POLICY BRIEF
THE BUILDING-SCALE PERFORMANCE OF BLUE-GREEN ROOFS

Colophon

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Author Information

Vrije Universiteit Amsterdam: Toon Haer, Tim Busker, Lieke Meijer, Hans de Moel, Marthe Wens, Jeroen Aerts, Josia Brüggen. *Hydrological effectiveness during extreme events.*

Hogeschool van Amsterdam: Anna Solcerova, Dante Föllmi, Lisanne Corpel, Jeroen Kluck. *Indoor and outdoor heat-stress reduction.*

RESILIO is derived from 'Resilience nEtwork of Smart Innovative cLImate-adapative rOoftops', a collaboration between the Municipality of Amsterdam, Waternet, MetroPolder Company, Rooftop Revolution, HvA, VU, Stadgenoot, de Alliantie and De Key.

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Contact address: toon.haer@vu.nl

Citing images/photographer: Wieke Braat & Rosanne Nieuwesteeg

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Smart blue-green roofs

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. 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 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). Moreover, a smart valve allows for an 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.

The municipality of Amsterdam is now testing these blue-green roofs in the RESILIO project (see Box 1). The RESILIO project, an acronymn for 'Resilience nEtwork of Smart Innovative cLImate-adapative rOoftops', aims to investigate the key 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 realize approximately 10.000m^2 of blue-green roofs on mainly social rental properties. In this policy brief, the hydrological performance and the performance on heat stress reduction is discussed. A more detailed description of the findings can be found in the final report (See RESILIO final report: Haer et al., 2021). The results for the hydrological performance are furthermore published as a peer-reviewed article in Busker et al. (2021).

Box 1 Smart blue-green roofs

Blue-green roofs (Fig. 1) can store more rainwater than "normal" green roofs. Under the green plant layer is a crate system in which the water is stored. The water reaches the plants through capillary rise cylinders, entering the substrate (soil) from underneath. The roofs can also choose whether to retain the water or release it. The smart blue-green roofs are equipped with sensors and valves. As the sensors measure the water level, the valves respond to the weather forecast and open and close at the right time. This is useful when, for example, there is going to be heavy rainfall or in times of drought.

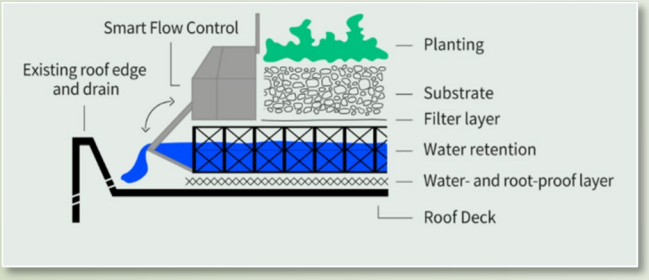

***Figure 1**. Schematic representation of a smart blue-green roof. Source: Metropolder Company*

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Hydrological effectiveness during extreme events

The smart valve (Box 1) allows for forecast-based operation of blue-green roofs, by regulating the roof's water level. This allows to tailor and maximize hydrological performance. The smart blue-green roofs have three main objectives from a hydrological perspective:

1. Maximize buffer capacity during rainfall events to decrease pluvial flood risk ($Performance_{BUFFER}$);
2. Maximize evapotranspiration (ET) for heat reduction through evaporative cooling ($Performance_{ET}$);
3. Minimize long-term drought events (28-days <10 mm of water in the green layer, $Performance_{DROUGHT}$);

These different objectives are conflicting: objective 1 requires a low water level to maximize buffer capacity, meaning that the smart valve should always be open except during rainfall, while objective 2-3 require a high water level to maximize ET and minimize the impact of long-term meteorological droughts, meaning that the smart valve should always be closed. The optimal configuration of the smart valve therefore depends upon changing weather conditions. When anticipating on precipitation forecasts, 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. Perfect forecast information would in theory therefore maximize the performance on all (three) hydrological objectives.

The three performance indicators were measured with sensors on four RESILIO roofs. Furthermore, considering the short time span of observed results, we developed a computational model of blue-green roofs (Fig.2) that analyzes the performance using longer rainfall and temperature time series (2013-2019) in the Netherlands.

Moreover, using the computational model we analyzed the performance of blue-green roofs when operation is based on weather forecasts, using forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF). Finally, we compared the performance indicators for different roof configurations (green roof, blue-green roof without drainage, blue-green roof with drainage), and different forecasted based drainage strategies (using the 30th, 60th, 90th and the 99th percentile of the forecast, as well as increasing and decreasing percentiles with lead time: see Busker et al. (2021) for details). Finally, we included a scenario based on perfect forecast information for benchmarking the results.

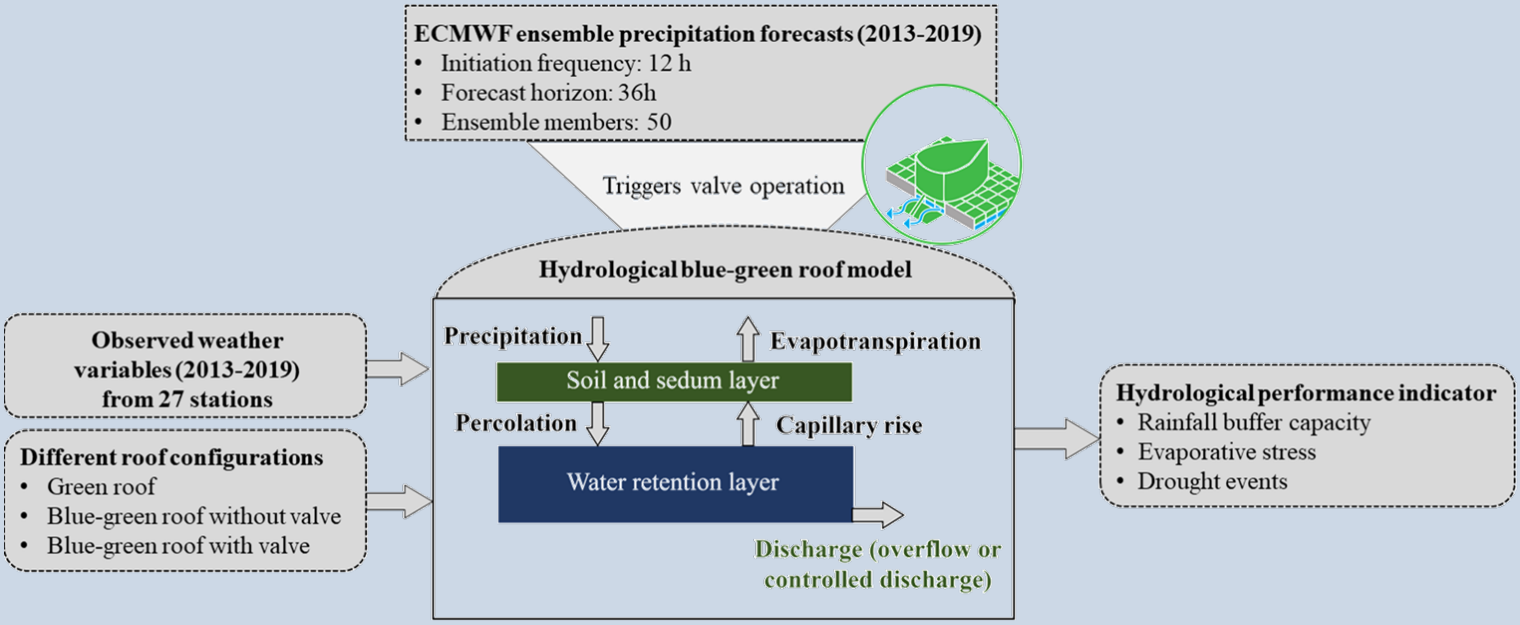

***Figure 2**. Framework for the computational model.*

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The results for the observations and the results from the computational model for the RESILIO roofs are shown in Table 1. Using the computational model, we were able to extent the analysis to seven years of observations, using 27 weather stations in the Netherlands for input data. The analysis (Table 1) shows that the model produces similar but more robust results when compared to the short and more uncertain observation results. Both the average results and the results for extreme conditions (>20 mm/h) show comparable high observed and modelled capture ratios. The ET performance from the model and observations is also high with comparable results: respectively 89% and 86%. For extreme events (T>25℃) the modeled and observed performance is also similar, respectively 73% and 67%. The overall analysis shows that the blue-green RESILIO roofs are performing well in the short timespan that they are implemented now, and that this performance is in line with expected average long-term performance. For more detailed see RESILIO final report: Haer et al., 2021.

***Table 1**. Modelled and observed performance of blue-green roofs for evapotranspiration and buffer performance based on 90th percentile forecast-based operation.*

Roof	*Evapotranspiration Performance*				*Buffer Performance*			
	All conditions		Extreme conditions (T>25℃)		All conditions		Extreme conditions ($>20mm/h$)	
	Modelled	Observed	Modelled	Observed	Modelled	Observed	Modelled	Observed
Benno Premselahuis	89%	86%	73%	53%	94%	86%	73%	-
Tweede Oosterparkstraat	89%	96%	73%	94%	94%	100%	73%	100%
Derde Oosterparkstraat	89%	49%	73%	26%	94%	100%	73%	100%
Ite Boeremastraat	89%	99%	73%	100%	94%	81%	73%	90%
Average	**89%**	**83%**	**73%**	**68%**	**94%**	**92%**	**73%**	**97%**

The performance indicators under different forecast-based drainage scenarios for the computational model are shown in Fig.3. The boxplots represent the distribution of accumulated values over the seven years under observation. Without the blue layer, the green layer would only store approximately 30% of the total precipitation, with the other 70% being uncontrolled overflow ($Performance_{BUFFER}$). 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 for water buffering considerably, with values in excess of 90% under most strategies. In terms of ET performance, blue-green roofs evaporate considerably more than green roofs. Performance is always above 80 % of potential ET (PET) when ECMWF forecasts are used. 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. This indicates the added value of using the blue layer as an irrigation source through capillary rise.

Concluding for hydrological performance, blue-green roofs show to be effective adaptation measures to reduce the impact of extreme weather events. They outperform green roofs in both water storage and cooling. When combined with a smart control valve to release water, and with forecast based operations, more than 90% of total rainfall (and more than 70% of extreme rainfall) can be captured on these roofs.

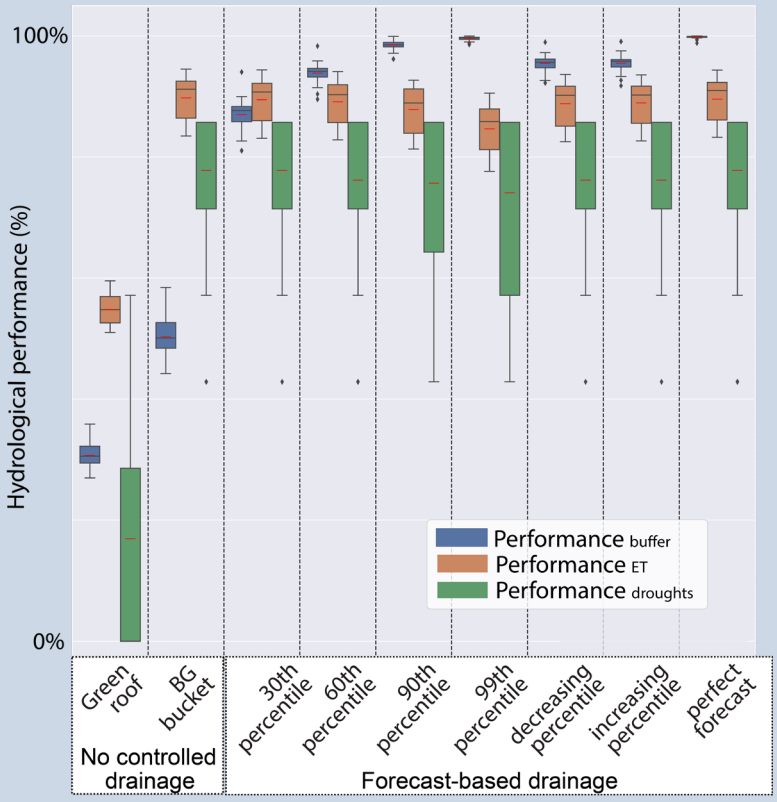

***Figure 3**. The hydrological performance of blue-green roofs, analyzed with the computational model.*

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Indoor and outdoor heat-stress reduction

The thermal impact of blue green roofs on building scale has been examined based on four RESILIO blue-green roofs, four reference roofs (black bitumen or gray gravel) and two conventional sedum covered green roofs. On each roof, temperatures were measured at and above the roof surface, together with air and ceiling temperatures inside the building (Figure 4) to investigate both the thermal effects on the inside environment and on the outside surface of the building. The measurements were done during both warm periods (>20 C° for seven consecutive days) and a cold period (< 5 C° for seven consecutive days) to investigate the cooling effect as well as the insulative effect of blue-green roofs.

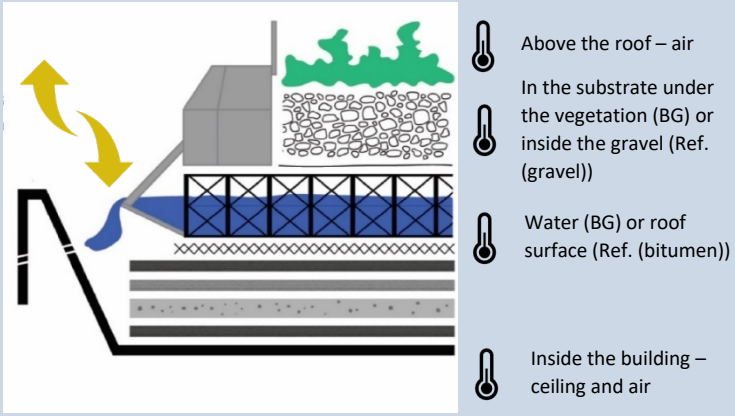

***Figure 4**. Overview of the placed measurement devices at the research sites for blue green roofs (BG) and reference roofs (Ref.).*

Results indicate the different thermal behavior of the different types of roofs. The temperature of the substrate under the vegetation was in summer only a few degrees colder than the temperature of the gravel roofs which indicates that the cooling capacity of the green layer alone is relatively limited. On the other hand, 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.

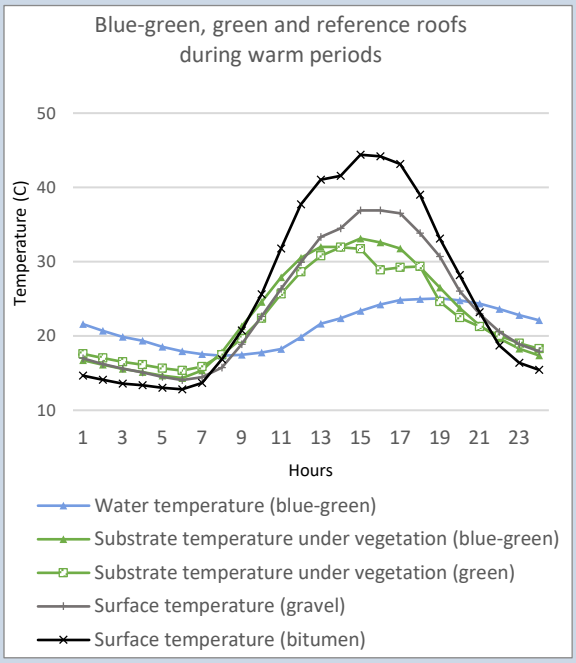

***Figure 5**. Graph of the hourly averages of measured temperatures during the three warm periods (4-16 June, 16-27 July, 6 -10 Sept. 2021) for the research locations at the Oosterparkbuurt.*

Measurements from summer 2021 show that during daytime, the water was significantly cooler than the gravel (~12 °C) or bitumen (~19 °C) (Figure 5). However, during summer nights, the physical properties of the water that prevented it from heating as fast as other measured surfaces also caused slower cooling. Therefore, we could measure higher nighttime water temperatures (5 - 9 °C higher) compared to other surface temperatures. This buffering effect might be beneficial during day time, but might negatively influence the heat transfer from inside of the building out and delay cooling of the building after a long heat wave.

During a cold period, the water crate layer remains empty. Nonetheless, it still functions as a buffer to the colder outside temperatures. Our measurements showed that the stagnant air layer in the water crates had up to 3 °C higher temperature at night than other measured surfaces.

The effect of the water crate layer was also measured inside the building. Average indoor temperatures showed that rooms under blue-green roofs were colder during summer and warmer in winter compared to reference roofs, indicating all-year-long benefits of blue green roofs when it comes to comfort inside the building.

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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. This was investigated by looking at the daily variation of the indoor temperatures, more variation means more influence from outdoor temperature. There is on average 0.19 C° and 0.23 C° less temperature variation underneath the blue-green roofs then underneath the reference roofs during the warm and cold periods, respectively. This effect is small in absolute values, however the differences in variation represents a relatively large proportion of the total daily variation (24% and 64% for warm and cold periods, respectively). This decrease in indoor temperature variation indicates that blue-green roofs positively influence the indoor climate during both summer and winter months. However, the exact influence of blue-green roofs on absolute indoor air temperature needs to be studied further and under more controlled conditions.

To examine the insulation properties of the roofs, U-values have been calculated from the available winter measurements of 2021. U-values show how much heat travels through the building and escapes to the outdoor environment during a winter night. The results for a gravel reference roof are twice as high as for blue-green roofs with empty water layer (0.43 vs 0.21 W/m^2*K) showing that double the amount of heat escaped through the roof construction with gravel as through the roof with a blue-green layer on top of it. This difference however also include the already implemented insulation layer in each roof.

In construction practice, R-values (reciprocal to U-values) are used to indicate the expected insulation values of the construction – in this case a roof – when a certain insulation material is used. Table 2 shows the R-values given by the manufacturer and R-value calculated from our measurement data. For the reference roof, the given and measured values are only slightly different (2.0 vs. 2.3). For the blue-green roof, the measured R-value was higher than the value expected based on insulation material (3.5 vs. 4.8). This higher difference suggests that the blue-green layer on the top of the roof contributes an additional 1 - 1.3 m^2*K/W of insulation.

Table 2 Insulation properties of a blue-green roof and a reference roof at the Oosterparkbuurt location. The Insulation layer properties *column shows the type of the insulation material in the roof and consequently the expected insulation of the roof as a whole. U- and R- values are calculated insulations values of the roof based on temperature differences in and outside of the building.*

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

All indoor measurements showed small, but systematic influence of blue-green roofs on indoor temperature. However, at this point we can not specify how strong this influence is. Both average temperatures and variation in the temperature were very small and might not be perceived by human body. The increased insulation values for blue-green roofs suggest that the additional blue-green layer might potentially influence the heating/cooling costs. 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.

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Bibliography

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

Cirkel, D.G., Voortman, B.R., van Veen, T., Bartholomeus, R.P., 2018. Evaporation from (Blue-)Green Roofs: Assessing the benefits of a storage and capillary irrigation system based on measurements and modeling. Water 10. https://doi.org/10.3390/w10091253

Haer, T., Solcerova, A., van Moorselaar, I., Busker, T., Meijer, L., De Moel, H., Wens, M. Aerts, J.C.J.H., Brüggen, J., Bos, L. (2021). Final report – The building-scale performance of blue-green roofs. RESILIO

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