

Article

The Potential of Stormwater Management in Addressing the Urban Heat Island Effect: An Economic Valuation

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Abstract: Urban green infrastructure (UGI) within sustainable stormwater management provides numerous benefits to urban residents, including urban heat island (UHI) mitigation. Cost–benefit analyses (CBA) for UGI have been conducted at neighborhood level with a focus on stormwater management, but valuations of reductions in heat-related hospitalizations and mortality are lacking. These benefits create significant social value; the quantification thereof is essential for urban planning in providing a scientific foundation for the inclusion of UGI in UHI mitigation strategies. This study assesses the potential of three UGI scenarios developed for an urban neighborhood in Berlin, Germany. First, climate data analyses were conducted to determine the cooling effects of tree drains, facade greening, and green roofs. Second, a CBA was performed for each scenario to value UHI mitigation by estimating the damage costs avoided in reduced heat-related hospitalizations and fatalities, using the net present value (NPV) and benefit–cost ratio (BCR) as indicators of economic feasibility. The results indicate heat mitigation capabilities of all three UGI types, with tree drains achieving the strongest cooling effects. Regarding economic feasibility, all scenarios achieve positive NPVs and BCRs above one. The findings confirm the potential of stormwater management in mitigating UHI and generating substantial social value.

Keywords: stormwater management; urban heat island; cost–benefit analysis; ecosystem services; urban green infrastructure



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1. Introduction

Urbanization combined with rising frequency and intensity of heat events as a result of climate change leads to increased occurrence of the so-called urban heat island (UHI) effect. This well-recognized phenomenon has been widely described in the literature and refers to increased ambient temperatures in heavily built-up urban environments as compared to rural areas [1]. The development of UHIs within cities are attributed to higher shares of sealed surfaces [2], for example, buildings and streets [3], and further exacerbate other urban issues such as stormwater management [4]. Moreover, building materials often absorb more heat during the day due to low solar reflectance, which is then emitted as thermal radiation during the night, reducing cooling phases between periods of daytime heat stress [5–7]. Average daytime UHI intensity recorded for European cities is currently 2.6 °C above temperatures in surrounding areas [8].

Besides the development of UHI as a result of urbanization, stormwater management becomes a pressing issue. Conventional solutions to stormwater management in dense urban areas attempt to convey stormwater quickly from the source to nearby water bodies or wastewater treatment plants [9]. Often, separated sewer systems are installed to convey the stormwater directly into nearby water bodies, carrying along polluting elements such as dust, heavy metals, and organic trace substances from construction and transportation [10]. Sustainable stormwater management is one alternative strategy to retain stormwater at the source and replicate natural processes in the water cycle, often referred to as sustainable urban drainage systems (SUDS) [11]. Such systems not only reduce stormwater runoff and

improve receiving river water quality [12] but also allow for the creation of numerous additional ecosystem services, which when monetarily valued provide substantial benefits that can outweigh the costs of installing and maintaining them [13]. With such a management approach, planners can instill multifunctionality in the planning process [14,15], addressing both stormwater management issues as well as numerous other issues such as the UHI effect [16]. In terms of mitigating UHI effects, measures within the framework of SUDS including tree drains (tree drains, or tree trenches, allow for the temporary storage and quicker infiltration of stormwater [17]), green roofs and façade greening provide substantial contributions and are further termed urban green infrastructure (UGI) [18].

UGI mitigates the UHI effect by offering heat regulation services through shading, evapotranspiration and thermal insulation of buildings [5,19–21]. Economic analyses of UGI have been conducted for individual measures, frequently with a focus on water management, e.g., [20–24]. Perini and Rosasco [25] also performed a monetary valuation of facade greening benefits such as heat regulation and air quality improvements. A complete analysis of UHI-related economic impacts on city scale has been carried out for Melbourne, Australia by Raalte et al. [26]. However, to date, the evidence of human health impacts of UGI in stormwater management is lacking [27], and only one study by Johnson and Geisendorf [13] assesses the economic performance of UGI measures on neighborhood level in Germany. The authors focus primarily on the valuation of ecosystem services ranging from water management to air quality improvement, but do not address heat regulation benefits provided by UGI. The purpose of the current study is to build on Johnson and Geisendorf's [13] study by quantifying the UHI mitigation effect of UGI for stormwater management and estimating the economic value of these temperature regulation benefits by identifying the damage costs avoided through reductions in heat-related hospital admissions and excess mortality. Three different UGI scenarios for a neighborhood in Berlin, Germany are compared to assess the potential of stormwater UGI to create net benefits for society by reducing urban dwellers' heat stress exposure. As the analysis is based on an actual management exercise within a research project that was developed for the Berlin study site, the calculation of UHI mitigation benefits can support the real planning process by providing quantitative information for objective evaluation of the different measures and scenarios and induce stakeholders to support the implementation of those UGI measures that create the highest net benefits for society.

2. UHI and Valuation

The UHI effect causes many negative impacts on urban life, resulting in high social and economic costs. Among the most commonly discussed effects are work productivity losses [28,29], increased energy consumption for indoor cooling [7,25], as well as increases in morbidity and mortality rates [5,30–32]. Heat-related mortality in particular represents a significant factor in UHI-related costs to society. Scherer et al.'s [32] comparison of approximately 1600 annual heat-related deaths in Berlin to an average of 64 road traffic fatalities in the German capital accentuates the topic's relevance and consequently the necessity for sustainable UHI mitigation strategies.

The effectiveness of UGI in lowering urban temperatures is well documented. Temperature regulation can be supplied by UGI mainly through evapotranspiration and shading, but also thermal insulation [8,20,21,33], and can be achieved in critical areas through tree drains supplemented with facade greening and green roof installation where space is limited. These measures not only positively impact the ambient air temperature [34] but also the indoor cooling loads [35], and the need for effects in urban areas have been apparent. For instance, Larondelle and Lauf [20] conducted a study investigating the supply and demand for different urban ecosystem services provided by UGI in Berlin, Germany. The demand for such services was found to be higher the more densely concentrated the infrastructure (e.g., in city centers). Moreover, Simperler et al. [36] found that areas in Berlin with high UHI correlated highly with areas also generating significant stormwater pollution and that UGI measures can combat both challenges at once. Such measures

require substantial financial investments, underlining the need for objective economic valuation of non-marketable goods such as heat regulation, in order to create transparency in policy making [37]. Although arguments against economic valuation as a comprehensive approach to encompassing the many facets of nature's value have their legitimacy [38,39], we see the importance of including monetary valuation of ecosystem services in enabling cost-efficient urban planning processes [40].

As the present analysis incorporates private and social elements, ecosystem services and health-related impacts over time, a brief discussion on discounting is warranted. We adopt a dual discounting scheme to discount private and social costs and benefits separately [41]. Although there are ethical concerns regarding the use of exponential discount rates [42], we do not pursue a hyperbolic discounting scheme since the impacts are analyzed over a shorter time horizon than typical climate-economic models that extend beyond the end of the current century [43]. The 3% discount rate for private costs and benefits is the same rate used in the KURAS project [44] and suggested by the German Association for Water, Wastewater and Waste for use in German economic analyses [45]. We use a lower 2.1% discount rate for ecosystem services accruing as social benefits, in light of recent research on the proper discount rates to be used for ecosystem services [46,47]. This rate is also used for health-related impacts, which resembles the rate suggested by Attema et al. [48]. However, it should be noted that there are grounds for discounting health-related impacts with a zero-discount rate, as society may place little to no difference in weight on future lives saved [49,50].

3. Materials and Methods

This study assesses the economic value of reductions in heat stress by three UGI scenarios on a neighborhood level while incorporating the monetary valuation of ecosystem services. First, the analysis is based on climate data from the KURAS project ("Concepts for urban stormwater management and sewer systems"; German: "Konzepte für urbane Regenwasserbewirtschaftung und Abwassersysteme", <http://www.kuras-projekt.de/> (accessed on 17 July 2017)) [12], funded by the German Federal Ministry for Education and Research. The project modeled an urban neighborhood within the district of Pankow, Berlin, which is the site for current investigation. The second part of the analysis concerns the economic valuation of the results obtained from the climate data analysis. The UHI mitigation effects of UGI for the three scenarios are combined with demographic statistics as well as heat-related morbidity and mortality data from the literature to calculate UHI mitigation-related benefits. Other UGI benefit and cost calculations for the Berlin study site were also taken from existing literature to supplement the UHI mitigation benefit data.

3.1. Study Site

The Berlin neighborhood is a residential area of 117 hectares within the urban district of Pankow, characterized by a combination of multi-story apartment buildings from the 1920s and 1930s, and higher residential buildings from the post-war period [44]. In terms of demographic indicators such as population density and age structure, it represents a typical Berlin neighborhood. Although the KURAS project focused on stormwater management and therefore included measures such as swales and ponds, the UGI measures relevant for this study were part of the project scope, and their effects could be isolated for the purpose of the benefit calculations. Moreover, we align the economic valuation of ecosystem services for the three UGI scenarios designed in the KURAS project according to the methodology described in Johnson and Geisendorf [13].

The KURAS project partners developed three independent scenarios for the implementation of urban stormwater management measures, including UGI, based on local requirements—for example, improving groundwater management, urban climate, and biodiversity—as well as stakeholder priorities and feasibility [44]. The creation of different scenarios allows identification of the most efficient UGI placement, which is an important factor because the strategic implementation of UGI measures in key areas yields better

results than simply increasing the share of green cover [21]. Furthermore, the scenarios were developed independently of one another within separate groups of stakeholders, planners and interest groups. Figure 1 shows the placement of UGI measures as part of the stormwater management scenarios.

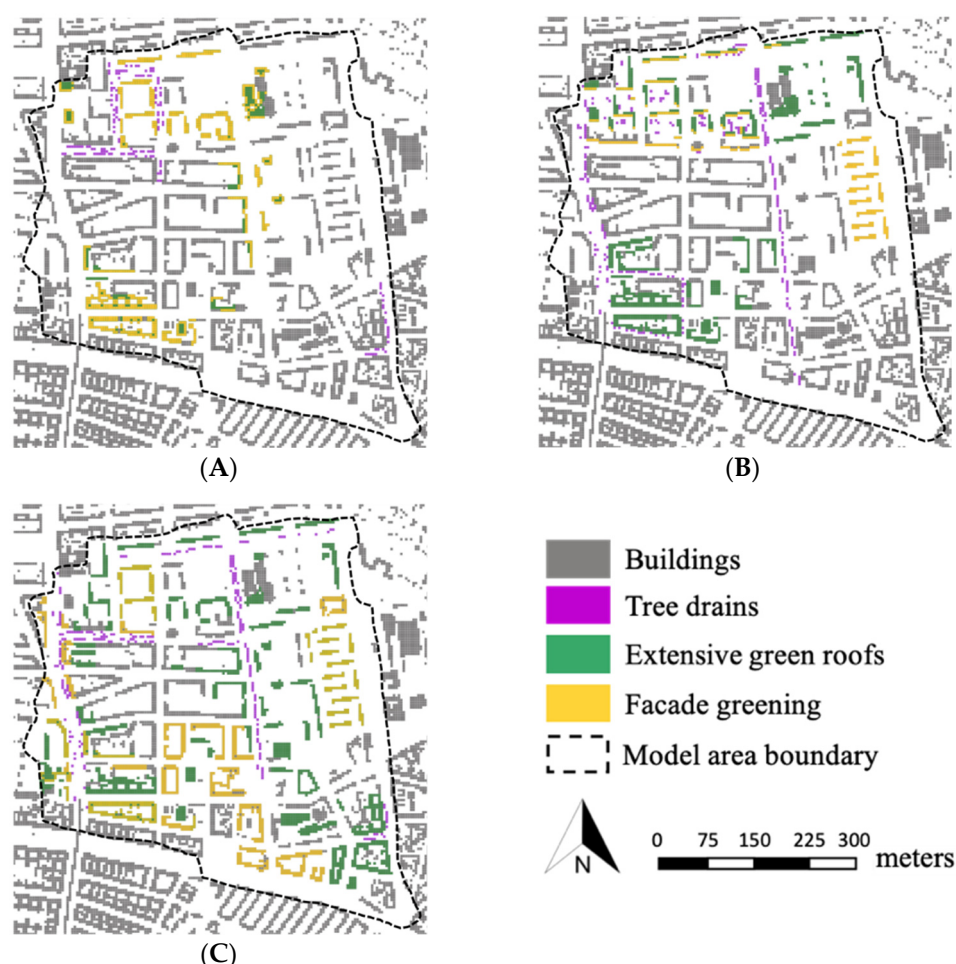


Figure 1. Placement of UGI measures for stormwater management scenarios (A–C).

Whereas Scenario A is characterized by the lowest coverage of greening, Scenario C is characterized by the highest overall greening coverage. In particular, Scenario C receives more façade greening and extensive green roofs than the other two scenarios, and the level of tree drain coverage is only slightly lower than Scenario B. Although Scenario B has a higher coverage of tree drains and extensive green roofs than Scenario A, the application of façade greening is greatly lower than in the other two scenarios, which significantly lowers the overall costs as seen below in Section 4.2.

3.2. Climate Data Analysis

The KURAS climate data that were evaluated for the current study is organized in a Cartesian coordinate system with $8\text{ m} \times 8\text{ m}$ grid cells. A value attached to each grid cell represents how the specific space is being used, that is, if the area is covered with buildings, streets, other (partially) sealed surfaces such as parking lots or railways, or if green or blue spaces such as grass, trees or ponds are present. Additionally, climate data for each grid cell is available with temperatures measured at a height of 2 m (i.e., pedestrian level), showing diurnal heat stress measured in hours per year. For categorization of daytime heat stress, the universal thermal climate index (UTCI) was selected, including UTCI classes strong heat stress (SHS; $>32\text{ °C}$ – 36 °C), very strong heat stress (VSHS; $>36\text{ °C}$ – 46 °C), and extreme

heat stress (EHS; >46 °C). This selection is consistent with the German Meteorological Service's (German: "Deutscher Wetterdienst", DWD) policy of issuing heat warnings above temperatures of 32 °C [51]. Daytime heat stress, that is, UTCI in hours per year, for the current situation in the Pankow study site is shown in Figure 2.

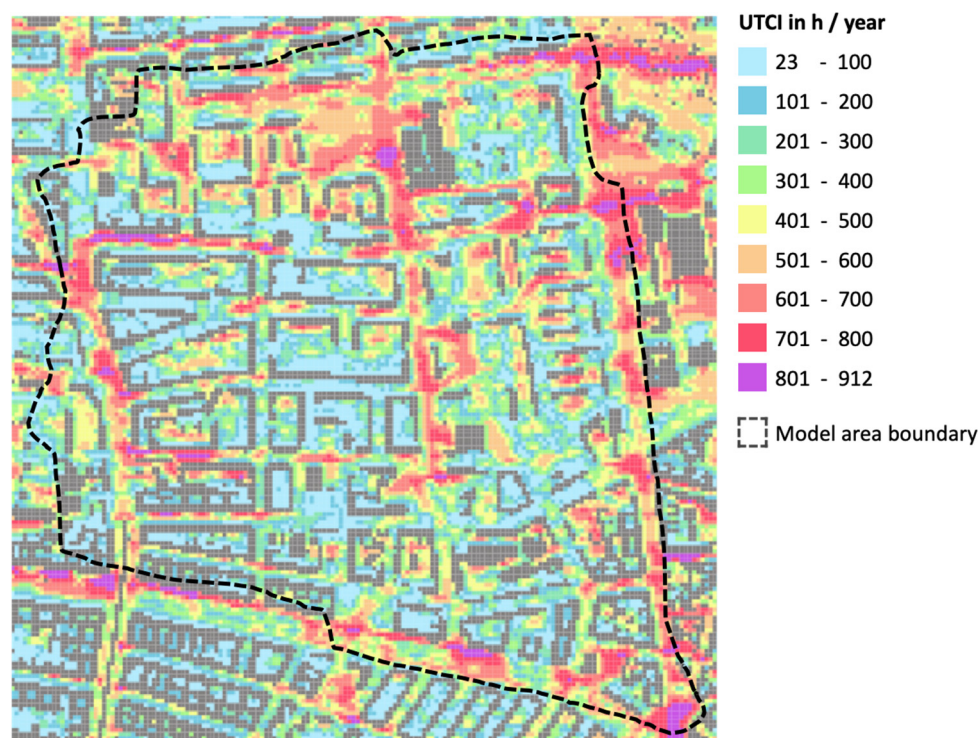


Figure 2. Heat stress in the current situation for the study site in Pankow, Berlin.

For all three scenarios, the grid cell values show where stormwater management measures were added. These measures include extensive green roofs, facade greening, urban trees, swales, swale-trench systems, swale-trench beds, ponds, permeable pavement, rainwater harvesting cisterns, and retention soil filters. R software [52] was used to filter out only those grid points where UGI (i.e., tree drains, facade greening, or green roofs) was added. Temperature differences were then calculated for these grid points as compared to the base scenario, specifically extracting minimum, maximum and mean temperature changes achieved by each UGI type, expressed in UTCI.

3.3. Economic Valuation

UHI mitigation effects achieved by UGI were valued in monetary terms. The damage costs avoided by lowering heat-related morbidity and mortality were combined with additional ecosystem services following the methodology of Johnson and Geisendorf [13]. Once quantified, those benefits were balanced against initial UGI installation costs as well as recurring maintenance and operation expenses taken from Strehl et al. [53]. In the final step, the resulting net benefits were calculated over a time span of 50 years and subsequently discounted to present value in order to obtain the NPV and BCR.

The first step in the monetization of UHI mitigation benefits was to calculate the share of the study site area covered with additional UGI in each of the three scenarios developed by the KURAS project. Next, the total heat stress reduction per scenario was calculated as the sum of all UTCI classes (i.e., SHS, VSHS, and EHS) and converted from hours per year to the number of hot days per year. This conversion was performed assuming an average of 16.03 h of daylight in Berlin for the months of June–August [54], which is the period during which most heat events and the majority of heat-related fatalities occur [32,55].

Demographic data from the German Federal Statistical Office (German: “Statistisches Bundesamt”) and Umweltatlas Berlin [56] were used to determine the number of residents that are reached by UGI measures in the Pankow neighborhood and consequently benefit from reduced heat stress and lower morbidity and mortality rates. The calculation method was modeled after a similar approach used by Bodnaruk et al. [19]: population data was first calculated on neighborhood level and then multiplied by the percentage of the model site area covered with UGI to obtain the number of residents who actually benefit from the additional green cover. Subsequently, the numbers of these citizens falling into the 0–74 years and 75+ years age groups were calculated based on the respective shares of 92.16% and 7.84% [57], since the latter age group has been found to be significantly more vulnerable to heat-related morbidity and mortality increases [28]. Different excess morbidity and mortality rates were consequently applied to both age groups. All demographic data used in the UHI mitigation benefit calculations is for the year of 2017. Using values from this single year rather than an average from a range of years was deemed appropriate because 2017 can be classified as a statistically average weather year: DWD climate summary reports for the years 2014–2018 reveal that all five years showed average annual temperatures of 1.4–2.2 °C above the international reference period of 1961–1990. The value for 2017 was 1.4 °C above average and no unusual number of heat events occurred during 2017 compared to the other years [58–62].

3.3.1. Reduced Heat-Related Morbidity

The demographic situation for the study site base scenario is as follows: According to Umweltatlas Berlin [56], the total population of the Pankow study site was 23,276 in 2017. A total of 21,451 of this number fall into the 0–74 age group with a 17.09% annual hospitalization rate for all causes, and the remaining population of 1825 are aged 75 years or older with a base hospital admission rate of 49.86%, consistent with hospitalization statistics for Germany [63].

Reductions in heat-related hospitalization cases by age group were calculated for each scenario using increases in morbidity rates for UTCI class SHS based on a study conducted by Johnson et al. [64] for the 2003 heat wave in England, and EHS morbidity rate increases as calculated by Hübler et al. [28] based on the data provided by Johnson et al. [64]. Excess morbidity for VSHS was not considered by either study, therefore linear extrapolation of moderate heat stress and SHS values from Johnson et al. [64] was used to determine the effect for VSHS. Total excess morbidity rates obtained in this manner amount to 1.82% for SHS, 2.91% for VSHS, and 3.99% for EHS. These values were then converted to a weighted average increase for hot days (i.e., days with average temperatures above 32 °C) by UTCI class incidence in the current situation, yielding relative morbidity increase rates of 0.76% for the 0–74 age group, and 16.93% for the 75+ age group. These rates were subsequently multiplied by the share of the model site population reached by UGI measures and applied to the reduction in hot days achieved by each UGI scenario as calculated from KURAS climate data.

Exact quantification of the costs related to heat-related hospitalizations is challenging as no data is available on treatment costs of heat-related illnesses in Germany [28,65]. Therefore, Hübler et al. [28] carried out an economic appraisal of the overall expenditures based on average hospitalization costs in Germany. According to the authors’ calculations, current heat-related hospitalization costs amount to EUR 82 million and will increase six-fold for the period 2071–2100, taking into account climate change as well as demographic changes such as population size and age structure. In relative terms, this figure represents 0.27% of total German healthcare expenses. Each prevented hospital admission case was estimated to account for an average of EUR 3300 in damage costs avoided, with the estimate referring to statistics on hospital treatment costs for heat-related illnesses [28,65].

We derive the estimated economic value of the reduced heat related morbidity (V_{morb}) in accordance with the damage cost avoided for age groups k (0–74 years) and K (75+ years):

$$V_{morb} = \sum_k^K Pop_{UGI,k} \cdot Morb_{2017,k} \cdot Morb_{heat,k} \cdot \frac{UTCI_{red,trees} + UTCI_{red,GR} + UTCI_{red,FG}}{365 \text{ days}} \cdot HC_{avg} \quad (1)$$

where $Pop_{UGI,k}$ is the number of residents reached by UGI in the specific age group (0–74 years: 4130 residents; 75+ years: 351 residents) [56], $Morb_{2017,k}$ is the base morbidity rate in 2017 for the specific age group (0–74 years: 17.09%; 75+ years: 49.86%) [63], $Morb_{heat,k}$ is the relative increase in heat-related morbidity rate for the specific age group (0–74 years: 0.76%; 75+ years: 16.93%) [28,64], $UTCI_{red}$ is the average reduction in UTCI exceedance in hours per year of cells by UGI (trees drains, *trees*; green roofs, *GR*; façade greening, *FG*), and HC_{avg} is the average hospitalization cost.

3.3.2. Reduced Heat-Related Mortality

Mortality cases in the current situation were calculated using the base mortality rate of 1.04% for Germany [66]. The base mortality rate was adjusted for seasonality, taking into account that winter mortality has been found to be 8% higher and summer mortality 8% lower than the annual average [28]. Reduced mortality for each scenario was determined by applying a heat-related excess mortality rate of 5% [32] to the base mortality rate and multiplying the result with the number of model site residents reached by UGI cooling effects, as well as the reduction in number of hot days as calculated from UTCI data (Table 3). Based on data from the 2003 European heat wave, 20% of the mortality reduction was attributed to the 0–74 age group, while the remaining 80% were assumed to occur in residents aged 75 years and older [28]. In order to express the value of these avoided deaths in monetary terms, population percentages by age were used to break down the average life expectancy in Germany of 78.81 years to the average number of life years lost per death, yielding 49.88 years for the 0–74 age group and 5.76 years for the 75+ age group [57,67,68].

Each lost year of life was valued at EUR 95,653 based on dividing the VSL for Germany (EUR 7.538 million), as estimated by Viscusi and Masterman [69], by the current average life expectancy. Viscusi and Masterman [69] provide the most up to date VSL by taking a base VSL derived through a meta-analysis of revealed preference data from hedonic wage studies and income elasticity for the U.S. and estimating country-specific VSLs. Although the OECD [70] proposes a base VSL of approximately USD 3.6 million (2005 dollars), this estimate is based on stated preference data, whereas Viscusi and Masterman [69] discuss the disadvantages of the OECD [70] values and base their data on revealed preferences to mitigate hypothetical bias. In order to account for uncertainty in such a large VSL, we test for sensitivity of the cost–benefit model to the VSL by incorporating the Germany-specific VSL estimate from Spengler [71] of EUR 1.978 million as a minimum value.

We derive the estimated economic value of the reduced heat related mortality (V_{mort}) in accordance with the damage cost avoided for age groups k (0–74 years) and K (75+ years):

$$V_{mort} = \sum_k^K Pop \cdot M_{2017} \cdot M_{heat,k} \cdot d_{season} \cdot UGI \cdot \frac{UTCI_{red}}{UTCI_{current}} \cdot (LE_k - AGE_{avg,k}) \cdot VOLY \quad (2)$$

where Pop (23,276 residents) is the population in the study site in 2017 [56], M_{2017} (1.13%) is the base mortality rate of Germany in 2017 [66], $M_{heat,k}$ is the excess heat-related mortality rate (5%) in Berlin [32] given the 0–74 age group (4%) and 75+ age group (1%) [28], d_{season} is the adjustment for seasonal mortality (i.e., summer mortality 8% lower and winter mortality 8% higher than annual average [28]), UGI is the share of the study site area (%) to be complemented with UGI, $UTCI_{red}$ is the average reduction in UTCI exceedance in hours per year of cells with UGI, $UTCI_{current}$ is the current average UTCI exceedance in the cells with UGI, LE is the average life expectancy for the specific age group, AGE_{avg} is average age of residents in the age group, and $VOLY$ is the value of life year derived from the average life expectancy (78.8 years [66]) and the inflation-corrected VSL of EUR 7.538 million [69].

3.3.3. Ecosystem Service Valuation

The UGI measures in this study bring about numerous additional ecosystem services. The methodology for economic analyses of these ecosystem services is described by Johnson and Geisendorf [13], and the applicable results from their research were included in the CBA performed for this study.

The ecosystem services valued for UGI in this study included reduced stormwater runoff [10], increased building longevity [72], habitat creation [73], increases in building value (aesthetic improvements) [74], heating and cooling savings [72], and pollution [75] and carbon dioxide (CO₂) reduction [25]. For example, green roofs and tree drains directly contribute to reducing loads on municipal treatment plants. Berlin charges a rainwater fee for sealed surface at 1.804 EUR/m² for home and property owners, but this fee can be reduced by 50% for such UGI measures [76]. We assume that tree drains provide additional stormwater retention for 250 m² area on average.

The remaining relevant benefits could be completely attributed to UGI implementation and were therefore computed directly according to Johnson and Geisendorf [13]: longevity increases apply to green roofs and facades, which can be replaced or restored at larger intervals compared to conventional roofs and facades due to the building materials' protection against weathering by greening. Habitat creation benefits are added by green roofs and could therefore also be transferred entirely. The same was true for aesthetic improvements achieved by facade greening, heat savings and avoided heat externalities resulting from green roof installation, as well as cooling effects of green roofs and facades. Air quality improvement calculations were equally based on UGI effects only. They include pollution removal by all UGI types, and carbon storage and sequestration by tree drains and green roofs.

3.4. Cost–Benefit Model

Unit investment costs as well as operation and maintenance costs for the three UGI types were taken from an interim report presenting the economic side of the KURAS project [53], as well as Johnson and Geisendorf [13], and used to calculate total costs of UGI measures implemented in each scenario. The unit costs for each measure are shown in Table 1. Tree drains are clearly the most expensive UGI type to install, but operation and maintenance costs are lower than for the other two measures. Green roofs are a low-cost choice both in terms of installation and running costs, while facade greening generates the second-highest installation costs as well as the highest annual costs.

Table 1. Unit installation (I)/annual operation and maintenance (O&M) costs of the three UGI types.

	I (EUR/m ²)	O&M (EUR/m ²)
Extensive green roofs	20	1.50
Facade greening	100	10.00
Tree drains	303	1.21

Benefits gained from lowering morbidity and mortality rates as a result of reduced heat stress were added to the additional ecosystem services. The economic analysis was calculated over a project horizon of 50 years, reflecting the typical lifetimes of UGI measures: green roofs are estimated to need replacement after 40–55 years, green facades after 40–45 years, and trees can remain in place for several decades beyond this time horizon [25,72]. Both the NPV and BCR were selected as indicators for economic comparison of the three scenarios. When the NPV of a project is greater than zero, or the BCR greater than 1, this indicates that the present value of all benefits outweighs the sum of the discounted costs over the project period, and pursuing the project is an economically sound option. Future costs and benefits were discounted to present value following the discounting regime described in Section 2.

3.5. Sensitivity Analysis

A sensitivity analysis was performed to test the sensitivity of the results to changes in the parameters of cost–benefit model. According to the European Commission [77], if a 20% change in a project parameter leads to a 20% change in the NPV, the NPV is assumed to be sensitive to the parameter. Johnson and Geisendorf [13] demonstrated that the NPV may be sensitive to the installation and maintenance costs as well as the property value increases due to green roofs. Given the VSL and discount rate may produce significant effects on the NPV, we additionally included these parameters in the sensitivity analysis.

The sensitivity analysis was performed in the form of a Monte Carlo analysis with 10,000 iterations of repeated drawings from distributions of the parameters for which the NPV can be sensitive. We varied the parameters according to distributions in Table 2.

Table 2. Input parameters and distributions for the Monte Carlo simulations with U(minimum, maximum) as a uniform distribution, N(mean, standard deviation) as a normal distribution and T(minimum, maximum) as a triangular distribution.

	Distribution and Parameters	Units
Installation costs	U(−20, +20)	%
Operation and maintenance costs	U(−20, +20)	%
Property value increase in green roofs	U(2, 5)	%
Heat-related mortality rate	N(5.2, 1.3)	%
Value of statistical life	T(1,978,165, 7,538,485)	EUR
Private discount rate	U(1, 5)	%
Social discount rate	U(0, 3)	%

Since the installation and operation and maintenance costs of the scenarios were partially determined through general and site-specific cost estimations, we assume a range of costs at $\pm 20\%$ for each of the scenarios. For the property value increases in green roofs, we assume an increase in building values in the range from 2–5% based on the study by Bianchini and Hewage [74]. For heat-related mortality, we follow the mean and standard error values given in Scherer et al. [32]. The VSL follows a triangular distribution because the Viscusi and Masterman [69] estimate is the most likely (also the maximum), although we acknowledge prior studies [71] estimating the Germany-specific VSL be much lower (minimum). The range of private discount rates used follow those tested in Johnson and Geisendorf [13], and the social discount rates are assumed to follow a uniform distribution but only maximizing to the private discount rate for a given iteration of the analysis.

4. Results

A visual representation of the UHI mitigation in each of the three scenarios can be seen in Figure 3. Results of the climate data analysis including minimum, maximum and mean reductions in UTCI by UGI measure and for each scenario are summarized in Table 3.

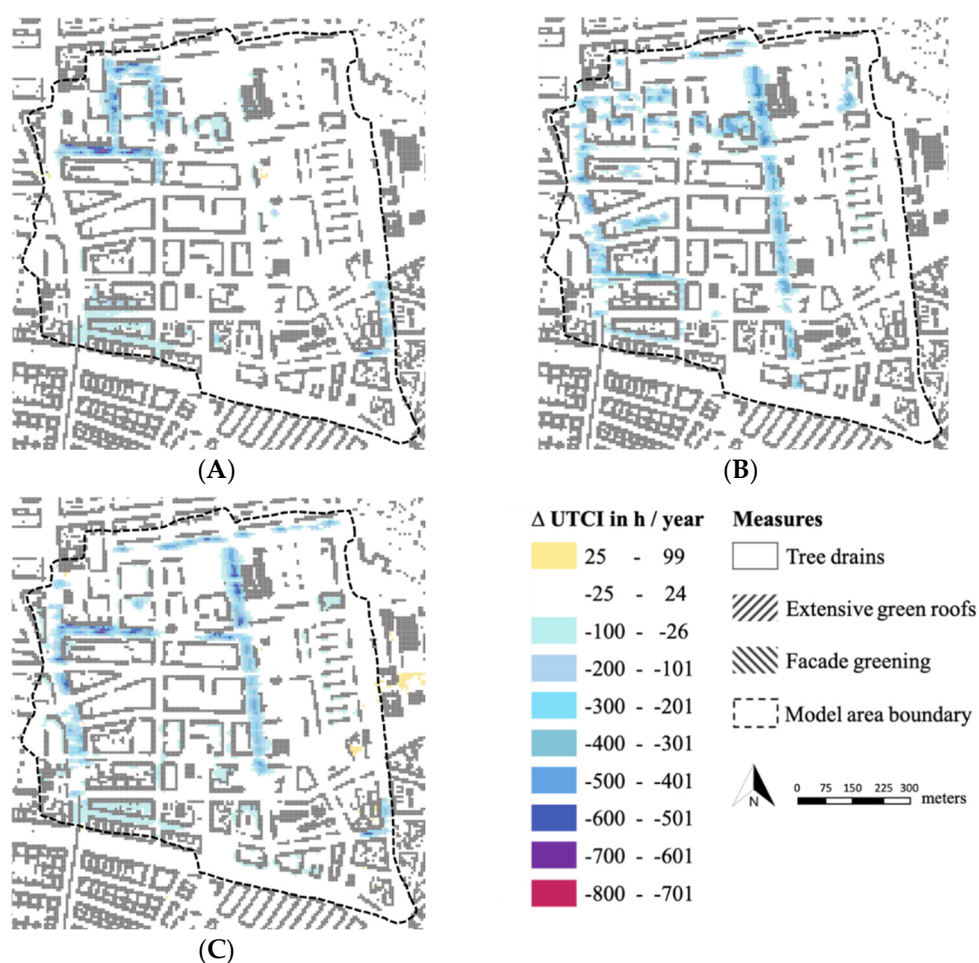


Figure 3. Changes in heat stress as reduced hours of UTCI exceedance for each of the scenarios, (A–C) is a visual representation of the UHI mitigation in each of the three scenarios.

Table 3. Changes in UTCI following the implementation of UGI measures for the three scenarios.

Scenario	UGI Measures	Areas	Change in UTCI (hours/year)		
			Min	Max	Mean
A	Tree drains	5341	−711.49	0.00	−319.52
	Extensive green roofs	58,515	−380.80	96.10	−10.94
	Facade greening	199,880	−380.80	96.10	−12.67
B	Tree drains	10,631	−593.14	0.00	−221.59
	Extensive green roofs	72,926	−316.5	19.18	−8.98
	Facade greening	79,008	−76.78	10.34	−3.01
C	Tree drains	10,118	−669.00	0.00	−285.71
	Extensive green roofs	121,658	−297.40	37.84	−4.68
	Facade greening	290,732	−230.21	22.08	−5.73

Comparing the effects of the different UGI measures, tree drains generally achieve the highest mean daytime heat stress reductions, whereas facade greening and green roofs perform at similar, lower levels across the three scenarios. Using mean heat stress reduction values and assuming an average of 16.03 daylight hours per day for the heat event season from June to August in Berlin, Scenario A experiences 21.41 fewer hot days compared to the current situation; Scenario B 14.57 days; and Scenario C 18.48 days.

4.1. Economic Valuation

The UGI benefits are shown in Table 4, with all benefits calculated over the project time horizon of 50 years and discounted at 3% for private benefits and 2.1% for social benefits.

Table 4. Present value (EUR) of all benefits over the 50-year time horizon discounted at 3% for private benefits and 2.1% for social benefits. Benefits provided by tree drains (TD), extensive green roofs (GR), and façade greening (FG). Valuation methods include damage cost avoided (DCA), market price (MP), replacement cost (RC), and benefit transfer with hedonic pricing (BT).

	Benefits	Provided by	Valuation Method	Type of Benefit	Scenario A	Scenario B	Scenario C
UHI Mitigation	Heat-related mortality reduction	TD GR FG	DCA	Social	35,057,726	20,436,515	34,460,982
	Heat-related morbidity reduction	TD GR FG	DCA	Social	208,386	95,900	270,181
Ecosystem services	Runoff reduction	TD GR	MP	Private	2,309,569	3,520,134	4,575,692
	Increasing building longevity						
	Roof longevity	GR	RC	Private	1,732,711	2,159,438	3,602,475
	Façade longevity	FG	RC	Private	8,985,805	3,551,884	13,070,148
	Habitat creation	GR	RC	Social	474,941	591,909	987,449
	Aesthetic improvements						
	Property value (w/façade greening)	FG	BT	Private	14,038,596	8,896,971	18,522,905
	Property value (w/green roof)	GR	BT	Private	20,050,658	24,988,683	41,687,285
	Energy savings						
	Heating savings	GR	MP	Private	1,842,809	2,296,651	3,831,380
	Cooling savings	GR FG	RC	Social	462,488	474,455	886,747
	Heating externalities	GR	DCA	Social	1,098,200	1,368,662	2,283,265
	Air quality improvements	TD GR FG	DCA	Social	392,520	311,150	682,411
	CO ₂ storage and sequestration	TD GR	DCA	Social	112,187	157,210	228,933
Totals					86,766,596	68,849,562	125,089,853

Regarding UHI mitigation benefits, heat-related hospitalizations are reduced by 2.05 cases per year for Scenario A, by 0.94 for Scenario B, and by the highest number of 2.66 cases for Scenario C. Heat-related morbidity reductions result in comparatively low monetary benefits, with Scenario C reaching the highest value of EUR 270,181 in damage costs avoided over the project horizon. In terms of mortality reduction, the results for Scenarios A and C are almost identical with 0.78 and 0.77 annual deaths avoided, respectively. For Scenario B, heat-related mortality cases are reduced by 0.46 per year, resulting in lower societal benefits for that scenario.

Combining both morbidity and mortality reductions, the results for both Scenarios A and C are similar, with the benefits of Scenario A being slightly higher at EUR 35,266,112 compared to EUR 34,731,163 for Scenario C. Scenario B achieved considerably lower UHI mitigation benefits of EUR 20,532,416. The similar performances of Scenarios A and C may initially seem surprising, particularly in view of the fact that Scenario C receives a much higher portion of additional green cover—28.92% of the entire study site area receive greening in this scenario, as compared to 19.25% for Scenario A. This means that a larger share of the population benefits from heat mitigation through UGI, which should result in higher UHI mitigation benefits for Scenario C. However, at the same time the mean heat stress reduction effect of UGI measures implemented in Scenario A is larger

(Table 3). The higher effectiveness seems to be due to particularly successful placement of UGI measures in areas affected by exceptionally strong heat stress. This finding is in line with the conclusion of Zölch et al. [21] who, as mentioned in the literature review, note that placing UGI in strategically advantageous areas is more important than aiming for sheer increase in volume.

When combining both UHI mitigation benefits and ecosystem services, the resulting total UGI benefits of the three scenarios were as follows: Scenario C performed best with EUR 125,089,853; even though UHI mitigation benefits are comparable with those of Scenario A, the other benefits tip the balance in total benefit calculations. Scenario A follows with considerably lower total benefits of EUR 86,766,596, and Scenario B amounted to EUR 56,831,176. UHI mitigation benefits contributed a share of 41%, 30%, and 28% to the total benefits of Scenarios A, B, and C, respectively, with only aesthetic improvements achieving higher contributions for Scenarios B and C. This identifies heat regulation as one of the main contributing factors in UGI benefit generation.

4.2. Cost–Benefit Analysis

Comparing the three scenarios' costs as calculated over the entire project time horizon (Table 5), it is clear that Scenario C is the costliest to implement and maintain with total costs for installation as well as operation and maintenance. These high costs can be explained by the much higher area to be covered with additional UGI measures for Scenario C as compared to the other two scenarios, particularly with regard to facade greening, which generates the highest operation and maintenance costs of all UGI measures (Table 1).

Table 5. Present value of all costs and installation (I) and annual operation and maintenance (O&M) costs of the three scenarios [54].

	Scenario A		Scenario B		Scenario C	
	I (EUR/m ²)	M (EUR/m ²)	I (EUR/m ²)	M (EUR/m ²)	I (EUR/m ²)	M (EUR/m ²)
Tree drains	1,618,348	5988	3,221,973	11,921	3,065,945	11,344
Extensive green roofs	1,170,294	87,772	1,458,511	109,388	2,433,156	182,487
Facade greening	19,988,560	1,998,856	7,900,800	790,080	29,073,220	2,907,322
Totals	22,777,202	2,092,616	12,581,284	911,389	34,572,321	3,101,153
Present value of all costs	76,619,718		36,031,108		114,364,256	

Table 6 shows the NPVs and BCRs of the three scenarios, combining both discounted costs (Table 5) and discounted benefits (Table 4) linked to each scenario. Scenario B clearly performed the best given the higher BCR and NPV. Despite greatly different implementation of UGI and corresponding costs, the performances of Scenarios A and C are very similar in both the NPV and BCR calculations and make the cutoff for economic feasibility. The significantly better performance of Scenario B despite its comparatively low benefit contribution is largely due to the fact that implementation costs for this scenario are by far the lowest. Scenario B included a high share of additional trees with tree drains, which are the costliest UGI type in terms of installation. However, tree drains are also the most inexpensive measure when it comes to operation and maintenance costs (Table 1), lowering the overall cost over the project life span. Scenario B also receives the lowest share of facade greening, which is the costliest measure in terms of operation and maintenance. In sum, these low costs compensate for the relatively low benefits to be gained from implementing Scenario B.

Table 6. Net present values (NPV) and benefit–cost ratios (BCR) of the three scenarios.

	Scenario A	Scenario B	Scenario C
NPV	EUR 10,146,769	EUR 32,818,400	EUR 10,725,544
BCR	1.13	1.91	1.09

The similar performances of scenarios A and C, even with Scenario C receiving a significantly higher share of UGI, can be traced back to the more efficient UGI placement for Scenario A mentioned above. This results in almost the same level of UHI mitigation benefits for both scenarios, which combined with lower costs for Scenario A ultimately leads to the slightly better performance of this scenario. In other words, Scenario A achieves the same level of UHI mitigation benefits at a much lower cost, meaning that benefits are reached in a more cost-effective manner. Nevertheless, both Scenarios A and C have low BCRs, which becomes a relevant factor in the sensitivity analysis presented in 5.3. This leaves Scenario B as the most robust option; while the scenario generates lower benefits than the other two, the discounted costs are also substantially lower, resulting in a higher positive net outcome and thus confirming that this scenario generates substantial value for society.

4.3. Sensitivity Analysis

A Monte Carlo analysis was performed with 10,000 draws from the given distribution of parameters in Table 2 to test the sensitivity of the NPV to the parameters. The number of draws is assumed to be amply large to obtain a random sample from each distribution with all possible combinations. We obtained probabilities of achieving an economically feasible result ($NPV > 0$) of 64%, 100%, and 63% for Scenarios A, B, and C, respectively. Therefore, the results are robust given the uncertainty of the tested parameters. Given that Scenario B would remain positive even with a significantly lower VSL estimate, we achieve a much higher likelihood of economic feasibility.

We also tested the probabilities of achieving the baseline NPV, which resulted in probabilities of 34%, 39%, and 40% for Scenarios A, B, and C, respectively. The triangular distribution of the VSL became a significant factor for these probabilities because the maximum VSL was already the estimate used for the baseline calculation. Additionally, the uniform distribution for a $\pm 20\%$ change in total installation and operation and maintenance costs lead to higher risks in terms of the likelihood of achieving a positive outcome. However, we maintain that the cost estimates provided by Strehl et al. [53] are already general costs estimates from the literature and expert estimations, and a 20% variation from these would likely gravitate to more extreme outliers.

5. Discussion

Statistical climate data analysis and CBA were used as methods for determining the effectiveness of three stormwater management scenarios developed for a neighborhood in Pankow, Berlin, in combating UHI effects and thereby creating value for society. The findings indicate two things: first, the climate data analysis reveals mean temperature reductions in locations where UGI measures were added, confirming that UGI measures in stormwater management can be effective in mitigating UHI effects. Secondly, lower morbidity and mortality rates resulting from this decreased heat stress created monetized benefits which contributed significantly to the positive economic performance of the three scenarios, allowing the conclusion that UGI measures can be implemented in an economically feasible manner.

The climate data analysis showed that UGI can be effectively employed to mitigate urban heat stress, with varying results depending on UGI type as well as strategic placement of measures. The results for all three scenarios generally match the findings of previous studies. For tree drains, the climate data analysis showed the highest daytime heat stress reductions of up to 711 h per year (Table 3). This is in line with the findings of existing literature, where trees are found to have the strongest heat mitigation effect which can even extend to several meters distance from the trees themselves [8,21,78]. Facade greening, by contrast, achieved considerably lower cooling effects; a maximum of 381 h in annual heat stress reductions could be confirmed. This pattern is also found in existing studies which are in general agreement that green facades contribute less to heat stress mitigation for residents, as the effect seems to be limited to the immediate proximity of the

walls [21,33,79]. One finding that could not be confirmed by the climate data analysis is the indoor cooling effect of facade greening, as the climate data were measured and simulated for outdoor areas only in the KURAS project. Green roofs reached cooling effects very similar to those of green facades, with the same maximum daytime heat stress reduction of 381 h per year. Existing literature offers mixed findings for the climate effects of green roofs, with some studies not finding any effect at street level, and others acknowledging very slight effects [7,8,21,31,65]. The effects that are revealed by the climate data analysis are mostly due to low roofs such as underground parking lots, but overall the UHI mitigation contribution of green roofs is low during the day [44].

Given the high heat-related benefits of the study, it is important to consider plausibility as few studies have empirically investigated the green cover and improved health outcomes relationship, i.e., [80]. The UHI mitigation benefits that were calculated for the study site, that is, reductions in heat-related hospitalizations and deaths, were tested for plausibility by extrapolating the CBA results to national level and comparing them with actual heat-related hospitalization and mortality statistics for Germany. For heat-related hospitalizations in Germany, 1856 cases were recorded in 2013, while 2003, the year of the European heat wave, resulted in 2561 hospitalizations [81]. Taking the maximum number of hospitalization cases avoided for the Pankow, Berlin study site, hospitalizations were reduced by 2.66 cases for a total of 23,276 residents. Linearly extrapolating this to a population of roughly 80 million for all of Germany yields a reduction of 9142 cases per year. This figure evidently exceeds the number of regular countrywide hospitalization cases by a factor of 4. Possible reasons for this could be that due to the UHI effect, urban dwellers are at a higher risk of suffering heat-related illnesses, leading to a higher share of hospitalizations in the city compared to the national average. Conversely, building resilience against heat stress through UGI has a greater impact and reaches a greater number of citizens in a more efficient manner in densely populated urban areas, which could also lead to the comparatively high number of avoided hospitalization cases in the model site area. Nonetheless, assuming that the benefits could indeed have been overestimated, this would be counterbalanced to a degree by a conservative hospitalization cost estimate. Calculating total treatment costs for Germany for 9142 heat-related hospitalizations at EUR 3300 per case—the amount used in the CBA—we arrive at just over EUR 30 million in annual costs, representing less than 40% of the EUR 82 million in national heat-related hospitalization costs [28]. Moreover, the economic effect of reduced hospital admissions on the CBA calculations remains in any event limited, as these savings account for only 1% of total UHI mitigation benefits.

Annual heat-related mortality cases for Germany have been estimated at 4500 deaths [65]. Taking the maximum number of deaths avoided for the model site area, we arrive at 0.78 cases for a population of 23,276, which would correspond to 2681 deaths avoided at national level. This equals only approximately 60% of the number of heat-related deaths in Germany estimated by Tröltzsch et al. [65]. Assuming that, as with hospitalizations, the occurrence of heat-related fatalities is not evenly distributed throughout the country, but that incidence is clustered in urban areas, the results appear to be even more conservative estimates. However, we tread lightly in this conclusion as there is evidence of urban-rural disparities in heat-related mortality, with higher rates being found in rural areas [82]. Despite this evidence, the outcome is consistent with observations made in the literature review of Berlin accounting for a disproportionate share of Germany's heat-related deaths. Looking at the economic valuation of heat-related deaths, Tröltzsch et al. [65] arrive at an inflation-adjusted annual cost to society of EUR 2.24 billion for 4500 deaths, assuming an average of 8 lost life years per death. Using the number of fatalities as calculated for the Pankow study site and extrapolating it to national level, total heat-related deaths in Germany amount to 2681 cases. Applying the same VOLY of 62,126 as calculated by Tröltzsch et al. [65] as well as a slightly higher average of 9.56 life years lost per case, total cost savings would amount to EUR 1.59 billion, or 70% of the total costs calculated by Tröltzsch et al. [65], suggesting conservative benefit estimates for this study.

Overall, the results show that by addressing stormwater management issues, specific UGI measures can be used as a cost-effective method for lowering urban heat stress, but at the same time the strategic selection and placement of measures is key to achieving economic feasibility. This becomes most evident when comparing the shares of green cover and temperature reduction effects for Scenarios A and C, with Scenario C receiving by far the highest share of UGI, but Scenario A still performs better in terms of heat mitigation due to more effective placement of the measures.

6. Conclusions

Urban areas are increasingly affected by stormwater management issues and the UHI effect due to a continuing urbanization trend leading to growing urban populations and further consolidation of already heavily built-up city centers. The implementation of UGI measures encompassed in sustainable stormwater management represents one solution to mitigating heat stress for the urban population while also providing numerous additional benefits. The purpose of this study was to quantify and value the UHI mitigation potential through heat-related mortality and morbidity reductions in three different UGI scenarios and assess the economic feasibility using a CBA approach. Two contributions were made to the literature on valuing UGI benefits in a UHI context. First, a climate data analysis with the aim of assessing the heat stress mitigation potential for different UGI scenarios in a typical neighborhood of Berlin, Germany was conducted. The second contribution was delivered in the form of CBAs with a focus on social benefits related to reduced morbidity and mortality rates as a result of UHI mitigation through UGI. While previous studies have addressed the UHI mitigation benefits of individual UGI measures, and stormwater management related UGI benefits on a neighborhood scale, this study proposes a method for analyzing complete UGI scenarios, including both ecosystem services and economic benefits related to reduced morbidity and mortality. The results of the climate data analysis indicate clear heat mitigation effects of UGI. The CBA results show that UHI mitigation through implementation of UGI measures at the neighborhood level is economically feasible. The methods for quantification of UGI project costs and benefits proposed in this study can be applied by urban planners in the objective evaluation of project proposals. Since UGI benefits create significant social value, the quantification thereof is essential for urban planning in providing a scientific foundation for the inclusion of UGI in UHI mitigation strategies. This is important as UGI installation and maintenance costs are high and delivering value to society can only be achieved through identification of the most suitable UGI measures and ensuring their effective placement.

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