Modelling Effectiveness of Environmental Greenery Systems as a Tool to Partially Eliminate Urban Overheating

Jaroslav Žák
Department of Civil Engineering, Institute of Technology and Business in České Budějovice, Okružní 517/10, 370 01 České Budějovice, Czech Republic
zak@mail.vsceeb.cz

Abstract. The paper describes the first results of modelling the effectiveness of environmental greenery systems as a tool for partial elimination of urban overheating. Environmental greenery contributes to the effective management of rainwater flowing from the paved surfaces of the cities. Technical measures will reduce temperature fluctuations, noise pollution and dust concentration. The new rainwater management will contribute to reducing the temperature fluctuations, especially in summer. The evaporation of vertical environmental greenery will at least partially reduce the negative impact of the climate change. Urban greenery is one of the effective measures for urban heat island mitigation and climatic change. The numerical model gives a first idea of how large areas of environmental greenery need to be installed in order to benefit the above-mentioned benefits.

1. Introduction
Addressing climate change and minimizing its impact is currently a global priority. Climate changes are phenomena of contemporary society [1]. Rainwater plays a key role in the balance of biogeochemical cycles of the environment [2]. For the Central European countries, there is no significant decrease in the total precipitation, but in their accumulation into the storm and torrential periods with prolonged droughts. A large proportion of urbanized urban areas are characterized by prevailing hard surfaces [3]. The hard surfaces quickly drain rainwater along with contaminants and do not allow its natural seepage into the soil environment or its natural evaporation. Rapidly drained water cannot evaporate or accumulate solar energy to the required extent. This results in reduced evaporation and poor urban vegetation due to lack of water in warm periods of the year. The lack of solar energy accumulation results in a higher temperature of the urban microclimate compared to the surrounding green environment. There are currently a number of studies dealing with rainwater recycling and seepage systems in urban areas [4-6].

Paved areas, such as concrete and asphalt surfaces absorb a huge amount of heat from the Sun, which then radiates back into the environment. Temperatures in the centre, higher by more than 2°C, are characteristic of large cities compared to the peripheral urban area of the city [7]. Overheating of the urban environment can be reduced by retaining the maximum amount of rainwater in the urban environment and its subsequent evaporation. Rainwater must be able to evaporate itself at the optimum time horizon, thereby cooling and improving the quality of the urban climate. The growth of vegetation and absorption of carbon dioxide and other impurities is dependent on a sufficient supply of...
water. Clearly, drinking water irrigation is not an obvious solution. On the contrary, due to contamination with surface impurities, rainwater is considered to be drinkable and its use thus represents not only significant protection of drinking water sources but also a solution for optimal irrigation of vegetation.

Urban greenery can be used as an indicator of air pollution [8]. In historical construction and densely urbanized areas, it is difficult to extend horizontal green areas. One of the potential options is the planting of new trees and their irrigation by accumulated rainwater. However, mature trees in the urban environment pose a number of problems. Growing trees and their uncontrollable root system gradually erode surrounding structures. Another problem is the extent of underground infrastructure in urbanized areas that limit the planting of new trees. These two main reasons hamper the massive expansion of tree planting in the urban environment. In addition, with regard to their life cycle, tree planting is a solution for future generations.

An effective and fast solution is the expansion of vertical environmental greenery. Environmental greenery is vertical or horizontal greenery additionally placed in cities in order to reduce temperature and mitigate dust and noise. This greenery may be part of another structure and buildings or located separately in the public space of the city.

Another advantage of environmental green is its ability to absorb airborne dust [8], absorb carbon dioxide and attenuate noise. Green barriers to noise are becoming increasingly popular in big and busy cities. To reduce noise by 5 dB (A), the greenery thickness must be greater than 1500 mm [9, 10]. In addition, greenery affects the mental health and well-being of the city’s inhabitants [11, 12].

Cooling the temperatures in cities will bring not only a more comfortable place for living but also significant financial savings. We assume that residents air-conditioned their dwellings to a suitable temperature. Lowering the outdoor temperature automatically decreases the need for air-conditioned rooms [13]. From 20 to 30% greenery coverage ratio is optimal for effective and optimal cooling [14].

2. Materials and methods
A numerical model was developed and tested to analyse the cooling of urban centres depending on the installation of a certain amount of environmental greenery. Figure 1 illustrates the basic scheme of heat fluxes on the surface of the ground in the city. Theoretical relations describing energy and temperature flows have been taken from [15] and are clearly shown in the following formulas:

\[
T_{sm} = \frac{\varepsilon C_{LW} T_{sky,m} + h p_r T_{am} + S_m - C_{EV} f h p (1 - RH)}{h p_e + \varepsilon C_{LW}}
\]

where:

\[
p_e = 1 + C_{EV} f a_p
\]

\[
p_r = 1 + C_{EV} f a_p \cdot RH
\]

where: \( T_{sm} \) is the annual average of the ground surface temperature (°C), \( \varepsilon \) is the emissivity of the surface of the ground, \( C_{LW} \) is a constant equal to 4.83 W/(m²·K), \( T_{sky,m} \) is the annual average temperature of the sky (°C), \( h \) is the convective heat transfer coefficient W/(m²·K), \( T_{am} \) is the annual average temperature of the air (°C), \( S_m \) is the annual solar radiation flux absorbed by the ground (W/m²), \( C_{EV} \) is a constant equal to 0.0168 °K/Pa, \( f \) is evaporation rate coefficient (-), \( b_p \) is a constant equal 609 Pa, \( RH \) is the relative humidity of the air (-), and \( a_p \) is a constant equal 103 Pa [15].
Figure 1. The basic scheme of heat fluxes on the surface of the ground in the city

The urban structure of the city is a spatial grouping of individual city-forming elements and components. The most important components include housing, transport, recreation, public infrastructure, technical infrastructure, production and trade. Urban greenery is one of the elements of urban space that play an important role. Urban greenery is a set of living and inanimate (natural or artificial) elements of greenery, intentionally based or spontaneously created, which is usually cared for by landscaping methods.

A typical Central European city was simplified and considered centrally symmetrical. Depending on the type, the density of buildings and the immediateness of urban links, the circulation city can be divided into a city-centre (core), a compact city, an outer zone and peripheral buildings. The city-centre consists of only 1%, the compact city 34% and the outer zone 65% of the ordinary city area. For the city-centre and compact city, the ratio of built-up and undeveloped areas is approximately the same, i.e. 80% and 20%. Basically, the reverse ratio of 30% of the built-up area and 70% of the undeveloped areas can be found in the outer zone of the city.

Modelling urban systems and segment analysis is one of the current systems within the urbanization and spatial planning process (Figure 2). The proportions of concrete, masonry and asphalt surfaces are given in Table 1. Table 1 also lists areas of green and environmental greenery. The results of the simplified study are summarized in Table 2. Row number one is the default state. Row number 2 corresponds to the situation where green roofs are installed as much as possible. In the following rows, a certain percentage of installed vertical façades and other vertical systems is always considered. The last line corresponds to 100% green façades and the maximum possible installation of vertical environmental greenery systems.
Table 1. Segments description

| No | Radius km | % concrete and masonry | % asphalt | % greenery | environmental greenery |
|----|-----------|------------------------|-----------|------------|------------------------|
| 1  | 0.35      | 78                     | 15        | 5          | 2                      |
| 2  | 0.80      | 71                     | 17        | 9          | 3                      |
| 3  | 1.50      | 65                     | 12        | 21         | 2                      |
| 4  | 2.50      | 43                     | 11        | 45         | 1                      |
| 5  | 5.00      | 34                     | 11        | 54         | 1                      |
| 6  | 7.80      | 26                     | 8         | 65         | 1                      |
| 7  | 10.00     | 25                     | 8         | 66         | 1                      |
| 8  | 20.0      | 22                     | 6         | 71         | 1                      |
| 9  | 30.0      | 21                     | 6         | 72         | 1                      |
| 10 | 50.0      | 19                     | 5         | 75         | 1                      |

Figure 2. Typical diagram of segments in the circular city

Table 2. Decreased Temperatures in the centre

| No | Add % env greenery | -T (C) | dCosts |
|----|--------------------|--------|--------|
| 1  | 0                  | 0      | 0      |
| 2  | Roofs              | -0.2   | 3      |
| 3  | 10                 | -0.3   | 5      |
| 4  | 20                 | -0.7   | 7      |
| 5  | 40                 | -1.3   | 11     |
| 6  | 80                 | -1.9   | 19     |
| 7  | 100                | -2.4   | 23     |
3. Conclusions
The results of the simplified numerical model have convincingly demonstrated that the installation of vertical environmental greenery can bring significant temperature reductions and cost savings. Furthermore, it has been shown that installing only green roofs does not provide sufficient effect. Environmental vertical greenery systems must also be used to achieve significant temperature reduction. Optimal results are achieved if 80% or more of the façades are installed with vertical greenery systems.

Acknowledgments
The support of IG VSTE is appreciated.

References
[1] L. S. Loy, and A. Spence, “Reducing, and bridging, the psychological distance of climate change,” Journal of Environmental Psychology, vol. 67, 101388, 2020.
[2] E. H. Martins, D. C. Nogarotto, J. Mortatti, and S. A. Pozza, “Chemical composition of rainwater in an urban area of the southeast of Brazil,” Atmospheric Pollution Research, vol. 10, issue 2, pp. 520-530, 2019.
[3] B. Dousset, and F. Gourmelon, “Satellite multi-sensor data analysis of urban surface temperatures and landcover,” ISPRS Journal of Photogrammetry and Remote Sensing, vol. 58, issue 1-2, pp. 43-54, 2003.
[4] A. Campisano, D. Butler, S. Ward, M. J. Burns, E. Friedler, K. DeBusk, L. N. Fisher-Jeffes, E. Ghisi, A. Rahman, H. Furumai, and M. Han, “Urban rainwater harvesting systems: Research, implementation and future perspective,” Water Research, vol 11, pp. 195-209, 2017.
[5] E. Wanjiru, and X. Xia, “Sustainable energy-water management for residential houses with optimal integrated grey and rain water recycling,” Journal of Cleaner Production, vol 170, pp. 1151-1166, 2018.
[6] U. Nachshon, L. Netter, Y. Livshitz, “Land cover properties and rain water harvesting in urban environments,” Sustainable Cities and Society, vol. 27, pp. 398-406, 2016.
[7] J. Žák, M. Kraus, P. Machová, and J. Plachý, “Smart Green Bridge – Wildlife Crossing Bridges of New Generation,” IOP Conf. Ser.: Mater. Sci. and Eng., vol. 728, 012010, 2020.
[8] Y. Liu, Z. Yang, M. Zhu, and J. Yin, “Role of Plant Leaves in Removing Airborne Dust and Associated Metals on Beijing,” Aerosol and Air Quality Research, vol. 17, pp. 2566-2584, 2017.
[9] A. M. Lacasta, A. Penaranda, I.R. Cantalapiedra, C. Auguet, S. Bures, and M. Urrestarazu, “Acoustic evaluation of modular greenery noise barriers,” Urban Forestry & Urban Greening, vol. 20, pp. 172-179, 2016.
[10] C. M. Kalansuriya, A. S. Pannila, and D. U. J. Sonnadara, “Effect of roadside vegetation on the reduction of traffic noise levels,” Proceedings of the Technical Sessions, vol. 25, pp. 1-9, 2009.
[11] R. Wang, M. Helbich, Y. Yao, J. Zhang, P. Liu, Y. Yuan, and Y. Liu, “Urban greenery and mental wellbeing in adults: Cross-sectional mediation analyses on multiple pathways across different greenery measures,” Environmental Research, vol. 176, 108535, 2019.
[12] T. Tsurumi, A. Imauji, S. Managi, “Greenery and Subjective Well-being: Assessing the Monetary Value of Greenery by Type,” Ecological Economics, vol. 148, pp. 152-169, 2018.
[13] A. Afshari, “A new model of urban cooling demand and heat island—application to vertical greenery systems (VGS),” Energy and Buildings, vol. 157, pp. 204-217, 2017.
[14] W. Ouyang, T. E. Morakinyo, Ch. Ren, and E. Ng, “The cooling efficiency of variable greenery coverage ratios in different urban densities: A study in a subtropical climate,” Building Environment, vol. 174, 106772, 2020.
[15] B. Larwa, “Heat Transfer Model to Predict Temperature Distribution in the Ground,” Energies, vol. 12(1), 25, 2019.