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Estimating the impact of blue-green infrastructure on household water demand

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ABSTRACT

Blue green infrastructure (BGI) is widely implemented as an adaptive stormwater management measure at the household level to reduce flood risk. However, more greenery also raises water demand during droughts due to higher evapotranspiration. This study examines the impact of 14 commonly used BGI types on household water balance under climate projections in the Netherlands. Several scenarios were modeled, from a 'Grey' setup with no BGI to a 'Greenest' option with an intensive green roof, facade, and orchard. Intermediate configurations were also analyzed, representing more common household configurations. On a typical 100 m^2 household plot, the 'Greenest' option results in an extra demand of 154.3 L/day. This exceeds the current average daily indoor water use of a typical household of 129 L/day. In contrast, intermediate setups with a native plant garden or fully grassed garden and a gray roof require 8.4 and 9.9 L/day, respectively. To meet 80% of the projected additional external water demand from intensified greenery, intermediate setups need up to 2.3 m^3 of rainwater tank. The 'Greenest' option requires 14.9 m^3 of water storage to achieve the same coverage, underscoring the challenge of balancing space for water harvesting systems and intensified greenery within a limited household plot.

Key words: blue green infrastructures, climate adaptation, stormwater harvesting, sustainable water management, urban water demand

HIGHLIGHTS

- Future climate projections indicate a water shortage for cooling urban environments.
- During extended droughts, the maintenance and irrigation of BGI increase water demand.
- The design, location, function, scale, and other parameters of BGI can impact urban water.
- Stormwater harvesting can meet internal water needs to maintain optimal performance in BGI.

1. INTRODUCTION

Cities are subject to constant change and improvement, experiencing socio-economic, technological, ecological, and climatic transformations. Adaptation to these kinds of changes often requires the development and application of technologies, leaving a physical imprint (Rijksoverheid 2023). One example of this is the expansion of blue green infrastructure (BGI) as an innovative approach to managing stormwater (Fletcher *et al.* 2015). Originally, BGI aimed to reduce or redirect stormwater from combined sewer systems and guide runoff to areas where it can be infiltrated, reused, or evaporated. These infrastructures are designed to reinstate natural urban hydrological conditions, increase infiltration within urban areas, expand water storage capacity within urban water infrastructure, regulate drainage rates, and enhance water quality (Alves *et al.* 2019; Taguchi *et al.* 2020). Soil and vegetation are used instead of, or coupled with, traditional grey infrastructure elements, including drains, gutters, pipes, and centralized treatment areas. BGI includes bioswales, green roofs, permeable pavements, and retention spaces in parks, among other similar infrastructures.

The implementation of vegetation as part of the BGI, has additional co-benefits as it can mitigate heat waves and offer a cooling effect in urban areas through its evaporative capacity (Wang *et al.* 2022) and, in case of trees, also shade. Extensive greening with a diverse selection of plants enhances biodiversity, improves the quality and esthetics of the urban space, and promotes a healthy environment (Ferreira *et al.* 2024). The adaptability and numerous co-benefits of BGI explain its active promotion in various legislative levels, from European directives to private initiatives (Van der Werf *et al.* 2023).

Governmental institutions, including municipalities and waterboards, have increasingly implemented BGI within the public space. However, the greatest potential for BGI implementation lies in private urban areas (Roest *et al.* 2023). Subsidising BGI implementation at a household level is therefore one of the key strategies to ensure the climate adaptability of a city. In the Netherlands, strategies such as 'Steenbreek', 'Amsterdam Rainproof' 'Rotterdams Weer Word', among others, confirm this rising trend (Stobbelaar *et al.* 2021). In the Dutch context, with a mild coastal climate, the design and implementation of BGI has focused on dealing with excess stormwater. However, BGI must now exist and operate under new climatic conditions: periods of prolonged droughts when water may become a scarce resource (AMS Institute 2020).

Climate change is expected to increase the duration and intensity of droughts (Vicente-Serrano *et al.* 2020). This expected increase, coupled with population growth, urbanization, and the decaying quality of water resources, has increased the pressure on drinking water production. Projections indicate that by 2035, this demand will exceed the capacity of existing resources, reaching a critical level in the Netherlands (Van der Borst & Dupont-Nivet 2023). The capacity of BGI to retain and store stormwater can partly contribute to the mitigation of emerging droughts, but this impact is limited due to size and storage capacity (Ambrosi *et al.* 2024). However, if precipitation is unable to provide sufficient water to maintain the transpiration rates of BGI, supplemental BGI irrigation is required. Drinking water is typically used for watering urban greenery at the household level, which intensifies the drought issues when they occur (Baggelaar & Kuin 2022; van Gaalen *et al.* 2024).

Avoiding BGI irrigation to reduce additional stress on the drinking water production also has significant drawbacks. A limited availability of water for evaporation, infiltration, or runoff can significantly impact the performance of BGIs (Back *et al.* 2021). The quantity of water that evaporates within a BGI depends on various factors, including surface permeability, vegetation density, and the scale of a BGI element. Additionally, other factors can either increase water consumption within a BGI or contribute to its accumulation and retention (Moravej *et al.* 2021). Although plants can survive under water stress, limiting the amount of available water may prevent plant growth and development (Carminati & Javaux 2020; Abdalla *et al.* 2022; Cai *et al.* 2023). Besides the visible effects on greening, reducing the availability of water for evaporation lowers Urban Heat Island (UHI) mitigation, thereby affecting living comfort (Aram *et al.* 2019).

Widely implementing BGI solutions and maintaining their functioning can therefore increase water demand, which strains the already stressed drinking water supply (McGrane 2016). Municipalities, water boards, and residents are concerned with the risk of unsustainable irrigation for urban greenery and overuse of local water resources (Rijksoverheid Nieuwsbericht 2024). The vision of green and sustainable urban environment with widespread use of BGI at household level, may therefore not be feasible in a changing climate. This requires a reconsideration of approaches to water resource management (Przestrzelska *et al.* 2024).

Starting in 2024, all new buildings in the Netherlands will be evaluated for their adaptation measures and use of BGI (Framework for Climate Adaptive Buildings (FCAB) 2024). Meanwhile, the government is expanding programs to subsidize BGI implementation at the household level (Klimaatadaptatie Nederland, 2024). Despite research on the efficiency of various BGIs and their combinations for flood management (Cavadini *et al.* 2024), there remains a lack of understanding about how BGIs influence water demand under future climate conditions.

This article presents a methodology to make an impact assessment of different BGI individually and in combination at the household level, focusing on both urban water balance parameters and associated co-benefits. These impacts are modeled using climate projections for the Netherlands up to 2050. The study explores the potential of implementing BGI and their combinations, relying solely on projected precipitation patterns.

2. METHODOLOGY

2.1. Mass balance approach

To assess the impact of different BGIs on the hydrological cycle at a household level, a hydrological mass balance approach was used as the guiding concept for the modeling framework in this study. It is based on the principle that the sum of inflows equals the sum of outflows and the change in storage within the urban hydrological cycle (Meng *et al.* 2022). This concept was translated into a customizable hydrological mass balance model to analyze water movement through key inflow and outflow fluxes (Figure 1).

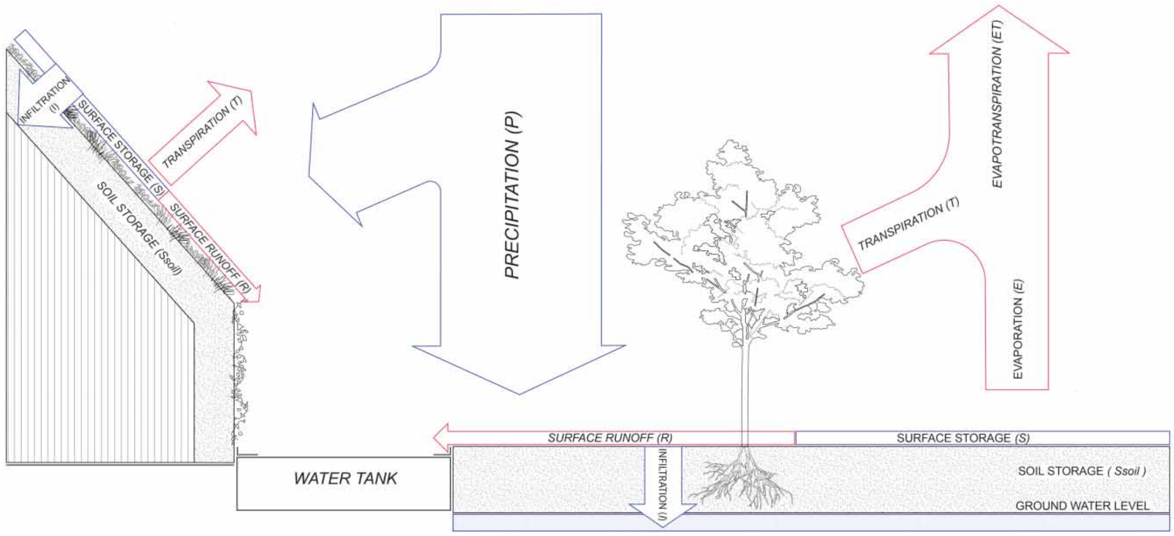

Figure 1 | Considered water balance fluxes in the model.

Using defined hydrological fluxes, the model solved the mass balance by representing direct precipitation as P on all household surfaces and surface runoff from the catchment area as R. ET referred to as evapotranspiration, which is the sum of transpiration (T) from vegetation and evaporation (E) from non-vegetated and impervious surfaces. Infiltration referred to as I. The change in surface water storage was expressed as S, while S_{soil} represented the soil moisture storage.

To implement the mass balance approach, we created a hydrological model at the household level that assesses the impact of different BGI implementations and monitors hourly water flows in their application areas (roof, facade, or garden). The model simulates how different BGI configurations, whether applied individually to one surface or in combination across multiple surfaces, influence the water balance by altering infiltration, storage, runoff, and evapotranspiration dynamics. Each surface is treated as a separate hydrological unit with its own parameters and is hydraulically connected to a rainwater harvesting (RWH) tank. The tank collects excess runoff and supplies stored rainwater when evapotranspiration losses cannot be met by precipitation or soil moisture.

The main objective of the model was to track how BGI interventions altered household level water balance dynamics under climate projections and to assess the potential of stormwater harvesting to reduce reliance on tap water irrigation. The model operated at an hourly resolution and used iterative simulations to estimate tank sizes required to achieve a target level of water self-sufficiency for different BGI setups.

2.2. Model inputs

To tailor the model for a typical Dutch household facing climate change, we configured the model environment with two input categories: climate projections and household settings. Each temporal and spatial input was essential for the urban water balance calculation (Brauer *et al.* 2009).

The first set of inputs includes climate projections from 2024 to 2050, providing essential data on precipitation and drought patterns. These projections help estimate the rainfall available to sustain BGIs, as well as the frequency and duration of droughts that could lead to water deficits (Wu *et al.* 2024). We used the downscaled Alaro-0 model by the Royal Meteorological Institute of Belgium (RMI), which is suitable for modeling climate change impacts in the Netherlands due to similar spatial and climatic conditions. With a resolution of 12.5 km, the model incorporates RCP 2.6, RCP 4.5, and RCP 8.5 climate scenarios from the Intergovernmental Panel on Climate Change (CORDEX; Jacob *et al.* 2014) and covers Belgium and parts of the Netherlands. Here, we used the key variables for an urban water balance calculation: (1) reference evaporation, (2) relative humidity, (3) precipitation, (4) solar radiation, (5) wind speed at 10 m, (6) near-surface air temperature at 2 m, and (7) daily maximum and minimum air temperatures (Termonia *et al.* 2018).

All climate data were sourced in NetCDF format from the Alaro-0 model and further analyzed using Python for modeling and visualization. For our study, we focused on the pixel corresponding to the coordinates (51.5852, 4.7767), which aligned with the geographical area of the Netherlands. This data enabled us to capture the environmental conditions relevant to our research. Hourly climate data from the RMI was used as input for the model. Output indicators were presented in standard units, enabling clear comparison of increases or decreases relative to the initial household state without BGI. Across the simulation period (2024–2050), the average annual rainfall was 1,043.94 mm/year, ranging from 843.47 to 1,248.32 mm/year. Reference evapotranspiration averaged 590.31 mm/year, with a minimum of 516.75 mm/year and a peak of 729.10 mm/year. Hourly extremes reached 5.12 mm/hr for rainfall and 0.31 mm/h for reference ET.

The second input category focuses on the spatial characteristics of a typical Dutch household (CBS 2024). The total plot area is 100 m^2, featuring a sloping roof (50 m^2), a fully paved garden (50 m^2), and a facade surface (27 m^2). Although the facade area is vertical and does not contribute to the horizontal surface area, it is included as a functional surface for BGI implementation. Stormwater is conveyed through a sewer system. This household setting serves as the reference, representing a standard Dutch household not designed to cope with climate change (Figure 2).

2.3. Model workflow

The sequence of processes simulated in each model run, as well as the corresponding equations and variables, are detailed in Table A1 (Appendix). This table reflects how the model tracks changes in water fluxes and storages throughout the system.

The simulation operated on an hourly timescale. For each timestep, rainfall added water to the roof and garden based on the BGI applied in those areas (Table 1), while potential evapotranspiration (PET) drove the demand for water loss per surface area where BGI was applied, defining the upper limit of water loss from vegetated surfaces. This demand was first met using water from surface storage (soil or substrate). If surface storage was insufficient, the model withdrew additional water from the RWH tank. If neither of these sources could fully meet PET, evapotranspiration was reduced accordingly, and the unmet portion was recorded as additional external water demand. This value reflects the gap between PET and the actual evapotranspiration.

If water inputs exceeded the storage capacity of the roof, facade, or garden, the surplus became runoff, which was directed to the RWH tank if space was available. A perfect operation of the tank was assumed, with no losses from overflow or system inefficiencies. Tank withdrawals occurred only after surface storage was depleted. If the tank was also empty, the remaining PET was left unmet. This logic ensured that actual ET could be lower than PET, avoiding overestimation of irrigation demand.

The simulation iteratively adjusted tank sizes in 0.1 m^3 increments to determine the optimal size for achieving 80% water demand coverage. The model served as part of a scenario-based evaluation, aiming to identify the smallest tank size that reliably met most of the irrigation needs. The volume of water supplied from the tank divided by the total irrigation demand for roof, facade, or garden vegetation was defined as efficiency. The 80% threshold was chosen as a practical target, offering a high level of self-sufficiency without oversizing the harvesting system. Due to natural variations in rainfall, some shortfall was acceptable. The 80% threshold was intended to balance sufficient coverage with a rational system size. Once this efficiency level was reached, the simulation stopped, assuming the tank was sufficient for the selected BGI setup.

2.4. Model scenarios

The shift in household water balance was determined by the spatial configuration of the household, where different BGI types were applied to the roof, facade, or garden. We selected 14 BGI types commonly used at the household scale (McEvoy *et al.*

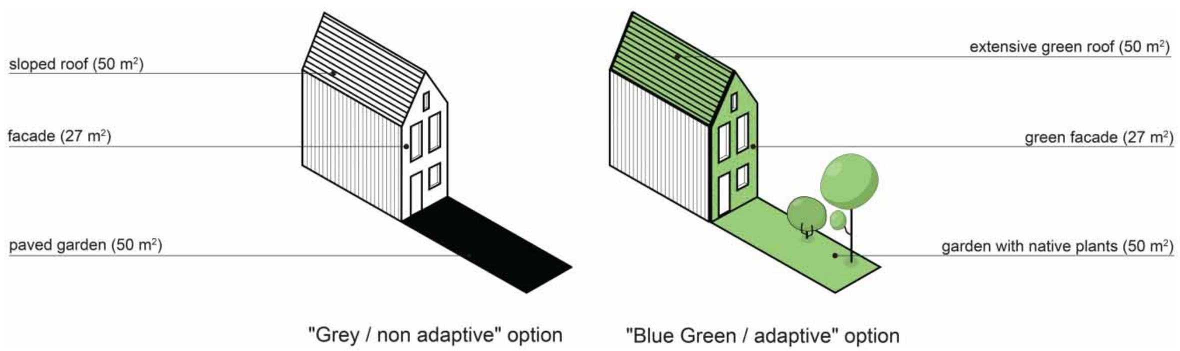

Figure 2 | Two distinct household setups with the same total surface area: initial state with no adaptive measures (left) and a 'Blue Green' setup with intensified greenery (right).

Table 1 | BGI design description chart

			Surface						
Application area	**Name**	**Area (m²)**	**Pervious**	**Green**	**Parameter**	**Value range**	**Approach**	**Description**	**Source**
Roof 	Intensive green roof	50	Substrate yes	Yes	Water storage depth	15–60 mm	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Crop factor (K_c)	0.7–0.9	Design standard	Design standards	Costello *et al.* (2000)
					Runoff coefficient	0.01–0.4	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Infiltration into the substrate layer	18–1,800 mm/h	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
	Extensive green roof	50	Substrate yes	Yes	Water storage depth	20 mm	Empirical test	100–150 mm substrate, minimum depth for extensive roof plants	Fassman-Beck *et al.* (2013)
					Crop factor (K_c)	0.1–0.3	Design standard	Design standards	Costello *et al.* (2000)
					Runoff coefficient	0.01–0.7	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Infiltration into the substrate layer	36–4,200 mm/h	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
	Water roof	50			Water depth	30 mm	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Runoff coefficient	0.7–0.95	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
Garden 	Permeable pavement	50	Yes		Infiltration	250–2,500 mm/h	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Runoff coefficient	0.01–0.04	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Water storage depth	30–160 mm	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
	Soil recomposition	50	Yes		Infiltration	19–25 mm/h	Empirical test	Empirical tests on soil infiltration rates with various vegetation types (sand)	Stolte (2003)
						3–8 mm/h	Empirical test	Empirical tests on soil infiltration rates with various vegetation types (clay)	Stolte (2003)
	Fully grassed garden	50	Yes	Yes	Water storage depth	45–90 mm	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Crop factor (K_c)	0.1–0.3	Design standard	Design standard	Costello *et al.* (2000)
					Runoff coefficient	0.01–0.05	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Infiltration	31.8–63.7 mm/h	Empirical test	Infiltration tests using different plant species	Hidayat *et al.* (2024)
	Garden with native plants	50	Yes	Yes	Water storage depth	60–120 mm	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Crop factor (K_c)	0.4–0.6	Design standard	Design standard	Costello *et al.* (2000)
					Runoff coefficient	0.05	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Infiltration	51.2–82.9 mm/h	Empirical test	Infiltration tests using different plant species	Hidayat *et al.* (2024)
	Garden with exotic plants	50	Yes	Yes	Water storage depth	90–180 mm	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Crop factor (K_c)	0.7–0.9	Design standard	Design standard	Sigalingging *et al.* (2018)
					Runoff coefficient	0.05	Design standard	SUDS manual standard	Costello *et al.* (2000)
					Infiltration	161–425.1 mm/h	Empirical test	Infiltration tests using different plant species	Hidayat *et al.* (2024)
	Vegetable garden/orchard	50	Yes	Yes	Water storage depth	150–240 mm	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Crop factor (K_c)	0.2–0.9	Design standard	Design standard	Costello *et al.* (2000)
					Runoff coefficient	0.035–0.05	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Infiltration	161–425.1 mm/h	Empirical test	Infiltration tests using different plant species	Hidayat *et al.* (2024)
	Raingarden	50	Yes	Yes	Water storage depth	50–200 mm	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Crop factor (K_c)	0.1–0.3	Design standard	Design standard	Costello *et al.* (2000)
					Runoff coefficient	0.01–0.05	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
					Infiltration	245–1,600 mm/h	Empirical test	Infiltration tests across multiple scales in the Norwegian context	Venvik & Boogard (2020)
	Rain harvesting facility	7,5			Water storage depth	5–10 m^3	Design standard	Recommendations and design standards for the household scale in Flanders (Belgium)	Vlaamse Overheid (2023)

(*Continued.*)

Table 1 | Continued

Application area	Name	Area (m^2)	Surface		Parameter	Value range	Approach	Description	Source
			Pervious	Green					
					Water reuse	5–10 m^3	Design standard	Collected rainwater should be used to the maximum extent possible for applications that do not require drinking water quality, including toilet flushing, cleaning water, washing machines, and outdoor use	Vlaamse Overheid (2023)
	Lowering garden	25			Water storage depth	50–300 mm	Design standard	SUDS manual standard	Woods-Ballard *et al.* (2015)
	Green pergola	9		Yes	Crop factor (K_c)	0.4–0.6	Design standard	Design standard	Costello *et al.* (2000)
Facade 	Green facade	25		Yes	Crop factor (K_c)	0.7–0.9	Design standard	Design standard	Costello *et al.* (2000)
					Infiltration into the substrate	22–700 mm/h	Empirical test	Cost-effective assessment of greywater reuse in green walls. A total of eight media were used in this study	Prodanovic *et al.* (2017)

2019). Each BGI was assigned to a single surface and assumed to cover 100% of the application area. Relevant coefficients and parameters were applied to customize the equations for each BGI type, considering variations in greenery, storage capacity, and surface permeability across three application areas (Table 1).

At the start of each simulation loop, household surfaces were parameterized for the roof, facade, and garden. The model allowed one BGI type to be assigned per surface, enabling the assessment of both individual and combined design scenarios. In individual setups, a single BGI was applied to one surface (either roof, facade, or garden), while the others remained unchanged. Each combination used the same total surface area, pairing one roof type with one garden type. This flexible setup supported the evaluation of different design scenarios and their effects on water balance dynamics.

2.5. Water balance indicators

For each simulation loop and design scenario, the model tracked key water fluxes and storage dynamics (Table A1, Appendix). These indicators supported a quantitative assessment of various BGI implementations and their influence on the household water balance.

PET (mm/year) was estimated using climate data and crop coefficients specific to each BGI type. It defined the upper limit of water loss from a surface and served as the basis for calculating irrigation demand.

Water storage capacity (m^3) was a predefined parameter reflecting the maximum amount of water that each BGI element could retain before runoff occurred. Although it functioned as an input in the model, it also served as an assessment indicator, since BGI adoption is intended to enhance household resilience to pluvial flooding.

Surface runoff (% of total rainfall) is calculated as the proportion of rainfall that exceeds surface storage and evapotranspiration capacity. It represented water lost from the system and was expressed as a percentage of the total rainfall over the simulation period.

Infiltration (% of total rainfall) indicates the portion of rainwater retained in the surface (or substrate) layer that is not lost through runoff or evapotranspiration. In our model, it was limited by the defined storage capacity of the surface (Table 1) and did not include deep percolation. Hourly values were summed and expressed as a percentage of total rainfall, reflecting the effectiveness of each BGI type in retaining soil moisture.

Additional external water demand (L/day) captured the irrigation shortfall that could not be met by precipitation, surface storage, or soil moisture. This unmet demand was compensated by withdrawals from the RWH tank.

RWH tank withdrawal (L/day) indicated the volume of water drawn from the RWH tank to meet the unmet evapotranspiration demand. The tank module simulated inflows from excess runoff, withdrawals based on irrigation need, and the dynamic storage volume over time.

Efficiency (%) was calculated as the percentage of total irrigation demand fulfilled by water from the RWH tank. This indicator served as a key performance benchmark for tank sizing.

2.6. Co-benefits indicators

In addition to water balance indicators, we accounted for a range of co-benefits provided by BGIs. These reflected broader impacts of BGI implementation (Kvamsås 2023). Table A2 (Appendix) presents the data sources used to define these co-benefits. While water balance indicators were derived from a hydrological mass balance model, co-benefits were based on publicly available data and literature sources. They were expressed either quantitatively or qualitatively.

Heat response represented the cooling effect of BGI, expressed as the percentage reduction in physiological equivalent temperature. Values were sourced from the Klimaatbestendige Stad Tool (Deltares), which quantified temperature reduction for various BGI types in Dutch urban settings.

Footprint indicated the proportion of household space occupied by BGI elements, calculated as the percentage of the total plot area covered by each feature. Initial values for a standard household were derived from CBR data, assuming each BGI occupied 100% of its applicable surface.

Unit cost, expressed per square meter, reflected the additional investment required to implement BGI measures relative to a baseline household. The baseline was defined as the initial state of the household with a pitched roof, bare brick facade, and paved garden. As this state required no additional investment, it was set as zero. Costs were calculated per surface type and excluded construction labor and operational expenses. They reflected average prices in the Netherlands in 2025 and may vary by supplier or region.

Qualitative benefits captured each BGI's contribution to biodiversity and esthetic value, rated on a scale from low to high based on a literature review.

Water balance fluxes, calculated across implementation surfaces and over the simulation period, allowed the model to quantify the impact of individual BGI interventions on the household water cycle. Co-benefits provided a broader qualitative assessment. Outputs from combined BGI scenarios helped identify configurations capable of covering additional external water demand through withdrawals from the RWH tank, reducing reliance on tap water for irrigation during dry periods.

3. RESULTS

3.1. Individual BGI performance and result visualization

The results from the first two modeling stages, where individual BGI types were tested one by one at the household plot under climate projections, are presented in a table format (Figure 3). The rows represent the spatial setup of each modeled household configuration, and the columns display outcome indicators, ranking each setup's impact on water balance and co-benefits. The first row shows the baseline configuration, referred to as the 'Grey' option, representing a household with no BGI implementation. This baseline serves as a reference point, capturing the natural household water balance and providing a standard against which all subsequent BGI interventions are evaluated. The subsequent rows in the table correspond to the 14 individually assessed BGI types. The columns in the table display both water balance indicators and co-benefits. Each

Figure 3 | (a) BGI impact metrics. The top row shows the baseline (original house setup). The remaining rows show 14 individual BGI types, each applied separately per application area (roof, garden, or facade). Columns present water balance indicators. (b) BGI impact metrics. The top row shows the baseline (original house setup). The remaining rows show 14 individual BGI types, each applied separately per application area (roof, garden, or facade). Columns present co-benefit indicators. (*continued.*).

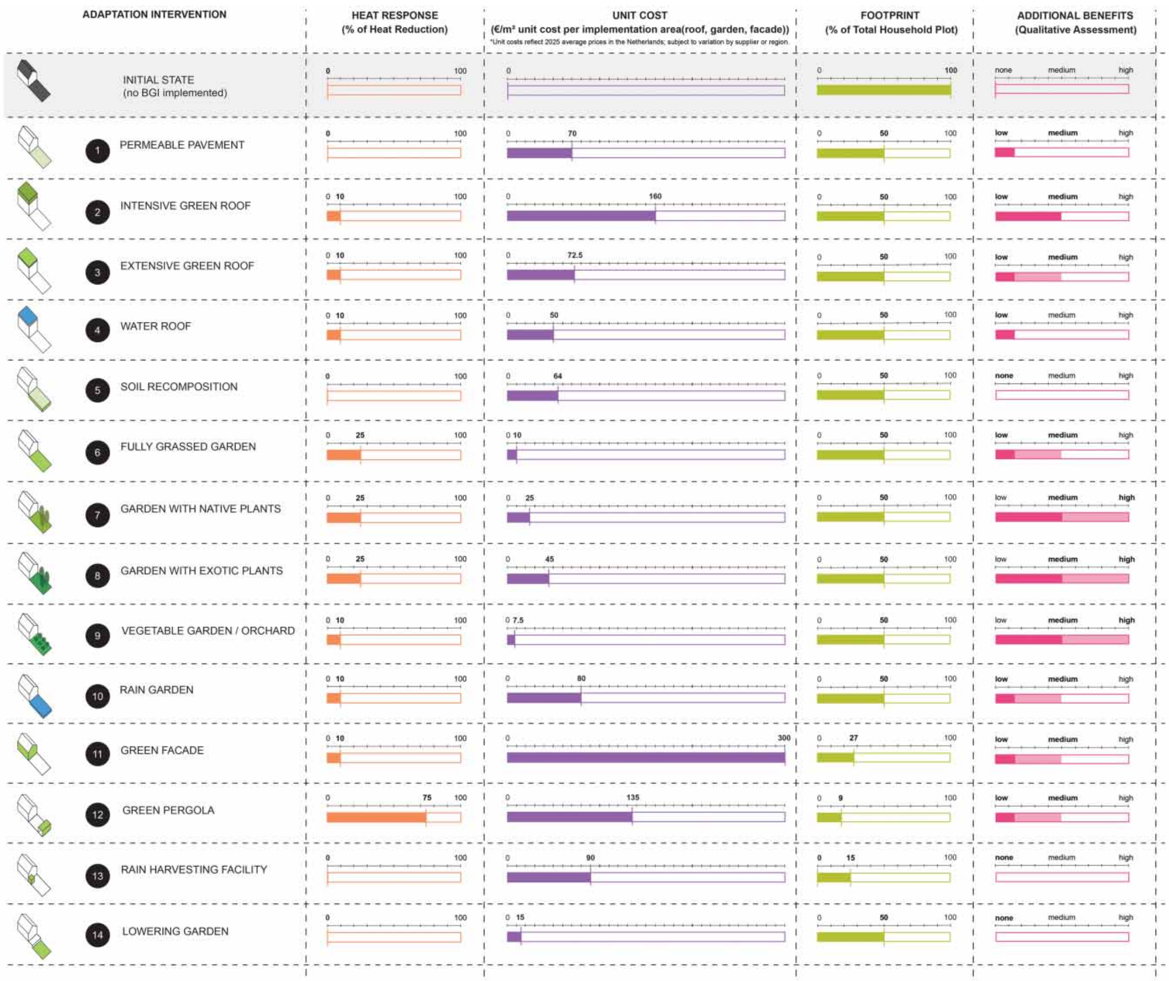

Figure 3 | Continued.

parameter is presented in standard units, allowing for a clear comparison of increases or decreases in value relative to the baseline configuration shown in the first row of the table. The first five columns contain the water balance indicators listed in Section 2.5. These indicators capture the direct impact of each BGI on household water dynamics, enabling comparisons of water retention, runoff, and water demand for each individual BGI intervention. Following the water balance indicators, the remaining columns address the co-benefits described in Section 2.6.

Reading the table horizontally provides a comprehensive profile of each individual BGI type, showing its impact across all water balance and co-benefit indicators. Conversely, reading the table vertically allows for a focused view of a single parameter, such as a specific water balance or co-benefit indicator, across all 14 BGI types. This approach makes it easier to identify which interventions have the most or least impact on that metric. The table layout offers a clear overview of the strengths and limitations of each BGI type and supports an informed selection of interventions that best align with specific goals or desired outcomes.

3.2. BGI impact table interpretations

To illustrate how findings from the BGI Impact Table can be interpreted, we selected two BGI strategies: intensive green roofs and native plant gardens (numbers 2 and 7 in Figure 3) and compared them with the baseline state. The baseline represents the initial condition of the household, featuring a fully paved garden, a sloped tiled roof, and brick facade walls. In the alternative scenarios, only one surface is modified, while all other components remain unchanged. In the first scenario, the sloped tiled roof is replaced with an intensive green roof. In the second, the paved garden is replaced with a native plant garden. In both cases, the intervention covers the same area, representing 50% of the total household surface. Greening the same household surface area results in significantly different outcomes.

In terms of storage, the baseline scenario has no retention capacity. The intensive green roof enhances storage by 2.85 m^3, while the native plant garden provides a greater capacity of 7.96 m^3. Regarding infiltration, the baseline remains ineffective due to its impermeable surfaces. The green roof allows for 26% of total rainfall to infiltrate, and the native plant garden substantially increases this to 70%. Surface runoff under the baseline condition is 81% of total rainfall, with some initial losses due to evaporation. This is reduced to 18% with the green roof and further to 6% with the native plant garden.

Additional external water demand refers to the volume of water to support vegetation within BGI elements when evapotranspiration losses exceed the supply from precipitation, stored rainwater, or available soil moisture. As the baseline scenario contains no vegetation, it does not require any additional water. The introduction of greenery increases water demand, but to different extents. The green roof requires 78.9 L/day, while the native plant garden requires 8.4 L/day. The annual PET demand for the intensive green roof is 32.84 mm/year, while for the native plant garden it is 27.37 mm/year.

The baseline has no effect on heat reduction, as it includes no climate-adaptive measures. The native plant garden offers a cooling effect of 25%, while the intensive green roof achieves a moderate effect of 10%. The footprint for both the intensive green roof and the native plant garden is 50% of the household plot, assuming each BGI fully occupies the roof and garden space, respectively. While the initial state of the household has no additional benefits, both the intensive green roof and native plant garden have an impact on biodiversity, enhancing urban greenery and visual appeal.

3.3. Design combinations

Previously, we assessed the application of each BGI separately on the garden, facade, and roof surfaces. In this section, we focus on combinations of two household surfaces: the roof and the garden. Each scenario covers the same total surface area, combining one roof type with one garden type (Figure 4).

The 'Grey' option lacks vegetation and thus does not require compensation for evapotranspiration losses, which results in no additional external water demand. An intensive green roof combined with an orchard household setup result in the highest water demand, at 154.3 L/day. Intermediate scenarios show varying levels of water demand. Thus, a house with a gray roof and a fully grassed garden requires 9.9 L/day, while the same garden settings paired with an extensive green roof increase

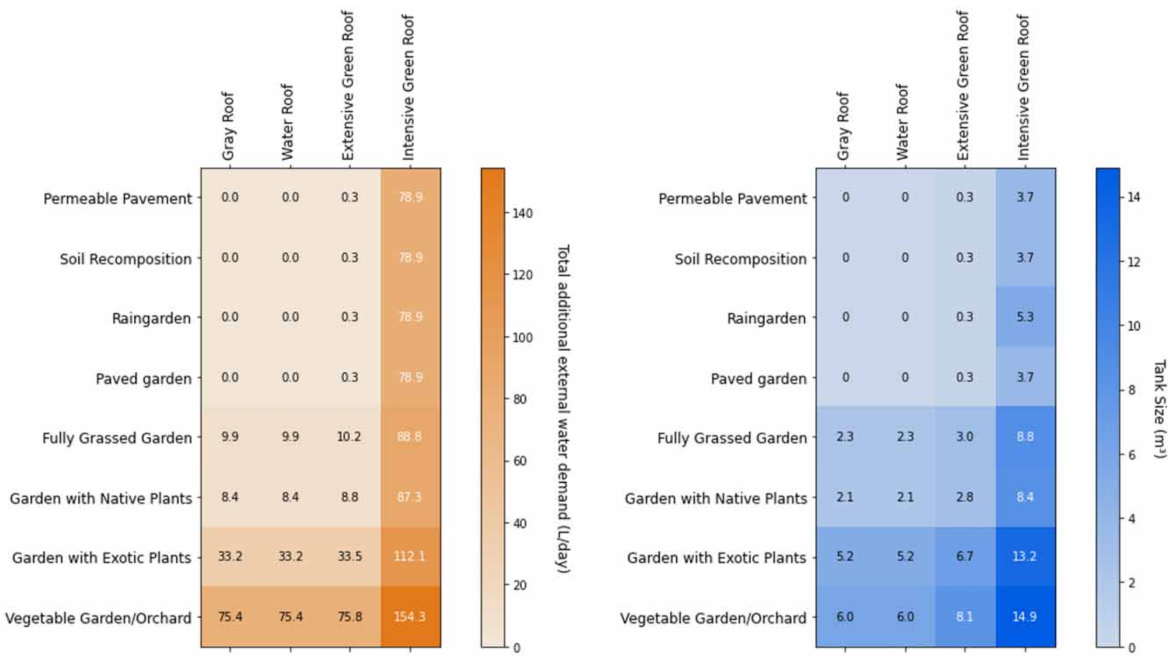

Figure 4 | BGI setup matrix with roof configurations as columns and garden configurations as rows. The left graph illustrates additional external water demand (L/day) projected to 2050. The right graph shows the required tank size (m^3) to meet 80% of that demand for each BGI setup.

the demand slightly to 10.2 L/day. A paved garden combined with an intensive green roof increases the demand to 78.9 L/day. The option that paired permeable paved gardens with an extensive green roof results in a minimal demand of 0.3 L/day, while a combination of an intensive green roof with a native plants garden leads to an additional water demand of 87.3 L/day under climate projections.

3.4. Balancing water demand with co-benefits

Implementing BGIs to enhance climate resilience involves a critical trade-off. Intensifying greenery enhances co-benefits, but its maintenance also leads to higher water demand. To maintain this balance without relying on tap water for irrigation, we investigated the potential of RWH. Water demand was evaluated at each time step as the volume withdrawn from an RWH tank to compensate for evapotranspiration losses not met by rainfall, stored rainwater, or available soil (or substrate) moisture. The simulation tracked rainfall and evapotranspiration on an hourly basis and calculated the amount of water required to support vegetation on both roof and garden surfaces. Scenarios with higher evapotranspiration losses resulted in a greater water demand and required larger tank sizes to meet irrigation needs.

As shown in Figure 4 (left), each configuration requires a different level of rainwater storage to sustainably meet its water demand, based solely on projected precipitation under future climate conditions. A configuration with an intensive green roof and an orchard represents the most water-demanding scenario, requiring a 14.9 m^3 rainwater tank to meet 80% coverage. Combining an intensive green roof with a native plants garden reduces the storage requirement slightly to 8.4 m^3. Highly efficient setups, such as permeable pavement with an extensive green roof, need just 0.3 m^3 of storage, while a gray roof paired with a native plants garden requires only 2.1 m^3. Intermediate scenarios show more balanced water demands. A fully grassed garden paired with a gray roof requires 2.3 m^3, while combining the same garden with an extensive green roof increases the need slightly to 3.0 m^3.

Incorporating a stormwater harvesting system enables households to meet their water demands, but the level of coverage varies with tank size (Figure 5). Coverage efficiency refers to the percentage of the total irrigation demand that is met by water withdrawn from the RWH tank over the full simulation period. The simulation iteratively increases the tank size to 0.1 m^3 until 80% of the modeled demand is covered. This threshold was selected as a practical target, providing a high degree of self-sufficiency while avoiding the oversizing of system infrastructure. Once this level is reached, the tank is considered sufficient for the corresponding BGI configuration.

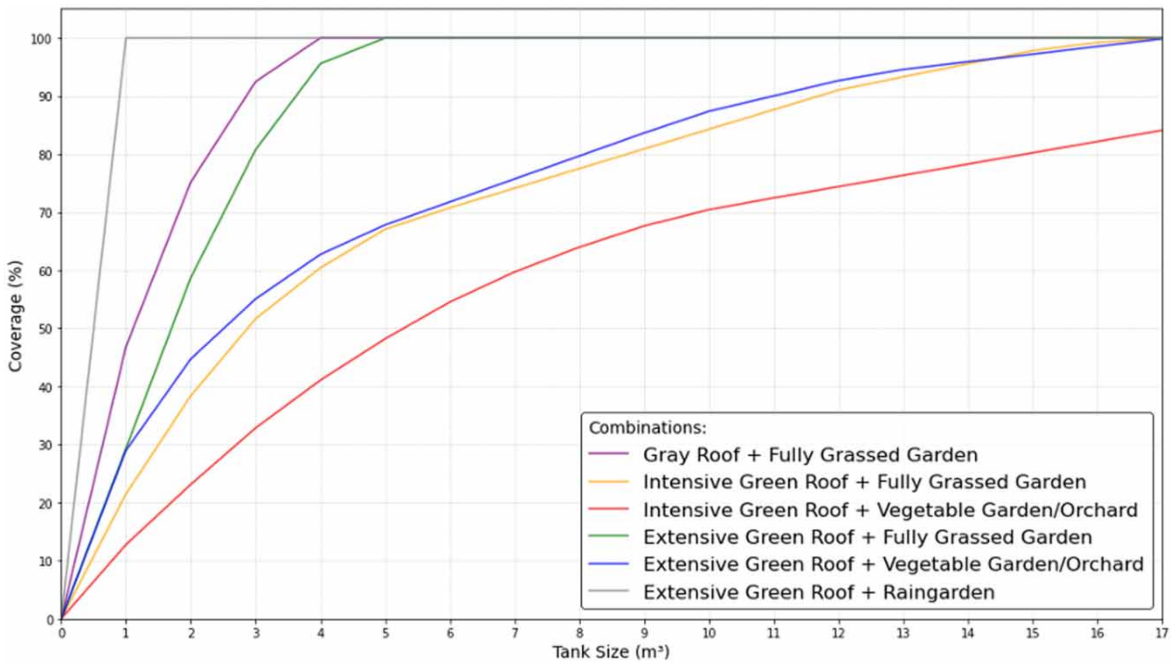

Figure 5 | BGI combinations efficiency: additional external water demand coverage (%) by tank size (m^3).

Configurations with extensive green roofs paired with a raingarden or orchard achieve high coverage with relatively small tank sizes. Setups with intensive green roofs and orchards demand significantly larger tanks to reach a similar coverage level. Fully grassed gardens, paired with either a gray or an intensive green roof, require moderate storage, offering a balance between water efficiency and a greener household.

4. DISCUSSION

The results demonstrate that extensive greenery notably increases water demand, particularly during dry periods. As drinking water consumption in the Netherlands is already approaching production capacity (Baggelaar & Kuin 2022), relying on drinking water to meet this additional demand is not advisable. In fact, the Dutch government aims to reduce per capita daily water consumption to limit the pressure on the water resources. Consequently, this additional water demand needs to be covered locally through stormwater-harvesting strategies. Implementing these solutions, however, can be challenging in small urban plots where space for both BGIs and water storage is limited. This tension underscores the need for thoughtful planning in urban water management to ensure sustainable use of water resources.

Our findings indicate that under projected climate conditions, the 'Greenest' household setup on a 100 m^2 plot would need an additional 154.3 L/day. This exceeds the current average indoor use of a typical four-person household, which is 129 L/day (CBS 2023). More realistic model scenarios, representing commonly used household setups, show significantly lower water demands. Households with a gray roof and a garden with native plants need 8.4 L/day; a gray roof combined with a fully grassed garden requires approximately 9.9 L/day of water to maintain the livability benefits of greenery. This underscores the challenge of sustaining BGIs with substantial greenery solely through precipitation and highlights the need for accessible water sources to maintain effective evaporative cooling. Consequently, alternative water management strategies are crucial for the upkeep of BGIs, as noted in previous studies (Back *et al.* 2021). This challenge is further complicated by the current gap in understanding the specific water requirements for urban plant maintenance, especially during droughts.

While water requirements exist for forestry and agriculture, they are not fully applicable to urban settings. These guidelines are typically linked to growing seasons when crops and trees require more water, especially during the development of new plants (Allen *et al.* 2020). Water needs vary throughout the season, increasing as crops grow to their maximum development and then tapering off as they mature toward harvest (Pereira *et al.* 2021). Irrigation recommendations to use one-tenth of the reference evaporation often fall short for new plants, highlighting the significant difference in water needs between young and mature vegetation (Costello *et al.* 2000). In urban environments, water demand is relatively steadier, dominated by mature trees and plants. Applying agricultural and forestry standards could lead to overuse of water resources, as these guidelines are designed for different plant growth stages.

In agriculture and forestry, irrigation focuses on maximizing plant growth and yield. In urban areas, especially during drought, the priority shifts to sustaining plant life, requiring a more sustainable and strategic approach. The goal is to apply the minimum water necessary to sustain plant health or reduce the UHI effect, avoiding the overuse of water resources. Defining a critical threshold before plants reach the wilting point is essential for efficient water management. Recent ecohydrology studies reveal that plant responses to water availability are non-linear, so that minor changes in the water supply can significantly impact plant health. This response depends on internal plant hydraulics, such as xylem vulnerability, as well as soil water conductivity, which is crucial for triggering stomatal closure during droughts (Carminati & Javaux 2020). Drought effects tend to peak in midsummer when soil moisture is most likely to be depleted, intensifying water stress and exacerbating the UHI effect. Identifying minimal water ranges to mitigate UHI may be the most effective way to reduce vapor pressure deficit and reduce plant water stress (Zipper *et al.* 2017). Understanding this complex soil-plant hydraulic interaction offers valuable insights for optimizing greenery selection and water management strategies for various BGIs.

One limitation of our research is the reliance on standardized parameters for various BGI. This approach provides an overview of 14 BGI types rather than focusing on individual systems. Vegetation was categorized into four groups: grass, native plants, exotic plants, and orchards. This categorization enables us to assess overall greenery performance in relation to different crop factors and water demand without enquiring into the specifics of individual species. While this simplification enhances model efficiency, a sensitivity analysis would help assess the impact of using average values.

We applied a simplified mass balance model to calculate the BGI influence on a household water balance. While suitable for small-scale insights, this model may overlook complex hydrological processes at larger scales due to spatial complexity.

For future research, we will consider more advanced models, such as the SWMM-UrbanEVA model (Hörnschemeyer *et al.* 2021), to expand the analysis to larger spatial areas like streets or neighborhoods.

While the model used in this study assumes that PET is fully met each day, which helps standardize comparisons across configurations. However, it may overestimate water demand in some real-world applications, especially for BGI systems designed to operate under limited water availability. In practice, many green roofs can withstand extended dry periods without irrigation. For example, sedum species reduce evapotranspiration as soil moisture decreases. This allows them to maintain functionality without external inputs. Field observations show that actual evapotranspiration rates decline in proportion to available soil moisture, particularly during prolonged droughts (Gobatti *et al.* 2023).

To address this limitation and enhance model accuracy, we are currently conducting an experimental study to explore plant–water management strategies under drought conditions, using mixed flowering grasses commonly applied in wadi systems. The experimental setup includes compartments with varying soil moisture conditions: one with a fixed water table, one maintained near the wilting point, and one with a freely fluctuating water table. This research aims to deepen our understanding of drought response dynamics and improve the accuracy of BGI modeling under changing climatic conditions.

5. CONCLUSION

This paper presents a comprehensive overview of the impacts of various BGI solutions on an urban water balance and associated co-benefits at the household level, considering climate projections in the Netherlands. Our results highlight the link between intensifying urban greenery and water demand. Insights from this study can assist municipalities, water boards, and residents in balancing co-benefits with sustainable water use. The main conclusions of this study can be summarized as follows:

(1) In urban water management, our usual concern is handling excess water efficiently with well-designed sewer systems or BGI. During drought periods, the importance of precipitation discharge processes takes on a different dimension. The focus shifts from managing excess water during rain events to preserving it, strategically using the scarce water resources for BGI maintenance during drought periods.

(2) The balance between the water demand and co-benefits highlights the challenge of effective BGI implementation. By carefully selecting BGIs that align their evaporation rates and water retention capacities, among other parameters, we can optimize or avoid the need for external water storage to meet the water demand. This approach maximizes co-benefits sustainably and helps prevent the overuse of drinking water for plant irrigation.

(3) While irrigation norms exist for agriculture and forestry, the specific water requirements for urban greenery remain largely underexplored. Understanding these water ranges is essential for optimizing BGI's performance and strengthening urban water management strategies, preventing the overuse of water during droughts. By identifying water ranges, we can prioritize our objectives, whether to maximize the cooling effects of intensified greenery or to ensure plant survival. Closing this knowledge gap will be the next step in advancing this research. In limited urban environments, understanding these processes will help to use water resources efficiently, and to optimize the size of water harvesting facilities, while maximizing urban greenery.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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