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Role of reservoirs of urban heat island effect mitigation in human settlements: moderate climate zone

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Abstract: This paper presents the problem of the increasing negative impact of urban heat islands (UHI) on urban residents based on land surface temperature (LST). It is assumed that water bodies in the agglomeration remain cooler than the air and surrounding urban areas. The study aimed to determine the impact of water bodies and surrounding areas covered by trees on the temperature of an urban area and to minimise the impact of UHI on the life quality of people in the temperate climate zone at day temperatures 25°C (W day) and 29°C (H day). In the adopted research methodology, 167 reservoirs, larger than 1 ha, located within 300 m of urban areas, were analysed. Satellite thermal imagery, spatial land use data (Corine Land Cover), and local land characteristics were used. The average temperature of the reservoirs was appropriately at 4.69°C on W day and 1.9°C for H day lower than in residential areas. The average temperature of areas at a distance of 30 m from the reservoirs was 2.69°C higher on W and 0.32°C higher on H than the water of the reservoirs. The area covered by trees was 0.52°C lower on W day and 0.39°C lower on H day than the residential areas located at a distance of 300 m from the reservoir. On terrestrial areas, the lowest temperature was observed in the area covered by trees within 0–30 m from reservoirs both on warm and hot days. Based on the results of this study, UHI mitigation solutions can be suggested.

Keywords: climate change, mitigation UHI, urban area, urban heat island, water reservoir

INTRODUCTION

It is well known that ongoing global warming and the projected development of cities by 2050, where more than 68% of the human population will live [UN 2018], are prompting the search for ways to mitigate high temperatures in this area. Urban heat island phenomena (UHI) are an extremely topical issue, and problems and literature mainly present the issue of UHI phenomena as a threat to future human existence. This problem was indicated as being in 1833 when Luke Howard hypothesised that excess heat in cities during summer is caused by greater absorption of solar radiation by vertical city surfaces and a lack of available moisture for evaporation [Gartland 2011]. Urbanisation has continued to increase and doubled from 1990 to present times [Gong *et al.* 2020], affecting residents' quality of life [Kotharkar *et al.* 2019]. UHI is defined as a local climate change characterised by higher temperatures in urban areas than in rural areas [Zhou *et al.* 2018]. In extreme cases, usually at night time, temperatures can reach up to 5–10°C higher in the centre of cities like New York or Birmingham than in the surrounding countryside; although on average, the UHI intensity is usually around 2 to 4°C [Gedzelman *et al.* 2003; Heaviside *et al.* 2015; Oke 1973]. The lack of moisture in urban areas and increased anthropogenic heating also contribute to the UHI effect. It has been found that the heat island effect in cities generally arises due to an increase in built-up and paved areas [Mohajerani *et al.* 2017], leading to reduced space for vegetation and evapotranspiration and increased anthropogenic heat production [Stone *et al.* 2010]. There is an ongoing search for ways to adapt to climate change in urban areas where UHI is recorded and these actions are considered one of the greatest challenges being faced by humanity [Sun *et al.* 2019]. This is all the more so as the UHI has a direct impact on the health of residents and this is due to the threat of heat, which is increased in urban areas, especially during heat waves [Heaviside *et al.* 2017].

It seems that suppressing the effects of UHI in tropical climates is a necessity [Grimmond *et al.* 2002] while in temperate zones the problem has begun to be recognised, especially during the season of summer [Funda, Santamouris 2017]. Mitigating the magnitude of UHI [Sharma *et al.* 2016] and its impact on residents is considered a key element in urban design to address climate change in cities in terms of temporal socio-economic development [Peng *et al.* 2020] and improving the life quality of residents. Bokaie *et al.* [2016] indicated that water reservoirs can effectively mitigate the intensity and rate of urban heat island spread, reducing the temperature to 0.9°C and 1.57°C, respectively [Qiu *et al.* 2017]. It was found that bodies of water are cooler than the surrounding environment, have high specific heat capacity, and can affect the rate of temperature change through a state change, which affects the latent heat transfer capacity. There is a clear negative linear relationship (correlation coefficient – 0.72) between the proportion of water surface temperature and land surface temperature [Li *et al.* 2013]. The cooling effects of different bodies of water will vary depending on the surrounding environment. Ghosh and Das [2018] found that there is a close relationship between the cooling effect of water reservoirs and the value of their shape and size index [Wu *et al.* 2020]. It is estimated that water reservoirs can reduce the temperature within a 70 m radius by more than 1°C. It is important to understand the mechanism of climate change on a regional scale with respect to landscape elements such as water reservoirs, especially with respect to the increasing severity of the urban heat island effect due to urbanisation [Heinl *et al.* 2015; Wu, Ren 2018]. Therefore, the smart design of urban environments needs to go beyond simplistic water reservoirs and vegetation-based solutions for mitigating uncomfortably high temperatures and consider interactions between surface materials, land use, UHI, and water use [Guhathakurta, Gober 2010] in other, then temperate climate zones. UHI can negatively affect the urban socioecological system [Phelan *et al.* 2015]. Higher temperatures directly affect the health and well-being of city dwellers, especially during heat waves, but also contribute to the deterioration of the quality of the environment [Lai 2018] and an increase in the mortality of the elderly [Heaviside *et al.* 2017]. In addition, UHI increases heat stress in living organisms, thus affecting biodiversity and to ecosystem functioning [Grimm *et al.* 2008] and energy consumption for cooling summer buildings [Santamouris *et al.* 2018]. An effective solution, based on nature, to improve the quality of life in cities, is the creation and strengthening of urban greenery, providing a wide range of ecosystem services [Srdjevic *et al.* 2019]. One of the regions located in a temperate climate and transformed by industrial activity is the Upper Silesian (South Poland) conurbation, with an urbanisation level of 77.6%. The central physical-geographical region that comprises this area is the Katowice Upland [Kondracki 2022]. For centuries, raw materials, mainly hard coal, have been extracted and processed in this area. On the one hand, the socio-economic aspect was developed in these areas. On the other hand, was a cause of a severe transformation of the landscape [Dulias, Hibszer 2004]. The effect of these activities is the numerous water reservoirs [Rzętała, Jaguś 2012], formed as a result of direct reclamation of pits on the surface or filling with water the places of land subsidence over underground workings [Pierzchała, Sierka 2020]. The decreasing number of water bodies by overgrowing [Sierka *et al.* 2012] or the transformation of natural habitats on a regional scale have consequences for the quality of life of inhabitants [Hunter *et al.* 2019].

The aim of our work was to identify the importance of water reservoirs in 1) minimising the urban heat island effect on warm and hot days, and 2) their importance in ultimately shaping the quality of life of residents.

Moreover, based on the obtained results the most favourable spatial layouts for the quality of life of residents within the UHI were indicated.

MATERIALS AND METHODS

THE STUDY AREA

In physico-geographical terms [Kondracki 2022] the Katowice Upland is located in the southern part of Poland and its territorial area is approximately 1,213.7 km^2 (Fig. 1). This area was carried out in the Upper Silesian Metropolitan Union (Southern Poland) and has a temperate climate. It is built of carboniferous rocks overlain by dolomites and Middle Triassic limestones.

The economy is based on the sector of mining of mineral resources, in particular deep exploitation of hard coal. The region is highly industrialised and urbanisation, but lake density is high to the presence of diverse bodies of water formed as a result of

Fig. 1. Location study area on the background Europe; *1* = state borders, *2* = mesoregions boundaries, *3* = Katowice Upland boundaries; source: own elaboration

human activity. These are located in urban-industrial, rural-agricultural, or quasi-natural areas [Rzętała, Jaguś 2012] in cities or in their vicinity and have a moderate climate. The average value of temperature in July is 24,4°C and in August 24,7°C and the average annual precipitation is 686 mm [Dulias, Hibszer 2004].

SAMPLING AND ANALYSIS TECHNIQUES

Land cover data from "Urban atlas" [Copernicus 2018] were used to delimit areas covered by reservoirs and urban fabric areas. The accessibility of water bodies was evaluated based on the distance from areas of residential buildings (urban fabric area). After Grunewald *et al.* [2017] the 300 m straight-line distance from the place of residence was set as the threshold value of the reservoir's accessibility. In this step of the analysis, the 167 urban reservoirs were selected (Fig. 2A). For the current analysis under consideration were only reservoirs over 1 ha area, that could be used every day as a place of rest and contact with nature by an urban dwelling.

The "Tree Cover Density" [Copernicus 2015] data were used in the analysis of the spatial distribution of areas covered by trees. The land surface temperature (LST) of selected reservoirs and their 30 m buffer zone, fabric residential areas covered by trees (groups) were measured using remote sensing data. The Landsat 8 OLI/TIRS remote sensing image provided by the United States Geological Survey [USGS undated] was used. The clear-sky image after a period wave hot (air temperature below about 27°C – warm day (W) and about 33°C – hot day (H)) on 24 and 31 August 2019 was selected for the LST analysis. The formula presented in the study of Avdan and Jovanovska [2016] was applied for measuring LST based on LS band 10 images. The spatial analysis using vector and raster data and map creation was carried out in QGIS desktop 3.4.9 (Fig. 2B).

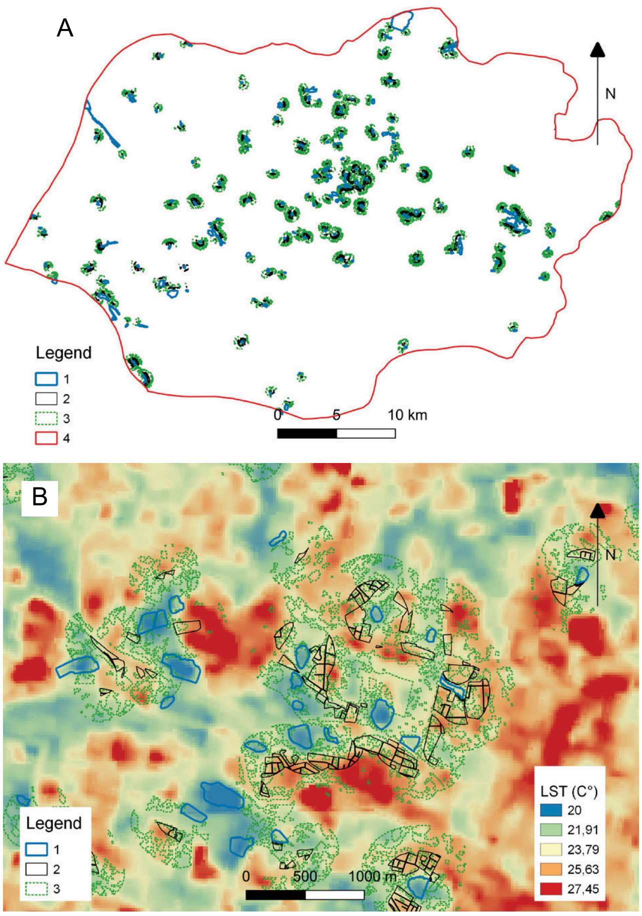

Fig. 2. Stages of the conducted analysis; location of the study water reservoirs (A) and visualisation effect of analysis on the temperature background (B): *1* = buildings, *2* = reservoirs, *3* = area covered by trees (ACT), *4* = Katowice Upland boundaries; source: own elaboration

STATISTICAL TREATMENT

The Shapiro–Wilk test was used to confirm the normal distribution of analysed data. The relationship between the area of reservoirs and LST was analysed using Pearson's coefficient of linear correlation. The differences between the groups (days, temperature of area elements) were compared using an analysis of variance one-way ANOVA and the post-hoc Tukey's HSD (Honestly Significant Difference) test. A probability level of a *p*-value less than 0.05 was considered statistically significant. The differences between the LST groups from W and H days were verified with Student's t-test for independent groups. The statistical analyses were performed with Statistica 12.0 software.

RESULTS

The total area of water bodies surveyed was 17.78 km^2 (and was smaller than green areas 210.21 km^2 and built-up areas (18.02 km^2). The mean tree cover of the analysed area is 30.37%.

The analysis of LST indicated that the average temperature of the water reservoirs (group 6) was on a warm day (W) about 4.62°C lower and on a hot day (H) about 1.9°C lower than on residential areas (group 1).

In the distance of 30 m from reservoirs, the average temperature was 2.63°C higher on W day and 0.32°C higher on the H day, than within water ecosystems (group 7). The average *LST* in the area covered by trees (group 8) was 0.52°C on W day and 0.39°C on H day, lower than that of the residential areas located at a distance of 300 m from the reservoir (group 1).

The lowest temperature was observed for both days (W and H) in the area covered by trees and 0–30 m away from reservoirs.

The highest temperature was observed around the residential area without trees covering the area in the vicinity and located at least 30 m for W and for H far from the reservoirs (group 5).

The residential area was located at a distance of 30 m for W and H from reservoirs (group 2) and ACT (groups 3 and 4), which was a lower *LST* than the rest of the residential areas (group 1).

There are no statistically significant differences between groups 2, 3, and 4 in both types of days (W and H) however, each of these groups has shown a significant difference compared with group 1 (Fig. 3).

The comparison of *LST* values for days H and W differs statistically significantly (p > 0.00). However, the temperature trends in individual types of analysed areas are similar both during warm and hot days. The difference in the mean value of *LST* is visible outside the reservoirs with an area of more than 1 ha, located 0–300 m from the buildings (group 6) – Figure 3.

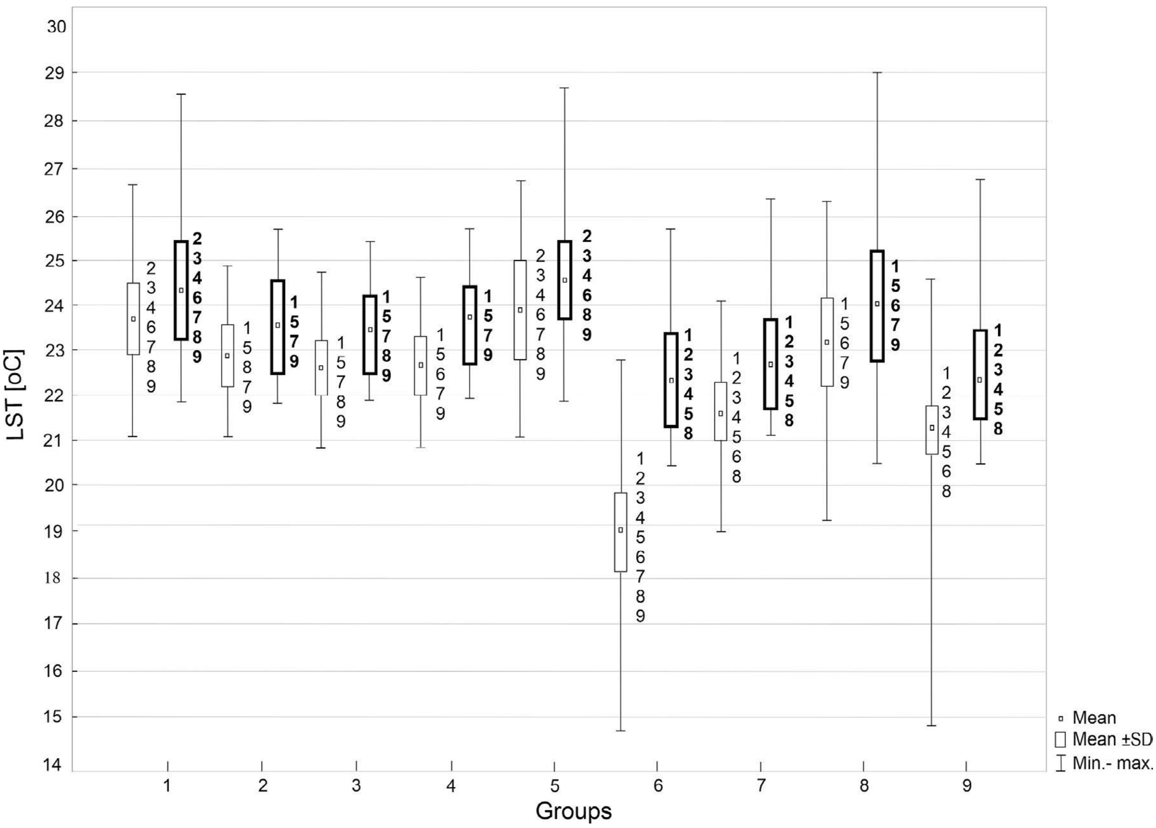

Fig. 3. Results of one-way-ANOVA, post-hoc Tukey HSD test (significant differences, $p < 0.05$ between groups); *1* = a residential area in a distance of 0–300 m from reservoirs, *2* = residential in a distance 0–30 m from an area covered by trees (ACT), *3* = a residential area in a distance 0–30 m from reservoirs, *4* = a residential area in a distance 0–30 m from ACT and from reservoirs, *5* = a residential area in a distance 30–300 m from ACT and from reservoirs, *6* = reservoirs over 1 ha, in distance 0–300 m from residential areas, *7* = 30 m zone around the reservoirs, *8* = ACT in a distance 0–300 m from the residential area, *9* = ACT in distance 0–30 m from reservoirs on a warm day (W = thinner line border) and hot day (H = bold line border); source: own study

DISCUSSION

Climatic warming and urbanisation have exacerbated urban heat island (UHI) effect globally. Waterbodies have significant cooling effect while the current UHI mitigation researches mostly focus on green spaces [Peng *et al.* 2020]. Many studies showed that the ability to regulate the temperature of a water reservoir varies with the season [van Hove *et al.* 2015] and even the time of day. The seasonal comparison study e.g. in Copenhagen showed the cooling intensity of waterbodies was the highest in summer. The results showed that the waterbody patches had significant cooling intensity, which could maximally cool the LST of the surrounding [Yang *et al.* 2020].

If the reservoir mitigates, the UHI effect by lowering the ambient temperature, this should be recorded during the most adverse high-temperature conditions [Yu *et al.* 2020] rather than the weather with low temperatures that do not create hazards and reduced quality of life.

Following the previous assumption, the reservoir study is based on Landsat 8 band 10 data for the 167 water reservoirs located within a temperate climate. The satellite images gathered during the period of a heat wave, which appeared between the 24th and 31st of August 2019 were used in the analysis. After a series of warm days, the air temperature increases up to 25°C on 24 August (warm day), and which air temperature culmination on August 31st, (the hottest day). In addition, conducting the research at the highest recorded temperature, contributed to the consideration of how local climatic conditions can be improved, the diversity of plants and associated animals protected [Imhoff *et al.* 2010] and ecosystem services provision. Analysis of beneficial effects, for both variants of analysis, within 30 m of the reservoir shore, compared to 600 m for Lake Qinghai in China [Shi *et al.* 2020], is due to the size of the water bodies. Reservoirs in urban areas are relatively small and with a large number of obstructions, such as buildings, impeding airflow, their beneficial effects on the surrounding environment are reduced. The biggest influence on changes in UCI (Urban Cool Island) intensity was the surface area of the water reservoirs. However, the effectiveness of UCI had a significantly negative correlation with the surface area of the water reservoirs. This means that for the same total water reservoir area, smaller ones may have more beneficial effects. It is probably possible to identify so-called threshold values for reservoirs analysed in temperate climates at the level identified by Sun *et al.* [2019], respectively at 100 and 200 m.

Not all cities have a distinct urban heat island, and heat island characteristics strongly depend on the climate in which the city is geographically located [Chakraborty, Lee 2021]. Studies have shown that UHI can affect temperatures in areas 2–4 times greater than in the city itself [Zhou *et al.* 2015]. On a regional scale, these temperature changes can be twice as large as projected warming from greenhouse gas emissions alone. It is important to quantify the impact of the urban environment on a regional scale, as it can affect the hydrological and radiological balance in megacities [KENNEDY *et al.* 2015].

The cooling intensity of water reservoirs is generally spatially heterogeneous and depends on the place in the world. PENG *et al.* [2020] showed that the average is 1.1°C and the maximum water in the reservoirs lowers the temperature by 5.54°C in Beijing and depends on the size of the reservoir.

The obtained results in the temperate climate zone showed that during hot waves analysed water reservoirs had the average *LST* 4.62°C lower on a warm day and 1.9°C lower on a hot day, than in urban areas. Studying the dynamics of *LST* is crucial to better understanding its impact on regional climates [JABER, ABU-ALLABAN 2020]. The analysis showed that both the reservoirs above 1 ha and the presence of ACT showed a positive effect on the reduction of *LST* (surface temperature) both during warm days (W) and the culmination of the heat wave (H). Thus, the role of green and blue infrastructure in reducing the negative effects of UHI in the temperate zone was confirmed.

An important issue in this respect is the size of the tanks and their vicinity. The presented data show that the creation of water reservoirs with a coastal zone covered with woody vegetation in close proximity to inhabited areas is an effective way to reduce the negative effects of UHI.

Such locations are also the most convenient for providing rest when temperatures exceed the limits of thermal comfort. Forested areas showed a large range of LST variability, however, they were always areas with lower temperatures than built-up areas. This is probably due to the type of woody vegetation and its percentage coverage in the vicinity of the reservoirs. However, determining the most effective types of woody vegetation in terms of UHI reduction requires a much more detailed study [ZHANG, BRACK 2020].

The water reservoir acts as a regional heat source in winter and a heat radiator in summer, and its thermal inertia causes a delay in relation to the adjacent ground surface. Therefore, further comparative studies of the seasons and the day are necessary.

Moreover, it was found that the most effective temperature reduction is recorded in inhabited areas in close proximity to reservoirs up to 300 m and ACH sites. This effect can also be observed in agriculture and natural ecosystems outside cities or in city parks [LI, YU 2013], and their quantification may be useful for developing solutions for the adaptation of cities to future climate change. When analysing a warm and hot day, a similar tendency was shown in the need to combine water-gathering sites with the appropriate type of vegetation, i.e. with trees.

CONCLUSIONS

1. Reservoirs with an area of more than 1 ha, in the temperate climate zone, reduce the UHI temperature on the warmest days of the year and can be a place for creating a UCI with an appropriately shaped green infrastructure.
2. Lowering the temperature within cities by water reservoirs depends on the reservoir's surface and the proportion between the surrounding trees and buildings.
3. Water reservoirs, in order to effectively reduce the negative effects of UHI and increase the comfort of the inhabitants' life, should occupy an area larger than 1 ha and be located in the vicinity of trees located up to 300 m away.
4. LST is a critical parameter for a better understanding of its impact on regional climates and characterising land use/land cover (LULC).
5. Landscape design and planning taking into account the role of reservoirs and their surroundings is becoming more and more important due to global warming and progressive urbanisation.

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