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Urban Heat Island mitigation scenarios by Blue-Green Infrastructures modelling

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Abstract. The integrated planning of cities landscape and blue-green infrastructures (BGI) is an approach poised to play an increasingly positive role in climate change adaptation for the human population. Cities worldwide are rapidly expanding to accommodate the increasing urbanization. Phenomena including Urban Heat Island (UHI) and urban flooding are thus more likely – the occurrence and severity of which will be exacerbated by more extreme weather events. BGI offer a network of semi-natural engineering solutions for the sustainable mitigation of such threats to urban liveability.

Scientists have developed scenario modeling tools capable of investigating either phenomenon. Yet their combination has been underexplored. In this study, we integrate, in a feedback loop, the inputs and outputs of two globally used BGI planning-support modeling tools (i.e., UrbanBEATS and TARGET) in one framework. UrbanBEATS allows us to optimally plan systems for managing stormwater quality and quantity based on user and policy requirements. The planned changes in land cover due to BGI is then used in TARGET, a one-dimensional urban climate model, to simulate the impact of BGI on the UHI effect.

We apply this framework to the Municipality of Modena, a medium-sized municipality located in the northern part of Italy in the River Po Valley. The area is particularly suited for the study given the tendency towards increasing imperviousness and worsening summer heat events evolving to longer dry conditions and shorter but more intense rainfalls.

The simplicity of the models and minimal data requirements guarantee widespread applicability of the framework by public authorities to plan the adoption of BGI and make cities more sustainable, liveable and resilient.

Keywords: urban planning, urban modelling, floods, urban heat island, blue-green infrastructures

1. Introduction

The human population will face important challenges by 2050. One is the warming of global temperatures due to climate change by 1.5 °C according to the Paris Agreement. The second is the achievement of more than 66% of the human population living in cities (UN Habitat, 2011). Furthermore, Europe is already highly urbanised with 74% of the population living in urban areas (Harris et al., 2020), with an expected increase to 80% by 2050 (UN Habitat, 2011).

Cities locally exacerbate the increase in temperatures, as compared to nearby rural areas and is commonly known as the urban heat island (UHI) effect (Oke, 1982). UHIs are expected to be amplified by the occurrence and the severity of extreme weather events, which already are a consequence of climate change. This is particularly due to the high heat storage capacity of construction materials as well as the reduction of land covers capable to cool down local temperatures. Blue (water bodies) and green (trees) spaces can support mitigation efforts. Open water bodies can absorb heat and reduce sensible heat through evaporation. Trees not only provide shadow from direct sunlight but also remove sensible heat through transpiration. Overall, urban areas, with their necessity to become resilient and adapt to the grand challenges of 2050 represent a current and complex research topic for the international scientific community.

Innovative approaches to the sustainable development of cities are focusing on the optimal use of Nature-based solutions (NBS), known also as Blue Green Infrastructures (BGI) to meet multiple objectives including water management (quality and quantity) and heat reduction among many other objectives (e.g., biodiversity enhancement).

UHI and BGI are topics studied and modelled by researchers not only for scientific research purposes (Bach et al., 2018; Kim et al., 2021; Adilkhanova et al., 2022; Marando et al., 2022) but also to actively support local authorities who have to plan the redevelopment of the territory and adopt NBS for climate change mitigation and adaptation actions (Deletic et al., 2019; Nguyen, 2022; Hayes et al., 2022) in a context of contested space, requiring the focus on multi-functional solutions.

The integration between models that analyse different aspects of urban areas is a fundamental procedure, that needs to be further investigated in the scientific literature. Strategies and actions related to one aspect of vulnerability of urban areas can have effects and consequences, positive or negative, also on other correlated aspects. For example, the integration of Green roofs also helps the absorption of rainwater, and so on.

This study demonstrates the application of two specific models, UrbanBEATS and TARGET on a medium-sized urban area where BGI would play a beneficial role in absorbing rainfalls and mitigating the urban heat island phenomenon.

2. Materials and methods

2.1. Study area

Modena is a city in the Emilia-Romagna region, in the northern part of Italy. It is located in the Po Valley, a vast flat area that extends from Piedmont to Emilia-Romagna and is crossed by the Po River.

According to estimates from 2022, the population of Modena is approximately 184,000 inhabitants. Over the last few decades, Modena has seen fluctuations in its population. For example, between 2002 and 2011, the population increased by 4%, going from 178,311 to 185,694 inhabitants. However, since the following years, the population has become relatively stable.

Modena has experienced a significant land consumption due to the expansion of anthropogenic activities such as building construction, roads, parking lots, industries, and various infrastructures. According to the data from the National System for the Protection of the Environment (SNPA), between 2015 and 2021, the area of artificial land in Modena increased by approximately 17 hectares per year. The net soil consumption from 2006 to 2022 is almost 200 hectares (Munafò, 2022). This has had a strong impact on the environment, with negative consequences on biodiversity, air and water quality, the risk of floods and landslides, and the capacity to absorb rainfalls.

The climate of the Po Valley is typically continental, with cold and foggy winters and hot and muggy summers.

Global warming is showing its effects in Modena with significant temperature increases throughout the year but particularly in the summer period. 2022 was the year with the highest temperature, 16.8°C, recorded in Modena by the Geophysical Observatory, a reference site for measurements from 1830. In summer, the phenomenon of "tropical nights", i.e. nights with a minimum temperature above 20°C, became increasingly widespread. In the months of June, July and August 2022, 86 tropical nights were recorded, as compared to 48 in 2000 or 23 in 1990.

Rainfall since 1991 has ranged from a minimum of 370 mm per year to a maximum of 921 mm per year, with an average annual rainfall of approximately 675 mm.

2.2 Modelling

UrbanBEATS

The Urban Biophysical Environments and Technologies Simulator (UrbanBEATS) integrates stormwater management with urban planning to support the design and implementation of BGI in urban areas (Bach et al., 2020). This spatial planning-support model requires a minimum of four spatial datasets and two time series of hydro-meteorological forcing. The input maps comprise: (1) topographic data to determine drainage conditions and sub-catchments, (2) population and (3) land use (13 classes as in Table 1) for urban form and water demand assessment, and (4) soil characteristics for infiltration potential and landscape integration of BGI. The model partitions surface areas into pervious (lawns, etc.) and impervious spaces (houses, parking, access roads, etc.), and the space available for BGI technologies based on pre-defined planning rules (Bach et al., 2018). Hydro-meteorological forcing comprises daily values of rainfall and evapotranspiration. BGI technologies are selected by the modeller among: (a) Bioretention systems/ Raingardens, (b) Infiltration systems, (c) Ponds, (d) Rainwater tanks, (e) Constructed wetlands and (f) Swales. For each technology, the modeller specifies typical design parameters, and designs are generated to meet defined targets for reducing: flow (Q), total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) pollutant loads. Through the use of elaborate spatial analysis, incorporation of urban planning ordinances and infrastructure design by means of empirical performance curves, stakeholder preferences and a Monte Carlo approach, UrbanBEATS generates entire, feasible BGI layouts for the input case study and filters these down to a select few based on a set of holistic, multiple criteria.

Table 1. Land use classes in UrbanBEATS

Land use Group	Land use (Abbreviation)
Residential	Residential (RES)
Commercial	Commercial (COM)
Mixed Commercial and Residential	Mixed Offices and Residential (ORC)
Industrial	Light Industry (LI)
Industrial	Heavy Industry (HI)
Municipal/Community	Civic (CIV)
Municipal/Community	Services and Utility (SVU)
Transport	Road (RD)
Transport	Transport (TR)
Open Space	Parks and Garden (PG)
Open Space	Reserves and Floodways (REF)
Open Space	Undeveloped (UND)
Others	Unclassified (NA)

TARGET

The Air-temperature Response to Green/blue-infrastructure Evaluation Tool (TARGET) model balances the mechanistic accounting for physical processes regarding radiative exchanges and computation efficiency (Broadbent et al., 2019). Drawing upon well-known existing microclimate models (e.g., SOLWEIG, SUEWS), this one-dimensional vertical model simulate each grid cell as an idealized urban canyon. TARGET requires the modeller to zonate land cover into seven classes (roof, road, water, concrete, vegetation, non-irrigated grass and irrigated grass) for each grid cell, with the latter having a resolution down to tens of metres (25 m in this study). For each land cover class, the modeller defines parameters regulating radiative exchanges. For each grid cell, the modeler defines the building height and the street width to robustly idealize the urban canyon. In TARGET, the radiative processes are forced by the following time-series: air temperature, relative humidity, wind speed, barometric pressure, incoming shortwave radiation and incoming longwave radiation. TARGET returns gridded time-series (time step of 60 minutes) of canopy (i.e., air volume up to roof height) layer temperature, above-canopy layer temperature, surface temperature, among others.

2.3 Application

In this study, we reclassified the detailed land cover map provided by Italian region Emilia-Romagna (+100) into 13 classes for UrbanBEATS and 7 classes for TARGET. UrbanBEATS and TARGET are not coupled. However, our approach ran UrbanBEATS to plan BGI technologies based on achieving the highest runoff reduction and annual pollution load reduction targets. Subsequently, we ran TARGET on the land cover before and after the implementation of BGI technologies (representing the implementation as a change of impervious or dry grass cover to vegetated or irrigated cover) to assess the impact of BGI implementation on surface temperatures.

3. Results

Over the urban area of Modena (10.5 km^2) (Figure 1a), TARGET predicts surface temperatures (from now on temperature) ranging between 22.2 °C and 52.2 °C in summer daytime (10 am) and using standard material properties (Figure 1b). As expected, the lowest temperatures correspond to water bodies, whereas the highest temperatures are related to roads. Urban forests keep the temperatures down to around 30 °C. However, non-irrigated grass in parks can reach simulated temperatures as high as 43 °C.

UrbanBEATS plans BGI technologies covering about 12,500 m^2 needed to achieve sustainable Q reduction and pollution load reduction targets (targeting TSS, TN and TP loads) by 50% upon using standard design parameters (Figure1 c and d). One pond (≈ 2,700 m^2) and one wetland (≈ 2,700 m^2) are planned in a large park in the north-western region. Two swales (≈ 40 m^2) are planned in the south and south-eastern regions. Several biofilters (≈ 8,000 m^2) are planned throughout the city in the smaller urban forest areas.

The difference in temperatures simulated by TARGET between pre- and post-BGI implementation indicate that the replacement of trees for biofilters caused a local increase in daytime temperatures by up to 7.3 °C. In contrast, ponds locally decreased daytime temperatures by a maximum of 8.7 °C. Interestingly, there is an opposite trend in night-time, when local temperatures decrease by a maximum of 4 °C where biofilters are and increase by a maximum of 4.9 °C where the pond is. Noteworthy, swales produce a cooling effect during day-time (-1,5 °C) and night-time (-0.3 °C).

4. Conclusions

Cities must become resilient and adapt to climate change and increasing densification. Engineered BGI solutions, inspired from nature, fit very well in the urban landscape. BGI can help manage water quantity and quality issues. However, they can both reduce and exacerbate surface temperatures in a time-dependent manner depending on how they are implemented. Therefore, it is fundamental to couple water and temperature management solutions in order to comprehensively protect citizens living in cities. For this important application, city councils, landscape planners, environmental agencies and civil protection agencies can substantially benefit from the developments of the presented tools.

Future work will focus on: (i) more detailed integration of the two models to allow better translation of data between models, (ii) automatic calibration of material properties and model output simulations through the exploitation of satellite data, which can provide for albedo values and Land Surface Temperatures (i.e., from LANDSAT 8), and (iii) development of BGI layout generations specifically tailored to urban microclimate just like how UrbanBEATS does it with stormwater management. The concurrent development of a friendly graphic user interface could boost its fast adoption among public authorities.

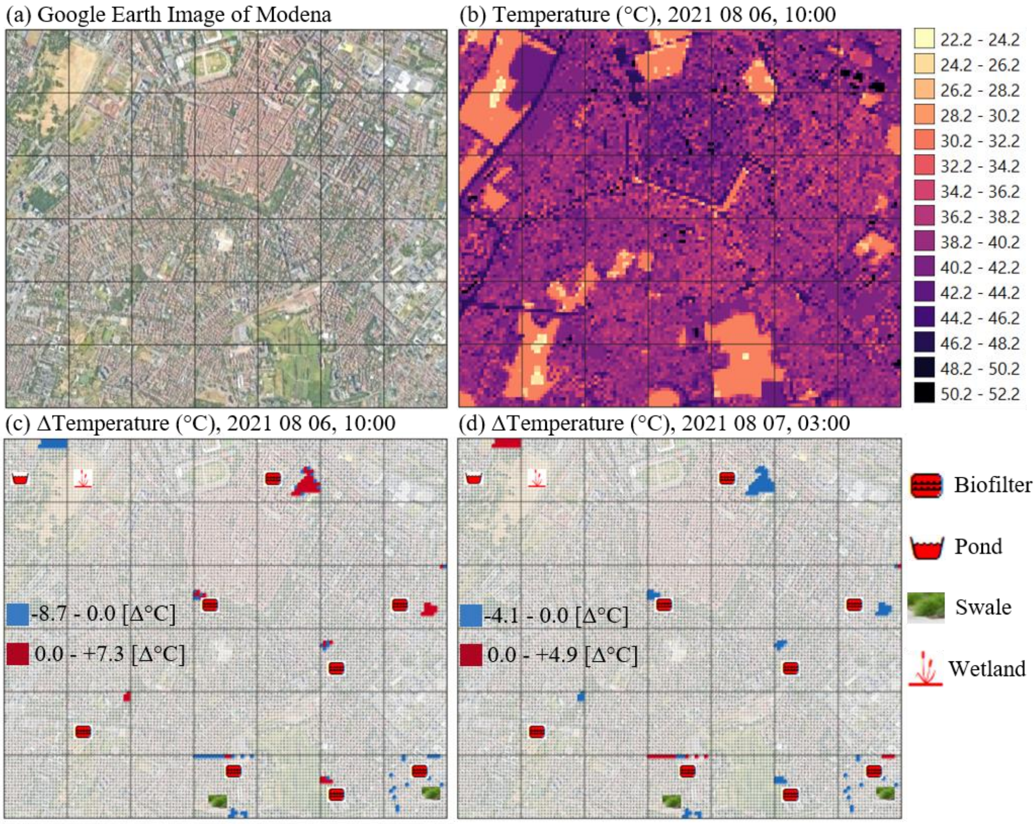

Figure 1. Maps depicting (a) the urban area of Modena used in this study, (b) the daytime temperatures simulated by TARGET, the difference in surface temperature in daytime (c) and night-time (d) calculated considering the land cover with the WSUD technologies implemented and without. Icons in the legend represent the WSUD technologies planned. Cells in blue or red indicate negative differences (cooling) or positive ones (warming), respectively. UrbanBEATS divides the study area in blocks of 500×500 m^2 (black grid) to perform computations.

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