily temperatures and their differences are presented in Table 6. For summer, the differences between blue-green and reference roofs remain small (less than two degrees). In winter, the difference of the daily averages reaches 4.9 °C for ‘Oosterparkbuurt_BG_1 vs R_1’. Before the installment of the blue-green roof at the Oosterpark location, these two locations (Oosterparkbuurt_BG_1 and Oosterparkbuurt_R_1), were on the same building block, consisted both of gravel and had the exact same roof characteristics (see the table in Appendix E for insulation properties and Appendix D for the scatterplot) which would suggest similar indoor temperatures. The differences in the indoor temperatures between these two locations indicate the potential effect of other factors, such as indoor settings, on the final results. The difference in degrees should therefore only be considered as indicative.

Consequently, the measured differences in absolute temperatures cannot be directly attributed to the effect of blue-green roofs. In light of these results, we have decided to step away from the absolute temperature differences and focus on temperature variation per day (i.e. daily temperature fluctuations), explained by the standard deviation (STD - in degrees per day). As such, we were not dependent anymore on absolute temperature differences.

The scatterplot (Figure 27) shows the daily standard deviations of the measured indoor air temperature for the reference roofs (x-axis) versus standard deviations for the blue-green roofs (y-axis) for multiple cold and warm period(s). Lower STD values represent less variation during a 24-hour period and lower variation in indoor temperature implies a smaller influence of outside climatological conditions (e.g., air temperature). In other words, all scatter points that are underneath the red reference line show days when the indoor temperature STDs were higher for reference roofs and lower for blue-green. This is the case for majority of the points, which shows that the buffer capacities of the blue-green layer, already indicated in previous chapters, also benefit the indoor environment.

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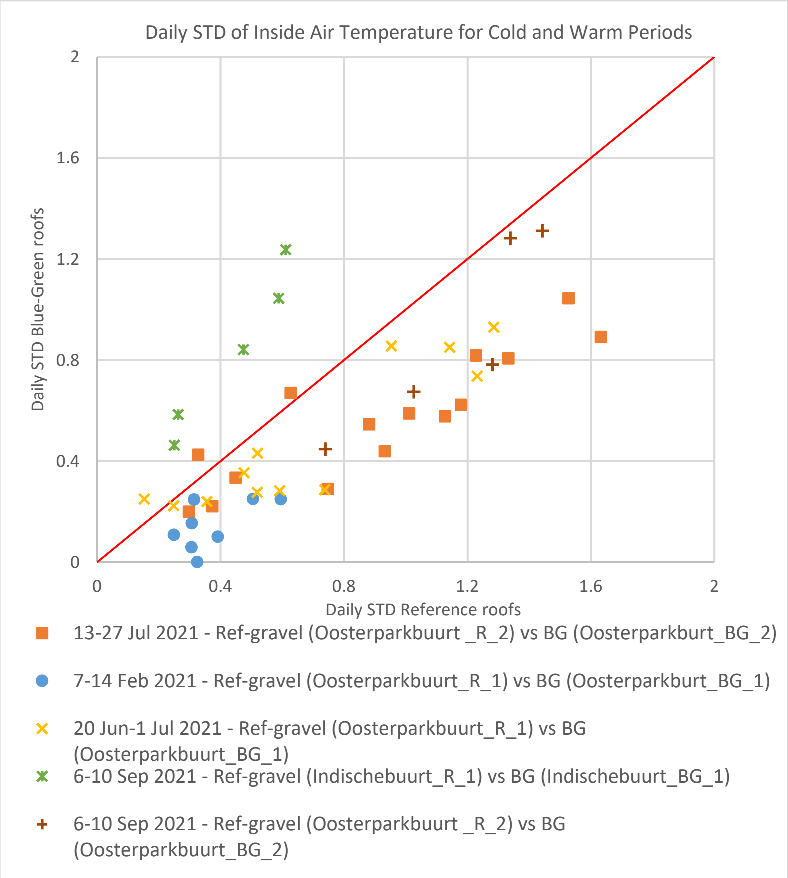

Figure 27 Scatterplot of the daily Standard Deviation of the inside air temperature during cold and warm periods

The lower air temperature variation under blue-green roofs can also be seen in average STD values for the warm periods and the cold period separately in Table 6. For warm periods we see an average reduction of 0.19 °C STD and for the cold period we see a reduction of 0.23°C STD. This means that the daily temperature change (or fluctuation) underneath the blue-green roof is 0.19-0.23°C STD less than underneath to the reference roofs. This effect seems rather small but represents a relatively large proportion of the total daily temperature variation of 24% and 64% for the warm and cold periods, respectively.

When including all possible measured data of inside air temperatures the average STD of the whole dataset per location shows a similar pattern as STDs for the cold and warm periods (Table 7, row 4-7). Next to the reduction in °C STD, the averages of daily inside temperature are shown, with higher values for the winter period (warming effect) and lower values for the summer period (cooling effect). The results show a reduction in STD for the blue-green roofs at the Oosterpark location of a magnitude comparable to the chosen cold and warm periods. This indicates a systematic temperature buffering under the blue-green roofs.

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	Measurement Period	Average STD (blue-) green roof (˚C)	Average STD reference roof (˚C)	STD reduction (˚C)	Average Daily Inside Temp. (ºC) (blue-) green roof	Average Daily Inside Temp. (ºC) reference roof	Average Daily Inside Temp. difference (ºC)
Warm Periods		0.62	0.81	-0.19			
Cold period		0.13	0.36	-0.23			
Whole datasets							
Oosterparkbuurt_BG_1 vs R_1 - blue-green roof installed	03/02/2021 - 06/04/2021	0.15	0.48	-0.33	19.6	14.7	4.9*
Oosterparkbuurt_BG_2 vs R_2	06/07/2021 - 21/10/2021	0.44	0.79	-0.35	21.5	23.0	-1.5
Indischebuurt_BG_1 vs R_1	27/07/2021 - 30/09/2021	0.62	0.26	0.36	23.8	22.8	1.0
Indischebuurt_G_1 vs R_1	12/08/2021 - 30/09/2021	0.29	0.25	0.04	22.2	22.8	-0.6

*Table 7 Average STDs for warm periods and one cold period (above two lines); and STDs for the whole period measured on the specific sites. *This temperature computation represents a winter period, so a positive temperature difference highlights the benefit of the blue-green roof.*

Measurements of the blue-green roof at the Indische Buurt did not show the same STD reduction. The indoor temperature underneath the (blue-)green layer at Indischebuurt_BG_1 varied more than under the reference roof. This lower 'STD reduction' can be assigned to two factors 1): There is an already low STD at Indischebuurt_R_1, which is the lowest of all reference roofs. This suggests that underneath the Indischebuurt_R_1 the roof experienced only small influence of outside air temperatures. The specific reason for this low influence is unknow due to the lack of detailed information about the insulation properties of this specific roof (see Appendix E). 2): The relatively high STD at Indischebuurt_BG_1 can be caused by a slightly different placement of the iButtons inside. Normally, the placement in the stairwell for all inside measurements is far away from influencing factors, but the sensors at Indischebuurt_BG_1 were more closely placed to the skylight. This skylight could have functioned as a greenhouse increasing temperatures during high sun radiation, which resulted in higher daily temperature fluctuations (and thus higher STDs).

Overall, the results indicate that blue-green roofs seem to positively influence the indoor climate during both summer and winter months. This is in line with earlier observed temperature fluctuations as shown in the time series plots (Figure 21 and 22). Nonetheless, due to the potential effects of external factors visible in both absolute temperature differences and STD calculations, the results should be taken as indicative. The exact influence on indoor air temperature variation needs to be studied further and under more controlled conditions.

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4.3.3.2 U-values

To examine the insulation properties of the roofs, U-values have been calculated from the available winter measurements of 2021. The resulting U-values are 0.43 W/m^2 K on the Oosterparkbuurt_R_1 gravel roof and 0.21 W/m^2 K on the Oosterparkbuurt_BG_1 blue-green roof, as shown in Table 8. The amount of energy escaping through this gravel roof is thus twice as high as for this blue-green roof, but this total U-value is partially dependent on the installed roof insulation underneath. Different insulation material with varying efficiency rates was used at each location (see Appendix E). This difference needs to be taken into account when calculating the final effect of the blue-green layer on the total insulation value of the roof.

The insulation material installed in the construction of a roof has an insulation value given by the manufacturer. This so-called R-value (m^2*K/W) is reciprocal to the U-values and represents the insulation of the whole roof, including the structure, the insulation layer, and the roofing material (Table 8). R-value calculated for the blue-green roof was higher than the value expected based on insulation material (4.8 vs. 3.5), while the calculated R-value for the reference roof came close to the expected value (2.3 vs. 2.0). This suggest that the blue-green layer on the top of the roof contributes an additional 1 - 1.3 m^2*K/W of insulation. In other words, the blue-green roof construction as a whole leads to an additional higher insulation value. Which part of the blue-green roof specifically contributes to this higher value, namely the water crate layer that behaves as a buffer between the outside and inside temperatures, or because of improved insulation material, needs to be studied further.

Location	**Roof type**	**Insulation properties**	**Measurement period**	**U-value (W/m^2*K)**	**R-value (m^2*K/W)**
Oosterparkbuurt_BG_1	Blue-green	Isomix 160-170mm, R value 3.5	2021 - Winter	0.21	4.8
Oosterparkbuurt_R_1	Reference-gravel	XPS 60 mm, R value 2.0	2021 - Winter	0.43	2.3

Table 8 Average U-values (W/m2K), R-values and Insulation properties of the construction of a reference and blue-green roof in Oosterparkbuurt for the month of February. U-values are based on night hours (00:00 - 06:00). R-values are based only on the insulation material inside the roof structure, this means that not the R-value of the whole roof construction is mentioned.

4.3.3.3 Conclusions and discussion of indoor temperature analysis

The results confirm that blue-green roofs have a small but positive systematic influence on indoor temperatures with higher inside temperatures in winter and lower in summer as compared to reference roofs. The variation in temperature is smaller underneath the blue-green roofs compared to the reference roofs during the warm and cold period(s). Third, calculation based on a roof with the blue-green layer showed higher insulation values than predicted based on the insulation material, which was not the case for a conventional gravel roof.

Analysis of the STDs showed to be more reliable than looking directly at the indoor air temperature differences. Nonetheless, daily STDs for all types of roofs where generally quite low and less than 1.0°C. This can be assigned to the fact that both reference and blue-green roofs have already existing internal insulation layers installed and the influence of outside air temperatures is therefore limited. The benefit of blue-green roofs is therefore expected to be higher on poorly insulated houses as also is given by Castleton et al, 2010).

Moreover, small indoor temperature differences also suggest that the indoor thermal comfort experienced by the human body would be negligible. The exact effect of blue-green roofs on the thermal comfort therefore remains unclear and needs to be studied further and under more controlled conditions to limit external influences.

While the effect on thermal comfort remains doubtful, some conclusions can be drawn about potential consequences of installing a blue-green roof for energy saving costs. Santin et al (2009) estimated that for the Dutch housing stock extra heating of one degree for a whole year represents an increase of ~4% of the total energy consumption for an average dwelling type. The calculated potential R-value increase of 1 – 1.3 m^2*K/W (based on measurements and estimation of one roof), together with a higher air temperature underneath the blue-green roof measured during winter of 2021, can therefore have a relatively large impact on the energy consumption.

Although the effects of blue-green roofs on indoor temperature and the insulation values of the roof are, due to the circumstances, difficult to quantify, we see many indications of a buffering effect both in winter and in summer. In summer, it is likely that the thermal mass of the water crate layer creates a temperature buffering effect. This has also been confirmed by the study of Van Hamel (2021) where the buffering effect of the water crate layer has been found for summer months. For winter, it seems that the empty water crate layer provides additional insulation layer due to the stagnant air layer. In this research, we were only able to measure one blue-green and one reference roof for one winter month. Further research is therefore recommended to confirm the significance and magnitude of the buffering effect of blue-green roofs on indoor environment and to check whether this is indeed caused by the water crate layer.

4.4 Discussion & conclusion

4.4.1 Discussion

The RESILIO project was an unique opportunity to study the effects of blue-green roofs in a northwestern European climate. The results of the field study presented here, allowed us to analyze the effect of a blue-green layer on the roof surface and indoor microclimate. However, the conducted field study also resulted in inevitable uncertainties because of its susceptibility to changes in the surrounding environment, as described in chapter 2. There are important remarks regarding the data collection process, different meteorological conditions and different vegetation maturity stages per roof.

4.4.1.1 Data collection

The data collection was influenced by external factors like construction work on the roofs, bird activity, or lost equipment due to stormy conditions. This resulted in data gaps. Also inside the building there were variables that could not have been fully controlled during the measurement period. Residents opening windows in the stairwell, the insulation of the whole stairwell, or heating systems in the building and adjacent apartments might have had negative effects on the measurements and therefore on the conclusions. For instance, it was not possible to conclude to what extend the inside air temperature differences between blue-green and reference roofs were caused by the roof characteristics and to what extend by these external factors. For that reason, we have used the extensive dataset recorded over long periods with 10 minute intervals to calculate daily STDs. We see this as a more reliable analysis compared to absolute temperature differences because it shows general thermal behavior of different roofs.

Even though using STDs minimized this influence of external factors, one should be careful with interpretation of the results. The insulation material underneath the blue-green layers is different for each roof (Appendix E) and potential irregular indoor heating next to the stairwell still might have caused an increase in STD. The uncertainties are therefore present even while using the STD values and conclusions can only be drawn about more systematic trends in the data set.

4.4.1.2 Meteorological conditions

The original objective of this research was to study the effect of blue-green roofs during summer heat waves. Although KNMI measured twice the number of tropical days (>30 ˚C) in the last thirty years compared to 1961-1990 (KNMI 2021), 2021 did not have any tropical days or heatwaves recorded. Meteorological conditions during the summer measurement period were representative for a relatively cold and wet summer. Therefore, the effect of blue-green roofs during extreme weather events could not be measured.

The lack of official heat waves resulted in the necessity to define suitable measurement periods. The warm periods have been chosen when the average air temperatures measured at the blue-green roof were at least above 20˚C for 5 consecutive days. This value was chosen arbitrarily with the intention to strike a balance between sufficient data availability and days that can still be defined as relatively warm compared to the rest of the summer. Hence, to show the impact of blue-green roofs related to weather extremes it is suggested to gather more data during heatwaves.

4.4.1.3 Vegetation maturity

As presented in the methods chapter, there were differences in vegetation coverage and maturity of the plants on the various (blue-)green roofs. It is expected that there might be an effect on the cooling of the surface and air above the roof caused by evapotranspiration of the vegetation and the substrate. However, the effect of the difference in vegetation maturity is quite small. Comparison of roofs with grown and juvenile vegetation during the measurement periods revealed only small difference in the maximum substrate temperatures for warm periods (~2.5 °C). For winter period this difference was even smaller(~1.5°C).

4.4.2 Conclusions

The main objective of this research was to investigate indoor heat stress reduction by examining the cooling and insulation effect of blue-green roofs on the indoor temperature. To assess the effect of the blue-green roofs, three main questions were defined. Each of the question focused on a specific topic related to the influence of roof construction on the indoor climate.

1. **What is the effect of blue-green roofs compared to conventional roofs on the roof surface temperature?**

   Our results show the strongest effect of blue-green roofs on surface temperature in summer. During the warm periods, the measured surface temperatures were clearly lower on the blue-green roofs than on gravel or bitumen roofs. During winter days, the surface temperatures were not significantly higher on blue-green roofs than on conventional roofs. Measurements further showed that there is no substantial difference in substrate temperatures when comparing these temperatures of a blue-green roof to more conventional sedum covered green roofs. The differences between blue-green and green roofs became obvious when looking under the vegetation and the substrate layer. The temperature in the water storage of blue-green roofs was much colder during hot summer days than all the tested surfaces (gravel, bitumen, substrate with plants). This suggest that the heat load entering the building through the roof is the lowest for blue-green roof compared to all other types of roofs. Similarly, the empty water crate layer showed the highest temperatures during cold winter nights. The vegetation and substrate on (blue-) green roofs play a role in the effect on the surface temperature, however, the effect of the water crate layer seems to contribute most with less daily variation and lower maximum average daily temperatures as compared to reference roofs.

2. **What is the thermal effect of blue-green roofs compared to conventional roofs on the indoor temperature?**

   During warm periods, blue-green roofs showed a small cooling effect (less than two degrees) on the indoor temperature compared to conventional roofs, based on the three locations. The decrease in absolute temperature was not possible to attribute only to the presence of blue-green layer as other external factors might have had a strong influence on the measurements. Besides the difference in measured temperature, the indoor temperatures also showed less fluctuations (daily variation) under the blue-green roofs than other conventional roofs. This suggests that rooms located under a blue-green roof are less sensitive to the outside air temperature values and its natural diurnal variation. The water stored in the crates warms up slower than conventional roof surfaces and therefore provides cooling during warm

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days. The decrease in diurnal fluctuations under a blue-green roof was also measured during a cold period, even though the water crate layer was empty. Hence, also in cold periods, blue-green roofs seem to contribute to more stable inside air temperatures reducing the impact of outside air temperature variations.

3. **What is the effect of blue-green layer on insulation properties of the roofs?**

   Computed insulation of a blue-green roof for the winter period is twice as high as for gravel roofs, even with an empty water crate layer (based on temperature measurements at one location). The calculated R-values (used in construction to indicate the insulation properties of materials) show that the blue-green layer on the top of the roof contributes an additional 1 – 1.3 m^2*K/W of insulation. However, this value is based on measurements from only one blue-green roof and only one cold period and therefore should be taken as a first indication of the potential effect. It is logical that an extra layer contributes to extra insulation, further research is needed to verify the magnitude of the additional effect.

4.4.2.1 Final conclusion and recommendations

In general, we see a clear trend of a buffering temperature effect of blue-green roofs on both surface temperature of the roof and indoor air temperature. This is particularly visible at the water temperature that stays very stable with only small daily changes. The buffering effect causes blue-green roofs experience lower surface temperatures in summer and higher in winter, and also lower diurnal air temperature variations indoors. Our measurements suggest a positive effect on the indoor environment under a blue-green roof compared to traditional types of roofs. However, the magnitude of the effect could not have been calculated due to the specific measurement conditions and potentially significant effects of the surroundings.

Implementing blue-green roofs might reduce high indoor temperatures. The exact effect of the blue-green roof on the air temperature inside the building and consequently the thermal comfort of the residents is unclear. The increased insulation values for blue-green roofs suggest that the additional blue-green layer might potentially influence the heating/cooling costs. The exact benefits of insulation of a blue-green roof on energy consumption and thermal comfort needs to be studied further. Besides the thermal effects, blue-green roof can have other beneficial properties on a building level, especially if accessibility to the roof is provided. Lower roof surface temperatures of blue-green roofs suggest a potential for creating a valuable and comfortable urban green space during hot summer days.

5 Effects on well-being

This chapter is written by the GGD Amsterdam

Due to a lack of respondents under smart blue green roofs it was not possible the answer research questions regarding effects on wellbeing.

5.1 Introduction

Exposure to extreme heat can lead to adverse health outcomes. Heat related illness include headache, concentration loss, fatigue, sleeping problems, breathing problems or even heart failure (RIVM, 2013). In addition to morbidity, heat waves can cause increases in overall mortality. The 2003 summer heat wave in Europe resulted in an estimated 70.000 excess deaths and a number of heatwaves in 2015 in France led to over 3275 excess deaths.

Some people are more vulnerable to heat than others. For elderly, chronically ill and people who are overweight heat is especially a health risk. Children are vulnerable to heat because they are not always able to take measures themselves to prevent overheating. Other risks relate to housing and neighborhood quality, such as presence of urban green spaces (European Environmental Agency, 2021).

Vulnerability to heat extremes is increasing in Europe, due to a growing urban population and an increase in the frequency and intensity of heatwaves (Kownaki, Gao, Kuklane and Wierzbicka, 2019). Heat exposure is greatest in urban areas. Most EU citizens live in cities and cities are vulnerable to the effects of urban heat islands.

People spend most time indoors. Therefore, indoor temperatures are important for heat related illness. Usually, apartments on top floors have higher indoor temperatures, especially when they are located directly under the roof. Due to COVID-19 there has been an increase in the number of people working from home, and it is estimated that at least a part of the workforce will keep working remotely. Productivity decreases in warm surroundings, therefore indoor temperature should not rise too much during summer. There is a call for strengthened links between environmental and health policies, including monitoring of human health impacts of- and adaptation to climate change (European Environmental Agency, 2021).

Rooftop insulation can aid in reducing heat during summer. Since different roof types variate in insulation value, it is expected that indoor temperatures change when a roof is replaced by a different type of roof. For instance, replacing a bitumen roof with a smart blue green roof. The previous chapter focused on heat measurements. In this chapter we aim to study heat experience in summer time of people who live directly below different types of roof.

5.1.1 Research objectives

We aim to study how people experience heat during summer in their home under different types of roof (bitumen vs green roofs) and if there is a difference in heat related illnesses. *Due to a lack of respondents under smart blue green roofs it was not possible the answer research questions regarding effects on wellbeing. We report our methods nonetheless for future reference.*

5.2 Material and methods

5.2.1 Study design and study population

The study was conducted among social housing tenants in Amsterdam. In total 237 addresses were selected from 9 different areas. The selected addresses had their apartment directly under the roof. Apartments with different kind of roof types were selected to make a comparison, including bitumen roofs (controls), sedum roofs, and smart blue green roofs.

At the end of the summer (end of August) of 2020 and 2021 residents were invited to digitally complete a questionnaire via a letter send by post. After two weeks a reminder was sent. The questionnaire was available in Dutch and English. Residents who experienced problems with the questionnaire could call the GGD to complete the questionnaire by phone. To enhance response rate gift cards were raffled among the participants after both measurements.

The questionnaire contained questions about house characteristics, heat experience in the past summer, health complaints due to heat, gender, age and household. The response rate was in 2020 (T0) 25% (n=59). In 2021 (T1) the questionnaire was only sent to people who completed the questionnaire at T0. For out analyses we needed complete data for T0 and T1. At T1 the response rate was 32% (n=19). The questionnaire is shown in Appendix C.

We aimed to make a comparison between three different types of roof. We used a pre- (T0: 2020) and post-measurement (T1: 2021) design. Three types of rooftops were differentiated: 1) bitumen or asphalt rooftops, 2) sedum rooftops and 3) smart blue-green rooftops (SBG).

The smart blue-green roofs were expected to have been implemented at T1 (2021). Sedum and bitumen roofs did not change during the study period. Table 9 shows the three different groups and the number of households that responded in 2020 and 2021 per roof type.

The pre-measurement was done in August 2020 and the post-measurement is done in August/September 2021.

Table 9 Different roof types studied

Types of roof	Summer 2020 Roofs at T0: pre-measurement	Summer 2021 Roofs at T1: post-measurement
Group 1 (Bitumen)	Bitumen (n=38)	Bitumen (n=10)
Group 2 (Sedum)	Sedum (n=14)	Sedum (n=9)
Group 3 (Smart Blue-Green)	Bitumen (n=7)	Smart Blue-Green (n= 0)

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5.2.1.1 Weather during summer of 2020 and 2021

Table 10 shows the average temperatures, number of days with average and maximum temperatures above 25°C and number of heat waves between the 1st of June and the 31st of august in 2020 and 2021. Summer temperatures were on average higher in 2020 compared to 2021. Furthermore, there were more hot days (>25 °C and > 30 °C) in 2020 compared to 2021.

Table 10 Temperatures between June 1st - august 31st at weather station 'Schiphol'

	Summer of 2020	Summer of 2021
Average temperature (°C)	18,3	17,6
Days with an average temperature >25°C	7	0
Days with a maximum temperature >25°C	27	10
Days with a maximum temperature > 30°C	8	0
Number of heat waves	2	0

5.2.1.2 Statistical analysis

Respondents who did not complete the questionnaire at post-measurement (T1) were excluded from analyses. Furthermore, we excluded respondents without a room (bedroom or living room) directly under the roof, resulting in a study population of 17 subjects. However, of these subjects none had a smart blue-green roof that was completed at the end of the summer 2021.

We planned to study whether heat experience and heat related health complaints differed between households living under different type of roofs using two way repeated measures ANOVA models. Due to lack of respondents these analyses were not possible.

Descriptive analyses were done in Jupyter Notebook using python 3 (packages pandas: 1.0.5, pingouin: 0.3.12, jupyter-notebook: 6.0.1)

5.3 Results

Due to a lack of respondents with a smart blue-green roof (that was completed by the end of August 2021) we could not analyse the data and show results.

5.4 Discussion and conclusions

We aimed to make a comparison between three different types of roof, including bitumen, sedum and smart blue-green roofs. Our goal was to study how people experience heat during summer in their home and if there is a difference in heat related illnesses between people living under different types of roof. We hypothesized that residents under smart blue-green roofs would have less heat related illnesses and would experience temperature at home as more pleasant compared to residents living under bitumen or sedum roofs. We designed our

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study under the assumption that all smart blue-green roofs would be completed at the beginning of the summer of 2021. However, in practice this was not feasible. In 2020 we selected a total of 237 addresses, which were directly situated under the roof. Out of these 237 addresses 122 were expected to have a smart blue-green roof at the beginning of the summer of 2021. In practice, due to changes in planning, this turned out to be only 19 addresses by the end of the summer of 2021. The response on our questionnaire was 25% in 2020 and 32% in 2021. However none of the respondents in 2021 turned out to have smart blue-green roof. Therefore it was not possible to do an analysis and answer our research questions. To our knowledge no other studies have studied human heat experience and heat related illnesses under (smart) green roofs. Effects on well-being remain an interesting study objective for future research.

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6 Conclusion

Hydrological performance: We estimated the hydrological performance of blue-green roofs under extreme weather conditions using a modelling study, and observations from four different RESILIO pilot roofs based on three key performance indicators: (1) maximizing buffer capacity during rainfall events to decrease pluvial flood risk; (2) maximizing evapotranspiration and therefore evaporative cooling, to decrease heat stress; (3) minimize the amount of long-term drought events. The results show that smart blue-green roofs can store >90% of total precipitation, and 70-97% of extreme precipitation (>20 mm/h) when using precipitation forecasts. Moreover, evapotranspiration rates on blue-green roofs are around 50-70% of the potential evapotranspiration on hot summer days, which indicates considerable evaporative cooling. These performance values show-case the hydrological performance of blue-green roofs under these extreme conditions and there potential as part of the solution for the impacts of climate extremes.

Indoor heat stress reduction: The indoor heat stress reduction was investigated by examining the cooling and insulation effect of blue-green roofs on the indoor temperature. On four different types of roofs, temperatures were measured at and above the roof surface, together with air and ceiling temperatures inside the building. Results indicate that the differences in temperatures measured above and on the roof surface was limited in winter and more pronounced in summer. the temperature inside the water crate layer was during both warm and cold periods more stable than other measured surfaces, which indicates that the additional water layer only present in blue-green roofs function as a temperature buffer. The effect of the water crate layer was also measured inside the building. All indoor measurements showed small, but systematic influence of blue-green roofs on indoor temperature. The increased insulation values for blue-green roofs suggest that the additional blue-green layer might contribute to this. The exact effect of the blue-green roof on the air temperature inside the building and consequently the thermal comfort of the residents is unclear and needs to be studied further.

Wellbeing: Exposure to extreme heat can lead to adverse health outcomes. Our goal was to study how people experience heat during summer in their home and if there are beneficial health effects associated with living under smart blue green roofs. We hypothesized that residents under smart blue-green roofs would have less heat related illnesses and would experience temperature at home as more pleasant compared to residents living under bitumen or sedum roofs. Unfortunately due to a lack of respondents it was not possible the answer research questions regarding effects on wellbeing.

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8 Appendix A Overview of the RESILIO pilot roofs

Table 11 An overview of the RESILIO pilot roofs, including their address, size, and neighborhood. Note: these roof dimensions are initial estimates and should be interpreted with caution.

Roof	*Location*	*Total roof size (m^2)*	*Roof size suitable for blue-green (m^2)*	*Neighborhood*
Roof 1	Sparrenweg 80-100, Tweede Oosterparkstraat 80-86	410	410	Oost
Roof 2	Derde Oosterparkstraat 39-67, Iepenplein 19-21	997	629	Oost
Roof 3	Tweede Oosterparkstraat 241-258, Kastanjeplein	1442	1003	Oost
Roof 4	Berghoefplantsoen 32-46, Noordzijde 353-423	580	580	Slotermeer-Geuzenveld
Roof 5	Riouwstraat	1151	1082	Indische Buurt en Oostelijk Havengebied
Roof 6	Makasserstraat 230-296, Javastraat 521-597	1286	1276	Indische Buurt en Oostelijk Havengebied
Roof 7	Bijltjespad 2-82, Kattenburgerstraat 10-28	1746	1721	Center
Roof 8	Wittenburgerkade 1-45	750	750	Center
Roof 9	Rhijnspoorplein 1 (Benno Premselahuis)	450	450	Oost
Roof 10	Ite Boeremastraat 1	950	950	Oud-West

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9 Appendix B Plant species list

Achillea millefolium – Yarrow

Allium schoenoprasum – Chives

Anthoxanthum odoratum – Ordinary fragrant grass

Armeria maritima – English grass

Campanula rotundifolia – Harebell

Clinopodium vulgare – Wild Basil

Dianthus armeria – Rugged Carnation

Dianthus carthusianorum – Carthusian carnation

Dianthus deltoides – Stone carnation

Erigeron acer – Erigeron

Erodium cicutarium – Common Storksbill

Festuca ovina – Blue Fescue

Festuca rubra – Red Fescue

Galium verum – Yellow bedstraw

Hieracium pilosella – Mouse-ear hawkeed

Jasione montana – Sheep’s bit

Linaria vulgaris – Common Toadflax

Lotus corniculatus – Birdsfoot Trevoil

Origanum vulgare – Wild Marjoram

Plantago media- Hoary Plantain

Potentilla argentea – Silvery Cinquefoil

Potentilla tabernaemontai – Spring Cinquefoil

Prunella vulgaris – Selfheal

Rumex acetosella – Sheep sorrel

Sedum acre – Biting Stonecrop

Sedum album – White Stonecrop

Sedum rupestre – Reflexed Stonecrop

Silene vulgaris – Bladder Campion

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Thymus pulegioides – Broad-leaved Thyme

Trifolium arvense – Hare’s foot

Arabidopsis Arenosa – Sand Rock-cress

Pilosella Aurantiaca – Orange Hawkweed

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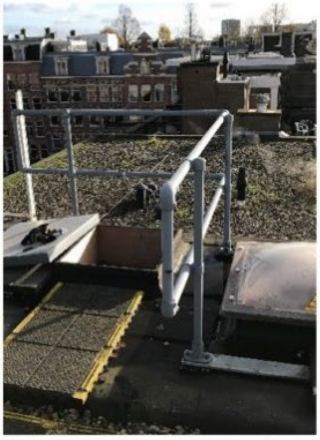
10 Appendix C Photos of the measurement locations

Oosterparkbuurt_BG_1


Roof surface of blue-green roof at Oosterparkbuurt. iButtons have been placed at the northside of the chimneys


Substrate of blue-green roof at Oosterparkbuurt. iButtons have been burried under the substrate


Entrance to the roof. iButtons have been placed on the ceiling of the hallway

Oosterparkbuurt_BG_2


Roof surface of blue-green roof at Oosterparkbuurt. iButtons have been placed at the northside of the chimneys


Example of the water crates installed under the substrate. iButtons have been placed in the crates


Entrance to the roof. iButtons have been placed on the ceiling of the hallway

Oosterparkbuurt_G_1

Roof surface of green roof at Oosterparkbuurt. iButtons have been placed at the northside of the chimney

Substrate of green roof at Oosterparkbuurt. iButtons have been burried under the substrate

Oosterparkbuurt_R_1

Roof surface of reference roof (gravel) at Oosterparkbuurt. iButtons have been placed at the northside of the chimneys

Roof surface with gravel, iButtons have been burried under the gravel

Entrance to the roof. iButtons have been placed on the ceiling of the hallway

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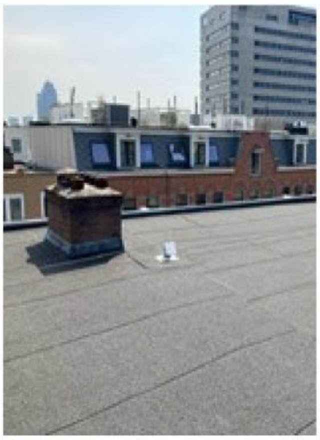
Oosterparkbuurt_R_2

Roof surface of reference roof (gravel) at Oosterparkbuurt. iButtons have been placed at the northside of the chimneys

Roof surface with gravel at Oosterparkbuurt, iButtons have been burried under the gravel

Entrance to the roof. iButtons have been placed on the ceiling of the hallway

Oosterparkbuurt_R_3



Roof surface of reference roof (bitumen) at Oosterparkbuurt. iButtons have been placed at the northside of the chimneys

Roof surface with bitumen. iButtons have been placed in the sun and in the shade on the surface

Entrance to the roof. iButtons have been placed on the ceiling of the hallway

11 Appendix D Scatterplot Oosterparkbuurt

The graph in the appendix show the scatterplots of the daily Standard Deviation for an unique case in Oosterparkbuurt for the whole time series.

In the graph the daily standard deviation of the inside air temperature is shown for the reference (y-axis) and blue-green roof (x-axis) in Oosterparkbuurt. Lower STD values represent less variation during a 24-hour period. Since temperature measurements at the Oosterparkbuurt_BG_1 have been carried out before and after the installment of a blue-green roof the result of the blue-green roof on the inside air temperature is visible. The points have moved more towards the lower left corner, indicating less variation of the inside air temperatures after the installment of a blue-green roof.

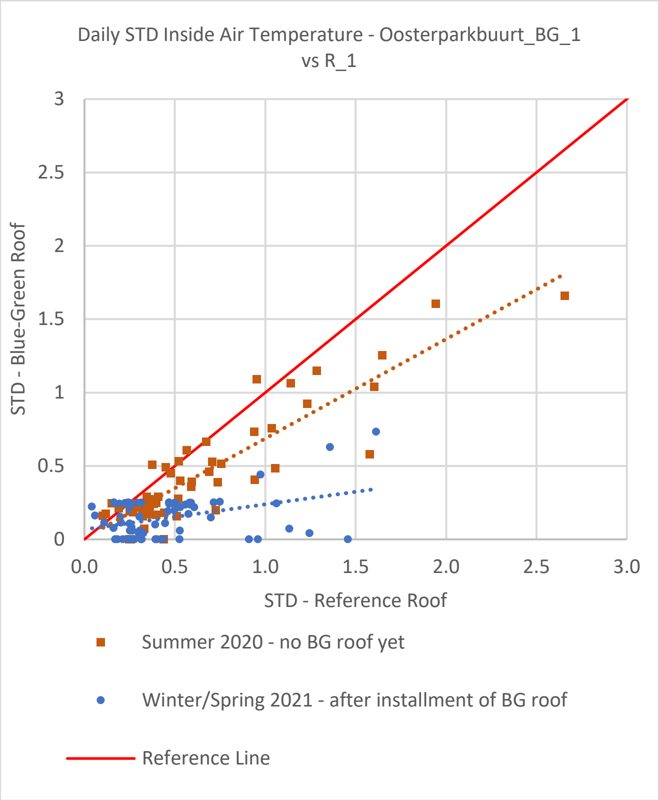


Figure 28 Scatterplot of the daily Standard Deviation of the inside air temperature for the blue-green roof and reference roof at the Oosterparkbuurt

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12 Appendix E Insulation properties of the roof

In table 11, the known insulation properties of the different roof types are listed. The information comes from the housing corporations or an open access database, published by the Municipality of Amsterdam. As can be observed, for some roof types the insulation properties are not known. Second, with the installation of a blue-green roof, the type of insulation also had to be changed due to the addition of a water crate layer, as can be seen at location Oosterparkbuurt_BG_1. The higher R value of the material and thicker insulation layer does already improve the insulation capacities of the roof, apart from the blue-green layer itself.

Location	Roof type	Insulation properties underneath the blue-green layer
Oostelijke eilanden_BG_1	Blue-green	Isomix 120 mm, R value 2.0
Oosterparkbuurt_BG_1	Reference-gravel	XPS 50 mm, R value 2.0
	Blue-green	Isomix 160-170mm, R value 3.5
Oosterparkbuurt_R_1	Reference-gravel	XPS 60 mm, R value 2.0
Oosterparkbuurt_BG_2	Blue-green	Isomix 160-170mm, R value 3.5
Oosterparkbuurt_G_1	Green	PIR dik 141 mm R van 6.0
Oosterparkbuurt_R_2	Reference-gravel	Roofmate, 50mm R value 1.5
Oosterparkbuurt_R_3	Reference-bitumen	Not known
Indischebuurt_BG_1	Blue-green	Isomix Plus,155mm, R value 3.0
Indischebuurt_G_1	Green	Not known
Indischebuurt_R_1	Reference-gravel	Not known

Table 12 Insulation properties of the different types of roof. R-values were based only on the insulation material inside the roof structure, this means that not the R-value of the whole roof construction is mentioned.

13 Appendix F Questionnaire health effects

Vragenlijst GGD: Warmte in de woning (2021)

The public health service (GGD Amsterdam) conducts research into the perception of heat in homes. We kindly ask you to answer a few questions on how you experienced heat in your home in the past summer.

The questionnaire takes about 5-10 minutes.

We thank you for your cooperation.

There are 27 questions in this survey.

Housing

Questions related to your house

1

Do you have a room in your home that is located directly under the roof? *

Please choose **only one** of the following:

Yes

No

2 Which room(s) is located directly under the roof? *

Only answer this question if the following conditions are met:

Answer was 'Yes' at question '1 [Woning2]' (Do you have a room in your home that is located directly under the roof?)

Check all that apply

Please choose **all** that apply:

Bedroom

Living room

Neither

3 Since what year have you lived at this address?

Your answer must be between 1920 and 2021

Only an integer value may be entered in this field.

Please write your answer here:

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4 Is there a side in the living room where the sun enters the room for most of the day? *

Please choose **only one** of the following:

Yes

No

5 Is there a side in the bedroom where the sun enters the room for most of the day? *

Please choose **only one** of the following:

Yes

No

Heat perception in the living room

Questions related to heat perception in the living room

6

How would you describe the temperature in your living room in the past summer? *

Choose one of the following answers

Please choose **only one** of the following:

Always pleasant

Usually pleasant

Sometimes to warm

Usually to warm

Unbearably warm

7 How would you describe the temperature in your living room on days with outside temperatures of 25 degrees Celsius or higher? *

Choose one of the following answers

Please choose **only one** of the following:

Always pleasant

Usually pleasant

Sometimes to warm

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Usually to warm

Unbearably warm

8 Which system(s) for cooling is present in your living room? *

Check all that apply

Please choose **all** that apply:

Airconditioning

Floor cooling(heat/cold pump)

Ventilator

No cooling in the living room

Other:

9 How often did you use one or more of the above-mentioned systems in the past summer? *

Choose one of the following answers

Please choose **only one** of the following:

Never

Rarely

Weekly

Daily

Does not apply

10

What type of shading mechanism is present in your living room? *

Check all that apply

Please choose **all** that apply:

Transparent blinds

Blinds or (roller) curtains (inside)

Outdoor blinds or drop-down awnings

No blinds

Other:

11 How often did you use this shading mechanism during the day? *

Choose one of the following answers

Please choose **only one** of the following:

Never

Rarely

Weekly

Daily

Does not apply

Heat perception in the bedroom

Questions related to heat perception in the bedroom

12

How would you describe the temperature in your bedroom in the past summer? *

Choose one of the following answers

Please choose **only one** of the following:

Always pleasant

Usually pleasant

Sometimes to warm

Usually to warm

Unbearably warm

13 How would you describe the temperature in your bedroom on days with outside temperatures of 25 degrees Celsius or higher? *

Choose one of the following answers

Please choose **only one** of the following:

Always pleasant

Usually pleasant

Sometimes to warm

Usually to warm

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Unbearably warm

14 Which system(s) for cooling is present in your bedroom? *

Check all that apply

Please choose **all** that apply:

Airconditioning

Floor cooling(heat/cold pump)

Ventilator

No cooling in the bedroom

Other:

15 How often did you use one or more of the above-mentioned systems in the past summer? *

Choose one of the following answers

Please choose **only one** of the following:

Never

Rarely

Weekly

Daily

Does not apply

16

What type of shading mechanism is present in your bedroom? *

Check all that apply

Please choose **all** that apply:

Transparent blinds

Blinds or (roller) curtains (inside)

Outdoor blinds or drop-down awnings

No blinds

Other:

17 How often did you use this shading mechanism during the day? *

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Choose one of the following answers

Please choose **only one** of the following:

Never

Rarely

Weekly

Daily

Does not apply

18 Do you have other ways, than the use of shading or cooling systems, to handle the heat in your home?

Please write your answer here:

Health

Questions related to health

19

Are you sensitive to heat?(*e.g. do you experience physical complaints, such as excessive sweating, shortness of breath or headache*)? *

Choose one of the following answers

Please choose **only one** of the following:

Yes

No

20 How would you describe your health in general? *

Choose one of the following answers

Please choose **only one** of the following:

Very good

Good

OK

Bad

Very bad

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21 Did you experience one or more of the following heat complaints in your house in the past summer *

Please choose the appropriate response for each item:

	Never	Rarely	Sometimes	Frequently	Usu
Bad sleeping					
Trouble concentrating					
Fatigue					
Headache					
Distress					
Thirst					
Excessive sweating					
Bothered by heat during exercise					

Feautures

Questions related to your personal situation

22 What is your gender?

Choose one of the following answers

Please choose **only one** of the following:

Male

Female

Other

23 What is your age?

Choose one of the following answers

Please choose **only one** of the following:

Under 18 years

18-25 years

26-35 years

36-65 years

66-75 years

75+

24 How many people belong to your household, including yourself?

Only numbers may be entered in these fields.

Please write your answer(s) here:

Children

Adults

Final

25

Gift cards are raffled among the participants. Would you like to win a gift card?

Please choose **only one** of the following:

Yes

No

26 If you want to have a chance to win a gift card, please enter your email address or zip code and house number below. We raffle gift cards among the participants.

Only answer this question if the following conditions are met:

Answer was 'Yes' at question '25 [Vervolg]' (Gift cards are raffled among the participants. Would you like to win a gift card?)

Please write your answer here:

27 Do you have any comments regarding this questionnaire?

Please write your answer here:

Thank you for completing the questionnaire
10-08-2021 – 09:11

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Submit your survey.
Thank you for completing this survey.

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