

Assessing flood, drought, and heat resilience: The dominant role of shading in urban cooling

Évaluation de la résilience aux inondations, à la sécheresse et à la chaleur : le rôle prépondérant de l'ombrage dans le refroidissement urbain

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RÉSUMÉ

La mise en œuvre d'infrastructures bleues et vertes (BGI) est une stratégie essentielle pour adapter les villes au changement climatique. À l'aide d'un cadre de modélisation intégré, nous évaluons dans quelle mesure les BGI et la déconnexion de surfaces imperméables peuvent réduire les inondations, améliorer le bilan hydrique et atténuer le stress thermique à Innsbruck, en Autriche. Les résultats montrent que les BGI diminuent les volumes et zones d'inondation et améliorent le bilan hydrique, notamment via une recharge accrue de la nappe phréatique, renforçant ainsi la résilience aux sécheresses. Toutefois, même avec 30 % de surfaces imperméables déconnectées selon les directives autrichiennes, l'augmentation de l'évapotranspiration reste limitée et n'entraîne aucune réduction mesurable de l'UTCI, ni à l'échelle de la ville ni des quartiers centraux. La végétalisation locale peut réduire l'UTCI jusqu'à 2,5 °C et l'ombrage des arbres jusqu'à 13 °C selon la météo, mais ces effets restent très localisés. De plus, la gestion des eaux pluviales des 30 % de surfaces déconnectées ne transforme que 3,2–5,1 % de la surface urbaine en espaces verts, ce qui est insuffisant pour réduire le stress thermique à l'échelle de la ville. L'ombrage apparaît ainsi comme un facteur déterminant, et la combinaison de BGI gérant les eaux pluviales avec une végétation procurant de l'ombre constitue une stratégie particulièrement efficace pour renforcer la résilience climatique urbaine.

ABSTRACT

Implementing blue-green infrastructure (BGI) is a key strategy for urban adaptation to climate change. Here, we employ an integrated modelling framework in which each model component predicts specific performance indicators. Using this approach, we assess how BGI and surface decoupling measures can mitigate urban flood risk, improve the water balance, and reduce heat stress in the city of Innsbruck, Austria. Our results show that BGI measures help to reduce flood volumes and flooded area, while improving the water balance, particularly through increased groundwater recharge, additionally favouring drought resilience. However, even with citywide decoupling of 30% of impervious surfaces using BGI designed in accordance with Austrian guidelines, the increase in citywide evapotranspiration is modest, resulting in no measurable reduction in the Universal Thermal Climate Index (UTCI), a human heat stress indicator, at city nor inner-city district scale. Although local greening can lower UTCI by up to 2.5 °C and additional tree shading by as much as 13 °C depending on meteorological conditions, these cooling effects remain highly localised. Following current Austrian design guidelines to manage the stormwater from 30% decoupled area using BGI converts only 3.2-5.1% into green space, which is insufficient to have a measurable effect on citywide heat stress reduction. Our findings emphasise on the strong influence of shading for local heat mitigation and on combining water-managing BGI with shading vegetation as an effective strategy for enhancing urban climate resilience.

KEYWORDS

Blue-green infrastructure (BGI), Climate resilience, Flood risk reduction, Human heat stress, Integrated modelling

1 INTRODUCTION

The targeted implementation of blue-green infrastructure (BGI) is considered a key measure for climate change adaptation in cities (Almaaitah et al., 2021). Proven to generate multiple benefits, BGI impacts the exchange of water and heat between the subsoil, vegetation, surface and atmosphere, improving the water and energy balance at the surface and thus urban microclimates (Back et al., 2024). Furthermore, BGI facilitates the decoupling impervious areas from the urban drainage system. By contributing to the runoff volume reduction, this approach effectively lowers pressure on infrastructure, flood risk and Combined Sewer Overflow (CSO) events (Hauser et al., 2026). BGI manages this additional runoff volume by storing, infiltrating and evaporating water. However, with changing precipitation patterns and longer lasting dry periods due to global warming, natural precipitation is increasingly unable to reliably supply urban vegetation. Therefore, sustainable and targeted irrigation is becoming increasingly important to ensure an evaporative cooling effect during heat waves (Back et al., 2025). This study investigates the potential of BGI to increase a city's resilience to floods, droughts and heat events, with a particular emphasis on greening and shading to reduce human heat stress, using the city of Innsbruck as case study.

2 METHODOLOGY

An integrated modelling toolset was established to assess urban flooding, water balance and heat stress in Innsbruck, Austria, combining a 1D hydrodynamic sewer model, a coupled 1D/2D cellular-automata flood model, a rainfall-runoff water balance model, and a GIS-based energy-balance and heat-stress model. The study uses climate data from a convection-permitting model bias-corrected with local observations, complemented by airborne-based CIR (Colour Infrared) imagery, Sky View Factor (SVF) data, detailed land-surface classification, building data and a digital surface model. Flood processes were simulated using a calibrated 1D SWMM network (6853 pipes, 6432 manholes) dynamically linked to the high-resolution Dynamic CA-ffé model (Hauser et al., 2025). Water balances were computed with SWMM-UrbanEVA (Hörnschemeyer et al., 2021) using 0.2 m land-use data and implementing decoupling measures as LID modules (soakaways, swales, raingardens and green roofs). Heat stress and surface energy fluxes were modelled in ArcGIS Pro using CIR-based surface properties and established methods for estimating UTCI (Back et al., 2024).

The case study is the city of Innsbruck, located at approximately 574 meters above sea level in the Inn Valley of the Austrian Alps. It covers an area of 51.3 km² with around 130,000 residents. The study examines each district of the city, which are distinct spatial units with specific boundaries and numbers, used for demographic, administrative and planning purposes.

Scenario simulations investigated 30% increases in area decoupling and BGI implementation across street corridors (roads and sidewalks) and rooftops, as well as citywide 30% decoupling, to quantify effects on flood volumes, water balance and thermal stress. The BGIs were dimensioned according to Austrian design guidelines (ÖWAV Regelblatt 45, 2025). In the 1D sewer network model and the 1D-2D flood model, decoupling was simplified by reducing the area, with no BGI implemented in the model. These two flood models evaluated the effects of 30% decoupling of impervious area on surcharge volume and flooded area and passed on information about the extent of the decoupled area to be managed using BGI, in accordance with Austrian guidelines, to the SWMM-based Urban EVA model. The SWMM-based Urban EVA model then used this information to evaluate the effects on evapotranspiration, groundwater recharge and runoff, and passed on information about the extent to which impervious areas had been converted into vegetated areas to manage rainwater, to the GIS-based heat stress model. The GIS-based heat stress model then used this information to account for the increase in vegetated areas resulting from the decoupling of 30% of impervious areas, evaluating its impact on human heat stress.

3 RESULTS & DISCUSSION

3.1 Impact of decoupling measures and BGI implementation

The results confirm that large-scale surface decoupling of 30% of the impervious area is an effective way of reducing both the flood volume (by -46.79% and -35.85% for 5- and 50-year rainfall events lasting 180 minutes respectively) and the flooded area (by -46.95% and -31.64% for 5- and 50-year rainfall events lasting 180 minutes respectively) at a citywide level. This effect decreases slightly with increasing precipitation intensity. Furthermore, large-scale decoupling with BGI, dimensioned according to Austrian guidelines, improves the water

balance at the citywide level. This is evident in the significant decrease in the runoff portion by up to -25.21% of the water balance. However, the reduction in runoff is offset by an increase in groundwater recharge. Conversely, the increase in evapotranspiration is very small (only up to +0.95%). Regarding heat stress reduction, the results show that converting an impervious surface into a green space can locally reduce the UTCI by up to 2.5°C. However, the results also show that decoupling 30% of the impervious surfaces with BGI in each district according to Austrian guidelines has no apparent impact on heat stress at district nor city scale, based on the calculated UTCI values. This is consistent with the very slight increase in evapotranspiration in the water balance model. This is because the change in area from impervious to vegetated is too small to reduce citywide heat stress. Depending on the size of the district, decoupling 30% of the impervious surface area in all districts will only convert 3.18% to 5.09% into green space using tree pits, raingardens, green roofs and swales. This small change in area results in only a slight reduction in the average UTCI or heat stress. In this context, tree pits were implemented in a simplified manner, with no change to the SVF in the urban climate model. Due to their shade-providing effect, they potentially have a larger influence on the UTCI more.

3.2 Effects of greening and shading on heat stress

Figure 1 shows the comparison of the average UTCI per district with the respective average greening ratio and SVF. The graph shows that the SVF, and therefore the amount of shade, has a greater effect on the UTCI than the greening ratio. This is primarily because of the significant reduction in average Mean Radiant Temperature (MRT), which is one of the key factors in how humans perceive heat stress. Reducing direct solar radiation reduces the thermal energy acting on the body, which directly affects the heat balance of the human organism. In addition to their effects on the water balance, greening measures primarily affect the energy balance of the surface, leading to a reduction in the sensible and substrate heat flux and consequently in surface temperature. However, the change in thermal radiation due to greening is significantly lower than the reduction in direct solar radiation due to shading, which explains why it has a smaller effect on the UTCI. Trees play a special role in this context because, depending on their crown diameter and age, they not only have an effect on the water and energy balance of the surface, but can also provide effective shade through their crowns. As they grow, their ability to reduce the average MRT increases, which directly contributes to reducing the UTCI. Trees therefore combine the advantages of both strategies, representing a particularly effective measure for improving thermal comfort in urban areas. The combined effects of evaporative cooling, surface cooling and shading mean that trees are a multifunctional adaptation measure in the context of climate-friendly urban design. As with dense forests, an increased tree density has an additional positive effect as the aforementioned processes reinforce each other, enabling a reduction in thermal stress across a large area.

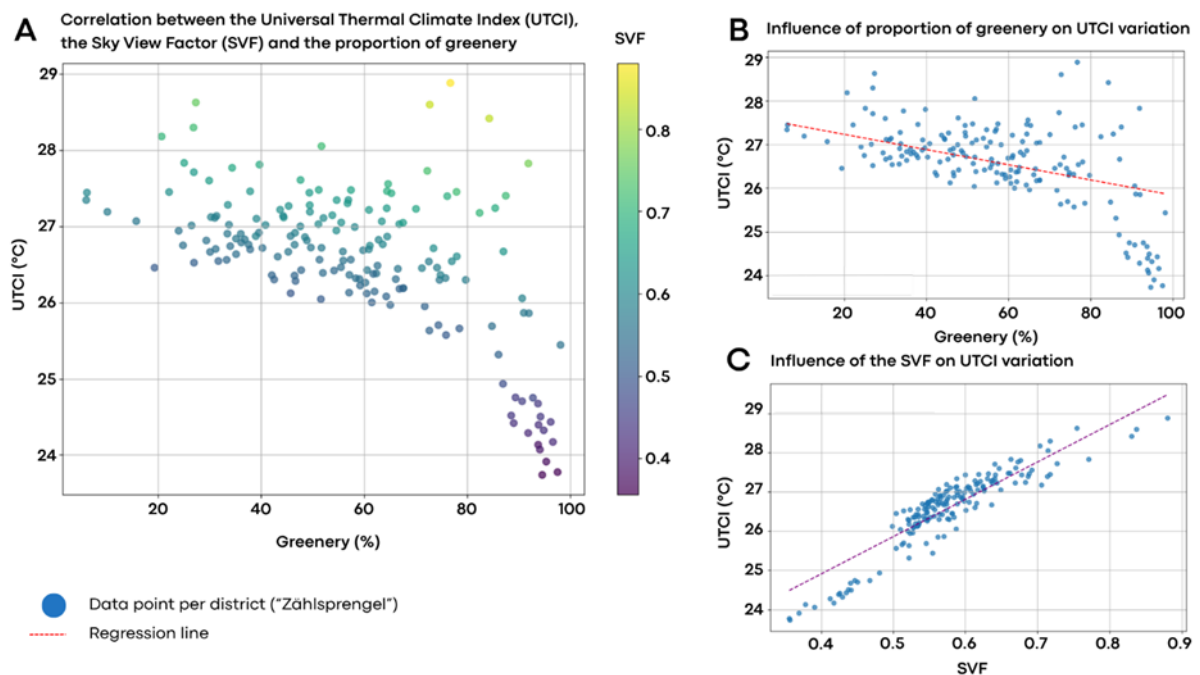


Figure 1. A - Correlation between the Universal Thermal Climate Index (UTCI), the Sky View Factor (SVF) and the proportion of greenery, here at an air temperature of 24.1 °C. B - Influence of the proportion of greenery on UTCI variation. C -

Influence of the SVF on UTCI variation.

In order to investigate the influence of greening and shading on the UTCI, a multiple linear regression was performed based on the available data in all districts across the entire city of Innsbruck (Fig. 1 A, B and C). This statistical method makes it possible to determine the individual effect of each factor on the UTCI while keeping the influence of the other factor constant. This determines how much °C the UTCI changes when the greening or SVF changes by a certain amount. This shows which of the two factors in the present data set makes a greater contribution to explaining the UTCI variations. The results are shown in Table 1. The influence of greening is less by a factor of 5 to 10 than that of shading, depending on the air temperature. It is also visible that the potential for UTCI reduction decreases with increasing air temperature for both greening and shading, shown to be more pronounced for greening than for shading.

Table 1. UTCI reduction with a 10% increase in greening and a 0.1 reduction in SVF, in relation to changes in air temperature and specifying the UTCI range in the data set for the respective air temperatures.

Air Temperature (°C)	UTCI (°C) Range	10% increase in greening	0.1 reduction in SVF	Factor (SVF/Greening)
		UTCI Reduction (°C)		
24.1	23.7 - 28.8	0.174	0.951	5.47
31.2	31.6 - 35.8	0.088	0.810	9.20
35.05	35.2 - 39.1	0.081	0.761	9.39
39.11	39.2 - 42.9	0.075	0.725	9.66

4 CONCLUSIONS

This study shows that implementing decoupling measures through blue-green infrastructure (BGI), designed according to Austrian guidelines, could improve the urban water balance and reduce flood risk at city scale. However, the study also reveals that these measures only contribute marginally to reducing citywide heat stress, as the increase in evapotranspiration is minimal in relation to the overall balance. Greening can reduce the Universal Thermal Climate Index (UTCI) by up to 2.5°C during the day, but this effect is very localised. Shading is particularly important for providing thermal relief in urban areas, with the Sky View Factor (SVF) being identified as a key explanatory parameter. Trees offer a double benefit in this context. They promote the water balance through root infiltration and evaporation, and their canopies reduce the average Mean Radiant Temperature (MRT) and thus human heat stress especially during extreme heat events. Planning and dimensioning of BGI should take a holistic approach, not only allowing rainwater to seep away and helping to prevent flooding but also designed to improve the urban climate. This requires, above all, more space and a higher proportion of shade-providing trees. Tree pits, swales and raingardens are particularly effective in improving the urban climate if they allow a large proportion of the rainwater to evaporate rather than feeding it into the groundwater.

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