Spatial Factors Influencing Urban Heat Island Formation: A Case Study of Zwolle, The Netherlands

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Abstract- Global warming trends have led to extreme heat events, which are predicted to worsen in the future. The effects of global warming are greater and more noticeable in urban areas than in nearby rural regions. A city is said to experience an "Urban Heat Island" when the temperatures in urban areas rise higher than the temperatures in the nearby rural areas. Additionally, some regions of a city are frequently hotter than others resulting in the formation of so-called "Intra-Urban" Heat Islands at the neighborhood level. UHI leads to an increase in the concentration of harmful pollutants such as CO2 emissions to the atmosphere, degradation of indoor and outdoor thermal comfort, affects health conditions, and increases mortality. This study aims to identify spatial factors contributing to UHI, with a particular focus on Zwolle. Using spatial analysis techniques and Geographic Information Systems (GIS), we assess land cover, urban morphology, and anthropogenic activities that influence UHI. Findings reveal that factors such as land surface materials, green space distribution, and building density significantly impact temperature variations. Understanding these spatial factors provides insights for urban planners to develop mitigation strategies, including Nature-Based Solutions (NBS).

I. INTRODUCTION

Urban Heat Island (UHI) is an emerging wicked problem, especially in cities around the world. In the last 40 years, heat hazards, such as heat waves and extensive extreme heat events, have worsened and are predicted to worsen in the future, endangering global adaptation efforts even in high- income countries (Alizadeh et al., 2022). Heat waves are periods with very high temperatures, sometimes accompanied by high humidity (Marx et al., 2021). According to climate predictions, over the next 50 years, heat waves will become more frequent and more severe. In the previous century, 38 heat waves hit Europe, with eleven occurring after 1990 and six following 2000 (Reay et al., 2007). The average global temperature has risen by 0.9°C between 1880 and today (Kennisportaal Klimaatadaptatie, 2022a). Temperatures in the Netherlands have risen higher: the temperature has risen 1.8°C warmer since 1901. Climate change will cause the Netherlands to warm up by 1 to 2.3°C by 2050 compared to the present climate (Kennisportaal Klimaatadaptatie, 2022a). By 2085, the temperature increase could reach 3.7°C (Kennisportaal Klimaatadaptatie, 2022a). Additionally, the proportion of people living in cities globally is rising. More than 60% of the world's population will reside in urban areas by 2030 (80% in Europe) (Kim & Baik, 2004). The predicted trends could have significant repercussions such as increasing the severity of Urban Heat Islands.

The effects of global warming are greater and more noticeable in urban areas than in the nearby rural regions

because air and surface temperatures in urban areas are often higher (Hove et al., 2011). When the temperatures in urban areas rise higher than the temperatures in the nearby rural areas, the city is said to experience a phenomenon known as "Urban Heat Island" (UHI) (Nwakaire et al., 2020). Furthermore, some regions of a city are frequently hotter than others. These neighborhood-level heat islands are referred to as "Intra-Urban" Heat Islands (EPA, 2022). The uneven, inequitable distribution of landcovers in the urban landscape results in more heat-absorbing structures and pavements and less cool places with trees and greenery, resulting in Intra-urban Heat Islands (EPA, 2022). UHI is brought on by differences in the radiative and thermal characteristics of urban infrastructure, as well as by the influence that buildings may have on the local microclimate (Hove et al., 2011). For instance, towering structures may reduce the pace at which cities cool down at night. The UHI effect will worsen the effects of urban warming, raising summer temperatures in urban areas relative to remote rural locations. UHIs may become more intense due to anticipated increases in solar radiation and decreased wind velocity (Hove et al., 2011).

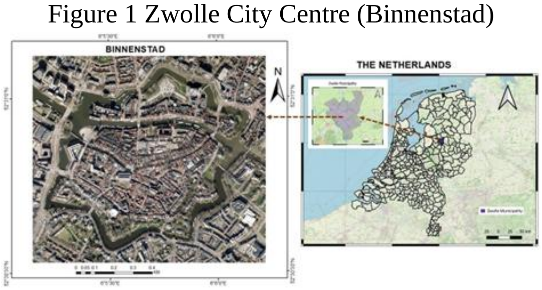
The consequence of Urban Heat Island is that energy consumption is exasperated during the summer as cities consume more energy to cool and function efficiently (Gago et al., 2013). It increases the concentration of harmful pollutants such as CO2 emissions to the atmosphere, degrades indoor and outdoor thermal comfort, affects health conditions, and increases mortality (Akbari & Kolokotsa, 2016). Furthermore, droughts, summer smog, and elevated levels of air pollution frequently occur with heat waves (Hove et al., 2011). An extensive corpus of studies on the adverse effects of UHI on human health as a result of the prominence of heat was studied in Australia (Zander et al., 2019). In Adelaide, for instance, during a particularly severe heat wave in 2009, the number of ambulances calls and admissions to hospitals directly connected to the heat was greater than in prior heat waves. (Zander et al., 2019).

II. METHODOLOGIES

2.1 Study Area

Zwolle, a medium-sized Dutch city experiencing urbanization challenges.

Figure 1 Zwolle City Centre (Binnenstad)



2.2 Data Collection

2.2.1 Literature Review

A literature review and desk research on spatial factors that contribute to Urban Heat Island has been conducted. The review evaluates the research methodologies and results of various published and unpublished research articles. The source for the literature review includes Online Library databases such as Web of Science, Sage Journals and Google Scholar, as well as websites. The criteria for choosing the research articles include preparing a list of key search words. The search words were selected based on their relevance to the topic. A credibility check was conducted for all sources considered in the literature review, such as the credentials of the author, the year of publication, and the credibility of the website. Most of the research articles are from the last decade (2013), and a few include previous decades to provide foundational support for the concepts. The most cited articles were also given preference. This step is necessary to access reliable information on the spatial factors that contribute to Urban Heat Island in Urban areas. Table 1 shows the search results considering the criteria mentioned above.

Table 1 Keywords and Results

Keywords	Google scholar	Web of science	Sage Journals
Spatial + Factors + Urban Heat Island	3410	21	24
Land cover + Urban Heat Island	1410	35	136
NDVI + Urban Heat Island	484	6	18
Urban morphology + Urban Heat Island	738	9	36

Table 2 UHI Data Source

Image	Source	Acquisition Year	Projection
UHI 2017	National Institute for Public Health and the Environment (RIVM)	2017	EPSG:28992 - Amersfoort / RD New

2.2.2.2 Land Cover and NDVI classification to identify the spatial factors that may contribute to Intra-Urban Heat Island in the study area.

Remote sensing and GIS methods were used for Land cover Classification and NDVI. The aerial orthophoto images used in the classification were acquired from PDOK which is a public Geo web service that has the most recent geospatial data sets of The Netherlands from the government (Publieke Dienstverlening Op de Kaart (PDOK), 2023b). The Geo web service provides access to downloads of the following datasets: the Luchtfoto 2017 Ortho 25cm infrared and the Luchtfoto 2017 Ortho 25cm RGB. Table 3 below summarizes the data properties.

Table 3 Orthophoto Data Properties

Image	Source	Acquisition Year	Projection
Luchtfoto 2017 Ortho 25cm infrared	PDOK	2017	EPSG:28992 - Amersfoort / RD New
Luchtfoto 2017 Ortho 25cm RGB	PDOK	2017	EPSG:28992 - Amersfoort / RD New

The Data processing and land cover analysis was done in ARC Map. Training data was used to determine the classes for supervised land cover classification before classification. Four classes were determined, that is Built-Up Area, Trees, Water and Grassland. Each class was assigned 20 training samples, making a total of 80 training samples. Supervised classification was then carried out. The Interactive Supervised Classification algorithm was used. To ensure the accuracy of the results, an accuracy assessment was conducted to validate the land cover classification results. Table 4 below shows the accuracy of the supervised classification. In addition, the three areas of interest selected in the study area are analyzed for a more comprehensive land cover classification. *(Area of interest A)* which exhibits high temperature, *(Area of interest B)* that exhibits lower temperature and (*Area of interest C*) that exhibits medium temperature.

Table 4 Accuracy assessment results of land cover

Classification	Classes	Producers Accuracy	Overall Accuracy	Kappa
Supervised Land cover classification	Built-Up Area	98%	95%	91%
	Trees	91%		
	Water	90%		
	Grassland	90%		

2.2.3 Spatial Statistical Methods

2.2.3.1 Correlation analysis to determine the relationship between land cover and temperature variations.

NDVI was computed using unsupervised classification. To test the quantitative relations between vegetation and Urban Heat Island, a statistical Pearson's correlation was undertaken between NDVI values and UHI values on excel using data points generated randomly from the maps. The NDVI values were plotted against the UHI values, the R co- efficient value was calculated. The coefficient R value is a statistical measure that quantifies the strength and direction of the linear relationship between two continuous variables A value of +1 indicates a perfect positive linear relationship, meaning that as one variable increases, the other variable also increases proportionally (Turner, 2022). A value of -1 indicates a perfect negative linear relationship, meaning that as one variable increases, the other variable decreases proportionally (Turner, 2022). A value of 0 indicates no linear relationship between the variables. The correlation results analyzed in a scatter plot (Turner, 2022).

III. RESULTS

3.1 The spatial factors that influence the formation of Urban Heat Island

Previous research has demonstrated that local temperature variations are caused by processes that include land cover- based physical and biological factors such as land use and land cover compositions, specifically the spatial distribution of vegetation (grass, shrubs, trees), impervious surfaces (buildings, roads, parking lots), water bodies and bare lands (Park et al., 2021). The intensity of UHI in a specific city results from various factors interacting on multiple spatial and temporal scales (Hove et al., 2011). To begin with, climate plays a crucial role in UHI formation: Urban climate is influenced by latitude, topography, and distance to large bodies of water. On the other hand, UHI intensity is influenced by urban characteristics such as the size of the city, urban design, building structures, and population- related factors (Hove et al., 2011).

Larger cities that are more compact and less stretched have stronger UHI intensity (Zhou et al., 2017). In addition, buildings that are close to each other interact with solar radiation, trapping them and causing many reflections between buildings and roads before the solar energy is reflected into space (Steeneveld et al., 2011). Furthermore, construction materials like concrete and asphalt absorb heat energy during the day and release it at night (Ujang et al., 2018). On top of that, rapid urbanization has resulted in profound changes in Land Use and Land Cover. The conversion of agricultural land, bare land, and other natural land types into urban commercial, residential, and industrial areas has resulted in impermeable surfaces replacing natural surfaces (Huo et al., 2021). As a result, the thermal conductivity of underlying surfaces has changed dramatically. This has greatly impacted the heat exchange between the earth's surface and the atmosphere (Huo et al., 2021).

Population also affects the Urban Heat Island effect in several ways. First, as population density increases, the amount of heat generated by human activities such as transportation, industry, and building operations increases (Elsayed & Elsayed, 2012). This excess heat can contribute to the UHI effect, especially in densely populated urban areas. Secondly, population density can affect the distribution and amount of land cover in urban areas (Elsayed & Elsayed, 2012). As population density increases, the amount of impervious surfaces such as roads and buildings also increases, which can contribute to the UHI effect (Elsayed & Elsayed, 2012). However, higher population density can also lead to more green spaces and vegetation, which can help mitigate the UHI effect. Thirdly, population density can affect the amount and type of energy use in urban areas, such as the use of air conditioning and refrigeration systems (Elsayed & Elsayed, 2012). Increased energy use can contribute to the UHI effect by increasing the amount of heat released into the environment (Elsayed & Elsayed, 2012) (See Table 5).

Table 5 Spatial factors and indicators that affect UHI.

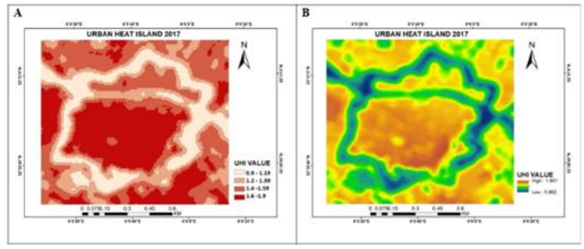
Spatial Factors	Indicators	Justification
Land Based physical and biological factors	Land Use and Land cover composition	Spatial Distribution of vegetation (grass, shrubs, trees), impervious surfaces (buildings, roads, parking lots), water bodies and bare lands can affect the UHI effect. Urban areas with a high proportion of impervious surfaces, such as roads and buildings, experience higher temperatures than areas with more vegetation and water.
Urban morphology	Size of the city	Larger cities that are more compact and less stretched have stronger UHI intensity
	Urban design	The arrangement of buildings and streets in urban areas can affect the flow of air and heat. Narrow streets, tall buildings, and lack of green space can impede airflow and exacerbate UHI.
	The concentration of building structures	High-density urban areas with a lot of buildings and infrastructure can trap heat more efficiently than low-density areas with less development.
	Population-related factors	Population can affect the UHI effect through its impacts on heat generation, land cover, and energy use in urban areas.
Building morphology	Building height	Taller buildings can block wind and sunlight, which can contribute to the accumulation of heat at street level.
	Building material (Brick, Concrete, Asphalt)	Different materials have varying abilities to absorb and reflect heat. Dark-colored surfaces such as asphalt and concrete absorb more heat than lighter-colored surfaces like grass and trees, leading to higher temperatures in urban areas.

	Roof type (Flat, Hip, Half hip, Gabble, Green roof)	Roofs made of heat-absorbing materials such as asphalt, tar, or gravel can contribute significantly to UHI. Conversely, reflective, or "cool" roofs that reflect sunlight can help reduce UHI.
Surface characteristics	Impervious surfaces	Different surface materials have different thermal properties, such as thermal conductivity, heat capacity, and albedo, which influence the amount of solar energy absorbed and reflected by the surfaces. For example, pavements with low albedo (i.e., darker surfaces) absorb more solar radiation and emit more heat than high-albedo surfaces, such as white roofs or green spaces.
	Pervious surfaces	
	Green surfaces	Trees and greenery can provide shade, evapotranspiration, and cooling effects that mitigate the heat island effect. However, urban areas often have less green space, which exacerbates UHI.
	Blue surfaces	Water can reduce the UHI effect in urban areas by acting as a heat sink, facilitating evaporative cooling, and providing shade.

3.2 Urban Heat Island and Areas of interest

The summer average UHI for 2017, which was analyzed for June, July and August by the National Institute for Public Health and the Environment (RIVM), as seen in Figure 2(A) and (B); where (A) is classified into 4 classes, and (B) the values are stretched, shows the spatial manifestation of the Intra-Urban Heat Island effect in the study area in a 10m resolution map (rivm, 2023). The maps show that parts of the study area experience warmer temperatures than others. The core of the study area in particular experiences a higher temperature compared to the outskirts of the study area.

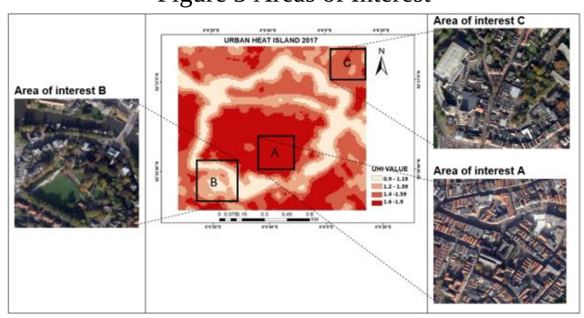
Figure 2 Intra-Urban Heat Island 2017 (rivm, 2023)



3.2.1 Areas of Interest

Three areas of interest were chosen within the study area based on the results of the 2017 UHI intensity analysis (RIVM). The areas are identified as *Area of Interest A*, which exhibits higher temperature, *Area of Interest B* which exhibits lower temperature and *Area of Interest C* which exhibits medium temperature without a water feature (See Figure 3). These areas are important to understand the cause of temperature variation within the study area, specifically the land cover, the indicators of UHI and the urban morphology based on the 3D model. These areas are also important for selecting locations for Nature-Based Solutions.

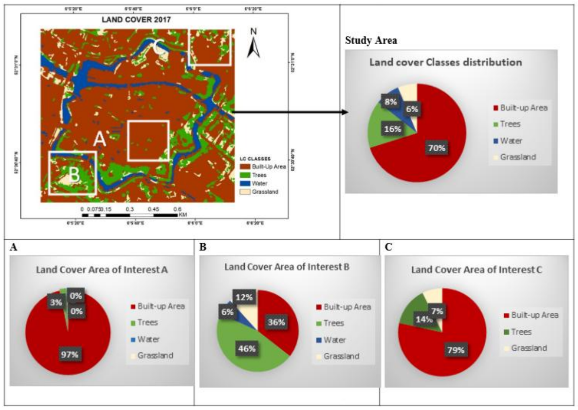
Figure 3 Areas of Interest



3.3 Land cover classification

Based on the results of the supervised Land cover classification analysis, the dominant land cover type in the study area is built-up area with a percentage of 70%, followed by trees at 16%, water at 8% and grassland at 6%. This spatial distribution of land cover in the study area as shown in figure 2 reveals that there is a high proportion of impervious surfaces, such as buildings, roads and pavements which are known to experience higher temperatures than areas with more vegetation and water. To have a better understanding of the relationship between land cover and UHI, three areas of interest chosen based on the results of the UHI intensity analysis; *Area of interest A* which exhibits higher temperature, *Area of interest B* which exhibits lower temperature and *Area of interest C* which exhibits medium temperature have been examined and the land cover in the three areas analyzed according to the percentage of occurrence of the different classes. The results are visualized in pie charts as shown in Figure 4.

Figure 4 Land Cover Classification

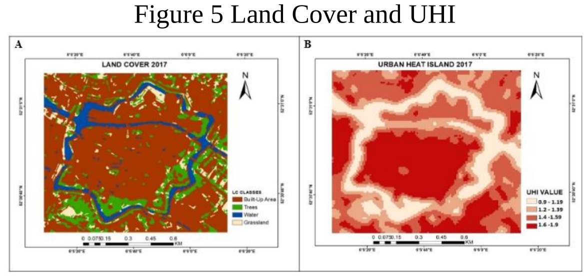


Area of Interest A which exhibits higher temperatures, has the highest percentage of Built-Up area at 97%, followed by *Area of Interest C*, which exhibits medium temperature at 79%, and lastly *Area of Interest B* which exhibits lower temperatures with 36% of built-up area. This supports the literature review findings that buildings and paved surfaces such as roads and parking lots absorb and retain heat, leading to increased temperatures in urban areas. In contrast, vegetation and water bodies have been shown to help cool urban areas by providing shade, evapotranspiration, and reflection of solar radiation. *Area of Interest B* which exhibits the highest percentage of trees, water, and grasslands with a total of 64%, exhibits lower temperatures compared to *Area of Interest A* and *C*. *Area of Interest A* has the least amount of vegetation and water, while *Area of* up area, and lastly, *Area of Interest B*, which has lower temperature and lowest percentage of built-up area at 36%. These results are supported by the literature review findings that a high percentage of built-up land cover with features like buildings and paved surfaces such as roads and parking lots absorb heat from the sun, leading to increased temperatures in urban areas (Park et al., 2021), (Zhou et al., 2017). In contrast, vegetation and water bodies can help cool urban areas by providing shade, evapotranspiration, and reflection of solar radiation (Zhou et al., 2017). This was supported by the results that *Area of Interest B*, which exhibits lower temperature has the highest percentage of trees, grass, and water (64%), followed by *Area of Interest C* which has 21% tree and grassland.

3.4 Spatial pattern comparison

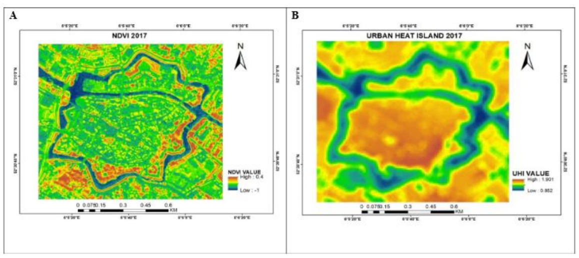
When comparing the spatial pattern between the Land Cover (Figure 5A) and Urban Heat Island (Figure 5B), the spatial pattern indicates that the core area of the study area, which comprises of majorly Built-up land cover class, with features like buildings, roads and pavements experiences a higher Urban Heat Island compared to the outskirts of the study area where the canal passes, and has a healthy vegetation combination of trees and grassland. According to research, the existence of vegetation may reduce the intensity of UHI. Tall mature trees provide shade while also lowering the temperature in dense built-up areas. This is because vegetation converts solar energy into latent thermal energy through water evaporation (Hove et al., 2011). The presence of a canal has a cooling impact on the surrounding area through the process of evaporation and heat absorption. The cooling effect of water bodies may also be because water bodies provide a free wind path. (ventilation zone) (Hove et al., 2011). The lowest temperatures are distributed along the water land cover. It can also be noted that the park and pockets of trees within the built-up area have a lower SUHI influence on the surrounding built-up area. Tree land cover also indicates a lower UHI effect compared to grass vegetation.

Figure 5 Land Cover and UHI



In general, the NDVI scale runs from +1.0 to -1.0. NDVI readings are typically quite low in areas of water, barren rock, sand, or snow (for example, 0.1 or less) (USGS, 2018). Moderate NDVI values may occur from sparse vegetation, such as shrubs and grasslands, or from senescing crops (approximately 0.2 to 0.5). High NDVI values (about 0.6 to 0.9) indicate dense vegetation, such as that found in temperate and tropical woods, or crops in their peak development stage (USGS, 2018). The results of the NDVI in this analysis (Figure 6A) shows the highest NDVI value is 0.4, which indicates a moderate NDVI that is characterized by shrubs, grasslands and sparse tree vegetation. Based on these results, the trees and grass in the study area have the highest NDVI value of between 0.2 and 0.4, buildings have a medium to low NDVI while water has the lowest NDVI value. A spatial pattern comparison between NDVI and UHI as seen Figure 6 shows areas with a high vegetation index exhibit a lower temperature, however, water, which has the lowest NDVI value, exhibits the lowest temperature. The buildings which have a medium NDVI value exhibit the highest temperature.

Figure 6 NDVI and UHI

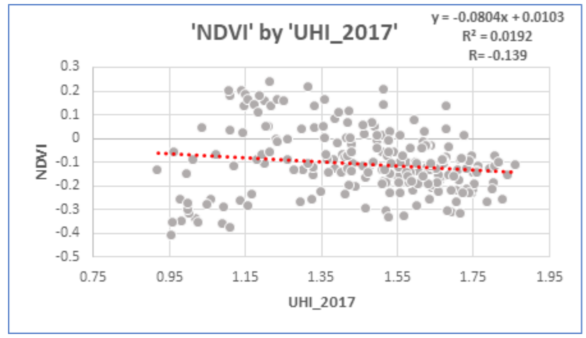


3.5 Pearson's Correlation analysis between NDVI and Urban Heat Island

Based on the results of the correlation between NDVI and UHI, there is a weak negative linear correlation. The points on the scatter plot are spread out in a general downward direction, but with a lot of variation in the data points (Figure 7). The correlation coefficient R value is -0.139 (The coefficient R value is a statistical measure that quantifies the strength and direction of the linear relationship between two continuous variables). This indicates that while there is a slight inverse relationship between NDVI and UHI variables, it is not a strong one. This also suggests that if NDVI variable rises, the UHI variable tends to fall slightly. The strength of the link is relatively weak and not consistent. The relationship between NDVI and UHI may be influenced by other factors such as the time of the day and the season affecting the prediction of one variable based on the other.

Based on literature, the time of the day and season affect the associations between LST and the Normalized Difference Vegetation Index (NDVI). The relationship between NDVI and LST is positive throughout the winter (Sun & Kafatos, 2007). Only during the warm seasons are there large negative relationships between LST and NDVI (Sun & Kafatos, 2007). The data used for the UHI in this case was collected on 21st June 2017, the beginning of summer, there is no information on the precise time, thus may explain the weak negative correlation results.

Figure 7 NDVI&UHI scatter plot



IV. DISCUSSION

When comparing the spatial pattern between the land cover map and the UHI map, as well between the NDVI map and the UHI map, the results are consistent with the findings of the land cover analysis. The core area of the study area, which comprises of majorly built-up land cover class with spatial features such as mid-rise buildings and impervious pavement surfaces and has a medium to low NDVI value, experiences a higher temperature compared to the outskirts of the study area where the canal passes. The lowest temperatures are distributed along the water land cover which has the lowest NDVI value. It was also noted that the park and pockets of trees within the built-up area, which have the highest NDVI value exhibit lower temperature. Furthermore, the trees exhibit lower temperature compared to grass. The relationship between NDVI and UHI from the Pearson's correlation analysis found a weak negative linear correlation. Although there is a lot of variation in the data points, the scatter plot's points are dispersed in a general downward direction. This can be interpreted that when the NDVI variable increases, UHI variable tends to decrease slightly.

The indicator-based field visit to observe *Area of interest A* revealed that the area has dense compact buildings with a majority of three to five-story buildings and narrow streets. The construction materials include bricks, concrete, asphalt, dark-colored roofs, and impervious pavement surfaces. The region lacks water and only has a few street trees. The construction materials used in the area have been demonstrated to influence the intensity of UHI because they alter how the sun's energy is reflected, radiated, and absorbed. *Area of interest B* is primarily made up of green and blue infrastructure, such as a park, street trees, and a canal. Trees and water have been demonstrated to aid in the reduction of the urban heat island effect through evapotranspiration, absorbing solar radiation and tree shading. *Area of interest C*, which registers a medium temperature, is made up of mixed-use land cover, with a mix of 2 to 3 story buildings, broad streets, impervious pavements, car parks, street trees, and grassland. The presence of urban greenery and a less dense building layout indicate that less dense low-rise built-up areas with green and blue infrastructure may experience lower temperatures than high density mid-rise areas with little green and blue infrastructure, as in *Area of interest A.*

CONCLUSION

The results show the Intra-Urban Heat Island effect in Zwolle city Centre has led to increased temperatures in some areas compared to others. The UHI occurs due to the presence and distribution of some spatial factors and their indicators such as land cover-based physical and biological factors, urban morphology, building morphology and surface characteristics. The main cause of the Intra-Urban Heat Island effect based on the findings of sub objective one can be attributed to the replacement of natural surfaces with concrete, asphalt, brick buildings, and impervious pavements which absorb and retain heat as well as reduced vegetation cover which have a cooling effect on the environment. Findings emphasize the necessity of urban planning interventions such as Nature-Based Solutions to mitigate UHI impacts. Future research should integrate dynamic modeling approaches to predict long-term urban Disc climate trends.

REFERENCES

[1] Akbari, H., & Kolokotsa, D. (2016). Three decades of urban heat islands and mitigation technologies research. *Energy and Buildings, 133*, 834-842. https://doi.org/10.1016/j.enbuild.2016.09.067

[2] Alizadeh, M. R., Abatzoglou, J. T., Luce, C. H., Adamowski, J. F., Farid, A., & Sadegh, M. (2022). Warming enabled upslope advance in western US forest fires. *Proceedings of the National Academy of Sciences, 118*(22), e2009717118. https://doi.org/10.1073/pnas.2009717118

[3] Elsayed, I. S., & Elsayed, M. S. (2012). Urban heat islands: Causes, impacts, and mitigation strategies. *Journal of Environmental Science and Engineering, 1*(3), 1-12.

[4] Environmental Protection Agency (EPA). (2022). *Heat island effect*. Retrieved from https://www.epa.gov/heatislands

[5] Gago, E. J., Roldan, J., Pacheco-Torres, R., & Ordóñez, J. (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews, 25*, 749-758. https://doi.org/10.1016/j.rser.2013.05.057

[6] Hove, B. V., Jacobs, C., Heusinkveld, B., Elbers, J., & Holtslag, A. (2011). Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Building and Environment, 46*(5), 1005-1014. https://doi.org/10.1016/j.buildenv.2010.11.008

[7] Huo, X., Li, Z., Wang, H., & Sun, Y. (2021). Impacts of land use and land cover change on urban heat islands: A case study of Beijing, China. *Remote Sensing, 13*(5), 898. https://doi.org/10.3390/rs13050898

[8] Kennisportaal Klimaatadaptatie. (n.d.). *Climate change in the Netherlands*. Retrieved from https://www.klimaatadaptatienederland.nl

[9] Kim, Y. H., & Baik, J. J. (2004). Daily maximum urban heat island intensity in large cities of Korea. *Theoretical and Applied Climatology, 79*(3-4), 151-164. https://doi.org/10.1007/s00704-004-0070-7

[10] Lauwaet, D., Hooyberghs, H., Maiheu, B., Lefebvre, W., Driesen, G., & van Looy, S. (2018). Detailed urban heat island projections for cities worldwide: Dynamical downscaling

CMIP5 global climate models. *Climate, 6*(1), 5. https://doi.org/10.3390/cli6010005

[11] Marx, W., Haunschild, R., & Bornmann, L. (2021). Heat waves: A hot topic in climate change research. *Theoretical and Applied Climatology, 146*(1-2), 781-800. https://doi.org/10.1007/s00704-021-03758-y

[12] Nwakaire, C. M., Onn, C. C., Yap, S. P., & Yuen, C. W. (2020). Urban heat island effects in tropical cities: A systematic review. *Environmental Science and Pollution Research, 27*(16), 19307-19319. https://doi.org/10.1007/s11356-020-08568-9

[13] Park, J., Kim, J. H., Lee, D. K., Park, C. Y., & Jeong, S. G. (2021). The influence of small green space type and structure at the street level on urban heat island mitigation. *Urban Forestry & Urban Greening, 21*, 203-212. https://doi.org/10.1016/j.ufug.2016.12.005

[14] Reay, D. S., Smith, P., & van Amstel, A. (2007). *Methane and climate change*. Earthscan.

[15] RIVM. (2023). *Urban heat island intensity maps*. National Institute for Public Health and the Environment. Retrieved from https://www.rivm.nl

[16] Steeneveld, G. J., Koopmans, S., Heusinkveld, B. G., & Theeuwes, N. E. (2011). Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect. *Landscape and Urban Planning, 121*, 92-96. https://doi.org/10.1016/j.landurbplan.2013.08.001

[17] Sun, D., & Kafatos, M. (2007). Note on the NDVI-LST relationship and the use of temperature-related drought indices over North America. *Geophysical Research Letters, 34*(24), L24406. https://doi.org/10.1029/2007GL031485

[18] Turner, M. G. (2022). *Spatial statistics for environmental and ecological data*. Cambridge University Press.

[19] Ujang, U., Anton, F., & Rahman, A. A. (2018). The impact of urban heat island on building energy consumption: A review. *Sustainable Cities and Society, 41*, 686-694. https://doi.org/10.1016/j.scs.2018.06.012

[20] USGS. (2018). *Normalized Difference Vegetation Index (NDVI)*. United States Geological Survey. Retrieved from https://www.usgs.gov

[21] Zander, K. K., Botzen, W. J., Oppermann, E., Kjellstrom, T., & Garnett, S. T. (2019). Heat stress causes substantial labour productivity loss in Australia. *Nature Climate Change, 5*(7), 647-651. https://doi.org/10.1038/nclimate2623

[22] Zhou, W., Huang, G., & Cadenasso, M. L. (2017). Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes. *Landscape and Urban Planning, 102*(1), 54-63. https://doi.org/10.1016/j.landurbplan.2011.03.009