Beat the Heat: The Effect of Urban Density on the Urban Heat Island Effect in Rotterdam

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Abstract

The urban heat island effect (UHIE) is a critical factor that augments the challenges of climate change. Its consequences on the wellbeing of citizens may be crucial for public health. Current health consequences due to heat can cause issues that range in severity but ultimately can lead to death. Previous studies showed that urban density contributes to the UHIE but lack policy guidance to mitigate the UHIE. They also employed different definitions of urban density and used specific parameters. This study investigates the effect of urban density on the UHIE within 5 neighborhoods in Rotterdam. Important aspects of urban density are horizontal and vertical density and land cover. The urban density of the studied neighborhoods is calculated based on their ambient address density (AAD). This discusses urban density by focusing on the number of addresses in a neighborhood. This study analyzed the association between quantitative data of neighborhood characteristics and air temperature within these 5 Rotterdam neighborhoods. Geographical data was used to determine the boarders of the neighborhoods. Moreover, cartographic aspects were included to evaluate the level of greenery. potential confounders were considered for the model but did not show strong association. The results of the study show that AAD is associated with the air temperature, and therefore UHIE, in Rotterdam. Future research should employ a more comprehensive definition of urban density to address its complexity. This will facilitate the establishment of meaningful policies for Rotterdam and other cities to improve the public health of its citizens by mitigating UHIE.

Keywords and abbreviations: Urban heat island effect (UHIE), urban density, Rotterdam, ambient address density (AAD)

1. Introduction

The continuous growth of cities in The Netherlands causes the urban environment to face unique challenges that impact the health and well-being of their residents. One of these challenges is the urban heat island effect (UHIE), a phenomenon where urban areas, such as cities, experience higher temperatures than their rural surroundings due to factors like reduced vegetation and increased heat-absorbing surfaces (Nieuwenhuijsen, 2021). Rotterdam is known for its skyline and fast urbanization, something that can exacerbate the UHIE. These temperature rises due to climate change may severely affect the health of the population.

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High temperatures can cause heat stress and dehydration. This may result in dizziness or muscle cramps, nausea and vomiting, or headaches and cardiac strain. Dehydration can eventually lead to heat stroke which may permanently damage vital organs or lead to death. Furthermore, high temperatures may cause heat exhaustion, which is fatal when treatment is delayed (Mueller et al., 2024). Heat associated health problems should be treated by removing the patient from heat. However, in an environment that continues to increase in temperature, this option may not be a viable long-term solution. Therefore, it is important to address how this urban heat can be battled at a policy level, instead of focusing on treating individuals or groups of patients affected by it.

Since the UHIE can exacerbate these health issues, addressing the root causes of urban heat exposure is important to enable mitigation of UHIE. Therefore, it is relevant to assess which aspects of cities contribute to UHIE. Urban density is a strong determinant of UHIE Mohajerani et al., 2017). High-density areas often have increased surface temperatures, reduced airflow, and trap more heat that intensifies the UHIE (Mohajerani et al., 2017). Rotterdam contains densely populated neighborhoods that make the inhabitants vulnerable to these consequences. As temperatures rise, these vulnerable populations in Rotterdam may face disproportionate health consequences.

The rising temperatures are driven by climate change. Climate change can cause longer and more intense heatwaves in the near future (Zhao et al., 2017). This means that the population of urban areas will have to carry the consequences of not only the UHIE, but also the additional heat stress from the heatwaves (Ward et al., 2016). The interaction between the UHIE and heat waves is argued to be significantly intertwined. When a heat wave occurs, the UHIE increases more strongly (Zhao et al., 2017). Given these risks, it is crucial to investigate how the structural layout of Rotterdam and its specific urban density contribute to elevated temperatures and the UHIE. Therefore, I composed the research question: How does urban density influence the urban heat island effect in heatwaves in Rotterdam?

With this research, this study aims to explore how the urban density in Rotterdam influences the city's air temperature and how this contributes to the UHIE. Examining this association will provide insights how urban planning and public health policies can include mitigation of UHIE risk factors. By understanding how urban environments affect local air temperatures, vulnerable areas can be identified and changes such as the alteration of building materials can be implemented. These changes can effectively mitigate the UHIE.

2. Literature review

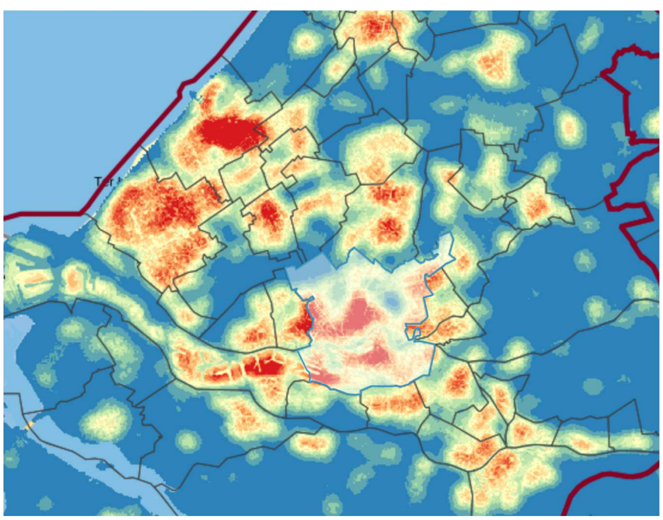
2.1 Urban heat island effect

The UHIE is defined as 'a heat accumulation phenomenon, which is the most obvious characteristic of urban climate caused by urban construction and human being activities' (Yang et al., 2016, p. 45). Rising temperatures within urban environments retain heat through the lack of evapotranspiration. This can be caused by a shortage of greenery and an overflow of buildings, roads, and sidewalks that 'keep' the heat (Vujovic et al., 2021). This remaining captured heat can temper with air quality and air flow which can negatively affect the health of residents from the area. There is a distinction between surface and atmospheric UHIE. This research will focus on the atmospheric UHIE, the difference in air temperature between an urban area and its surrounding green area (van der Hoeven et al., 2018). Atmospheric UHIE has a circadian rhythm, varying between day and night. During night, just after dusk the difference is highest (van der Hoeven et al., 2018).

UHIE may be caused by different factors. Hypothesized causes of UHIE are air pollution, urban energy balance, surface albedo (reflection), and urban density. Research has shown that an increase of air pollutant concentrations for O3 (ozone) increases the UHIE (Wang et al., 2021). Paradoxically, other air pollutants such as PM2.5 help to lower the surface temperature due to their ability to absorb long-wave radiation. Urban energy balance refers to the anthropogenic heat production in urban environments. This contributes to the UHIE as the cooling of buildings will radiate heat that is retained in the city (Shahmohamadi et al., 2011). The surface albedo is a measure for the proportion of light a surface reflects back into the atmosphere, where a high albedo indicates that all light is reflected back. A low surface albedo contributes to the UHIE as heat is not reflected but retained and drives up temperatures (Morini et al., 2016). An important cause of UHIE is the urban density, which is defined as a measure of human occupation. This measure of human occupation differs per residential area and may be recognized by urban planning.

2.2 Rotterdam

The urban planning in Rotterdam is characterized by its dense population and high level of urban density (Bakker, 2018). The city is filled with compact vertical development and extensive use of concrete and asphalt. While this might aid the growing population of Rotterdam in their daily use of infrastructure, it reduces the natural cooling benefits that vegetation would normally perform. It also increases the absorption and retention of heat by artificial surfaces (Van Hove et al., 2015). Moreover, in Rotterdam’s planning of transportation, urban functionality is prioritized over ecological use (Nieuwenhuijsen, 2021). The resultant lack of vegetation amplifies the heat stress in densely populated neighborhoods. Therefore, it is important to take urban density into consideration in urban planning to potentially mitigate the UHIE. The urban planning strategies and building projects in Rotterdam aim to increase green areas and continue to develop high-rise buildings (Municipality of Rotterdam, n.d.). By increasing green areas, Rotterdam shows that it focusses on ‘cooling down the city’ and addressing the UHIE. However, it remains uncertain to what extent urban density is currently integrated into policies. While addressing the UHIE with inclusion of green spaces is beneficial, additional aspects of urban density may be taken into consideration for a comprehensive approach towards the UHIE.



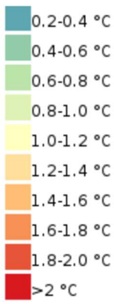


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Figure 1 The urban heat island effect in 2017 in the Greater Rotterdam Area (*Kaartviewer - Klimaateffectatlas*, n.d.; Rijksinstituut voor Volksgezondheid en Milieu [RIVM], 2020)

In Figure 1 the UHIE in Rotterdam is visualized by the Dutch governmental institution 'Atlas Natuurlijk Kapitaal' (Atlas Natural Capital) in cooperation with the Climate Impact Atlas. It shows the area of Rotterdam that struggles with increased heat compared to its surrounding rural areas and therefore suffers from an UHIE. To understand how this UHIE might be related to urban density, the following section explores the concept of urban density in more detail and addresses its different dimensions.

2.3 Urban density

Urban density is an important factor that influences UHIE when it comes to climate change, heat, and the retention of heat in this urban environment (Li et al., 2020). Hess defined urban density as "the degree of concentration or compactness of people or development in a city" (p. 1554, 2014). Building density and a combination of population density and land cover affect heat retention. Within building density, there is horizontal and vertical density. Horizontal density is the concentration of buildings within an area of measurement, vertical density is the concentration of building upwards on existing structures instead of new structures (Al-Kodmany, 2012). When an area with high vertical density also has high horizontal density, microenvironments of buildings affect each other. The shadows, building structure and street canyons can thus affect heat retention on larger scales and contribute to the UHIE (Nugoho et al., 2020). Findings in Hong Kong have shown that areas with high-rise buildings with high horizontal density can increase the UHIE (Giridharan et al., 2004). However, Hong Kong differs from Rotterdam in influential UHIE factors such as altitude or urban structure, which raises the question if these results are generalizable.

Land cover refers to biophysical attributes of the earth's surface and urban morphology. A study done in Bogota, Colombia includes the spatial dimension of urban elements and population density to understand the contribution of land cover and urban form to the UHIE (Ramírez-Aguilar & Souza, 2019). Results showed that the UHIE increases with denser land cover (Ramírez-Aguilar & Souza, 2019). Land cover combined with population density addresses more aspects of urban density than building density. However, Rotterdam and Bogota differ significantly in urban characteristics and population density, which makes it difficult to extrapolate these results.

To address how the population density and urban morphology of Rotterdam might explain differences in air temperatures between neighborhoods, population factors should also be considered. The population aspect of urban density is addressed by the ambient address density (AAD). AAD is "the average amount of addresses per squared kilometer within a circle with a radius of one kilometer" (CBS, 2022). By using addresses as parameter, AAD aims to combine population and building density. In contrast, a Japanese study defined ambient population density, a slightly different parameter, as 'the spatial population density that takes daytime movements and collective travel habits into account' (Roiradtanasari et al., 2024). This focuses more on day-to-day interaction of Japanese people and their distribution, while AAD focuses on building density as well by looking at the number of addresses. AAD aims to reflect the concentration of human activities within a certain area including all human activities, such as living, working, and going to school. Thus, urban density incorporates a high level of complexity, reflecting building density and morphology, land cover and population density.

Based on the information above, this study will test the null and alternative hypothesis for the research question "How does urban density influence the urban heat island effect in a heatwave in various neighborhoods in Rotterdam"? by looking at AAD and air temperatures throughout various neighborhoods in Rotterdam. The null hypothesis states that ore urban density (reflected by AAD) does not influence the air temperature and thereby the UHIE, while the alternative hypothesis states that urban density increases the air temperature and therefore the urban UHIE in Rotterdam.

3. Methodology

3.1 Study design

A natural experiment approach is applied with a focus on one specific heatwave in Rotterdam. The heatwave was present from August 9th to August 16th in 2022, creating an observation period of eight days (KNMI – Augustus 2022, n.d.).

3.2 Data sources

3.2.1 Air temperature data

Air temperature data was collected from TU Delft's weather station network. The network was originally used for rainfall research in urban areas, but measurements contained data on air temperature as well. Only five weather stations (Capelle, Delfshaven, Ommoord, Oost, Spaanse Polder) out of the 16 existing weather stations had usable data. Other stations were excluded due to missing data regarding the measurement period, relocation of the weather station, or because they were not a part of municipality of Rotterdam. Each station's coordinates were verified to match corresponding neighborhoods via the PDOK (Publieke Dienstverlening Op de Kaart) viewer using CBS-defined area boundaries.

The weather stations are located on Roofs of residential buildings in their neighborhood and differ slightly in their microenvironment. As detailed in appendix A, the weather stations differ in their microenvironment due to their locations. The shade and immediate surroundings of the weather stations, as well as their position towards the sun are factors that could influence measurement results. These potential measurement biases will be acknowledged in the limitations section and discussed in relation to the internal validity of the data.

3.2.2 Urban density data

Data regarding urban density was retrieved from the Central Bureau of Statistics (CBS) from dataset “Kerncijfers Wijken en Buurten 2022”. From CBS’s dataset, obtained variables that were relevant regarding urban density were included in the dataset (total surface area, total water surface area, number of vehicles, AAD)

3.2.3 Geographical data

Geographical data was retrieved from PDOK to categorize the corresponding weather stations with neighborhood in CBS. TU Delft assigned names to its weather stations that do not correspond with their prospective neighborhood by the classification of the CBS. To prevent confusion in data analysis, the name of the weather station was linked to its corresponding CBS residential area. During data analysis, the name that TU delft assigned to the weather stations was used to describe the residential area (appendix B). In Figure 2, an outline of each neighborhood is presented.

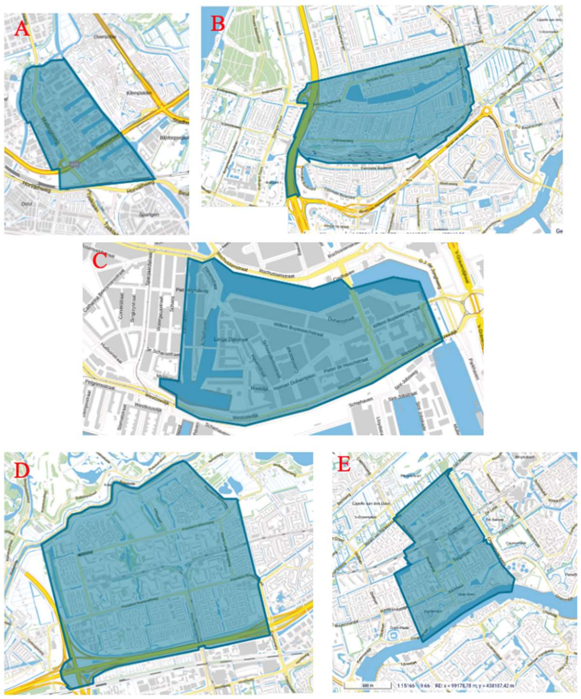

Figure 2 cartographic display of the five neighborhoods. A. Spaanse Polder, B. Oost, C. Delfshaven, D. Ommoord, E. Capelle (adapted from PDOK).

3.2.4 Cartographic data

Since no data was available in the CBS dataset regarding level of greenery, cartographic data from PDOK was used to retrieve information on the level of greenery for each neighborhood in Rotterdam.

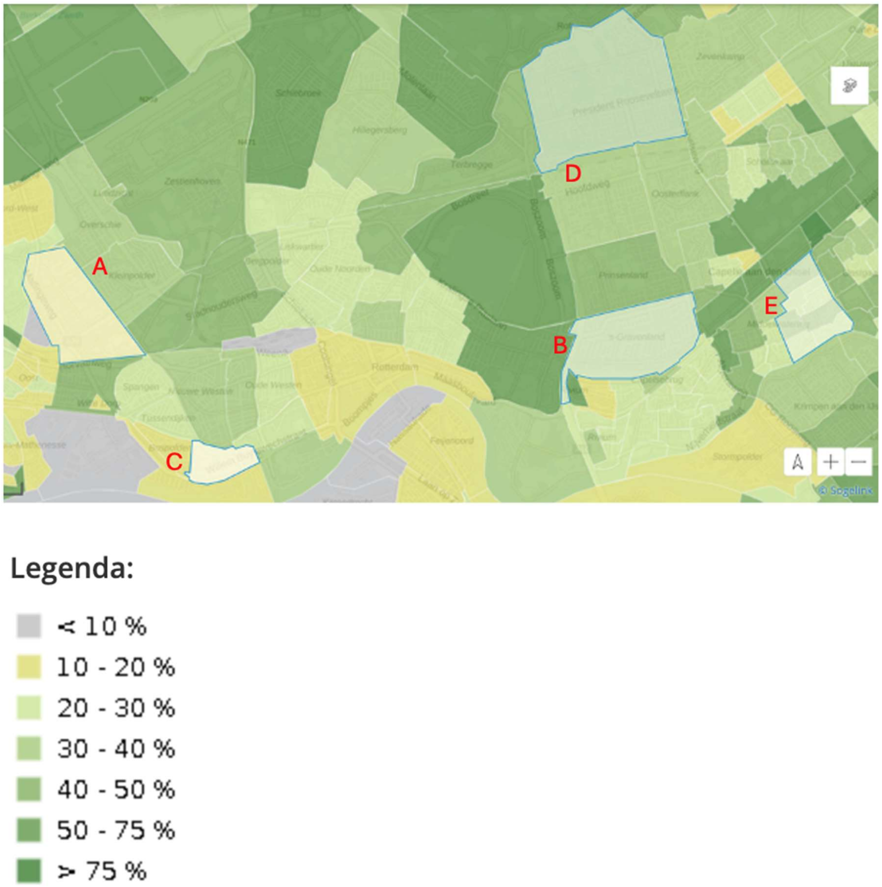

Figure 3 cartographic data from PDOK (Publieke Dienstverlening Op de Kaart) displaying the percentage of greenery in Rotterdam for the studied neighborhoods. A. Spaanse Polder, B. Oost, C. Delfshaven, D. Ommoord, E. Capelle.

3.3 Statistics

3.3.1 Independent variable

Air temperature in degrees Celsius was used to measure UHIE. Previous literature indicated that measurements after dusk are more stable and better reflect the UHIE. Therefore, daily data on air temperature measured at 22:00 during the heatwave was used, creating a sample size of 40 temperature measurements.

3.3.2 Dependent variable

The urban density is measured with CBS's ambient address density (AAD). The AAD differs per neighborhood and is expressed in average number of addresses per squared kilometer within a radius of one kilometer on January 1st of 2022. The neighborhood and its corresponding AAD value can be found in the table below:

Table 1 ambient address density per neighborhood (CBS, 2022).

neighborhood	Ambient address density
Capelle	2899
Delfshaven	5066
Oost	2039
Ommoord	2931
Spaanse polder	1486

3.3.3 Potential confounders

Potential confounders for the air temperature and AAD are measurements that are correlated with the AAD and are related to air temperature. Potential confounders that could influence both variables are: level of greenery, (it could determine how many addresses can be created within an area and helps in cooling temperatures as well), number of vehicles (a higher number of addressed would mean more vehicles would be present for transportation and air temperatures are influenced by emissions), the total surface area (this can determine the number of addresses and influence air temperature with heat absorption and reflection rate), and the total surface area of water (this influences AAD as less addresses can be build when more water bodies are present and the presence of water bodies influence the air temperatures). Linear

Regression between the independent variable and potential confounders were performed to determine if significant potential confounders could be included into the model. The definitions and description of these confounding variables can be found in appendix C.

3.4 Statistical analysis

IBM SPSS Statistics 28 was used to perform statistical analysis. This is grouped into two phases: preparatory analysis and hypothesis testing.

3.4.1 Preparatory analysis

The data on AAD violates the assumption of normality. Therefore, one-way ANOVA could not be used. Instead, A non-parametric t-test was performed to determine if AAD differs significantly between neighborhoods. A graph was created to visualize the difference in temperature over five days for each neighborhood. To determine if there was a statistically significant difference in mean temperature between neighborhoods, ANOVA test was used. To determine if the samples were independent, the assumptions of ANOVA were tested. Normality, homogeneity and outliers were tested. When no violation of assumptions was established, the one-way ANOVA test was performed. The potential confounding variables were tested to be significant with linear regression of the independent variable to determine whether or not they should be included in the model.

3.4.2 Hypothesis testing

After preparatory analysis was performed, two models were made, an unadjusted model (model 1: simple linear regression for the influence of AAD on air temperature) and an adjusted model to consider potential confounders (Model 2: multiple linear regression for the influence of AAD on air temperature, including potential confounders as control variables).

4. Results

4.1 Preparatory analysis

The difference in AAD between the five neighborhoods was tested to evaluate if it was statistically significant. A non-parametric t-test (Kruskal-Wallis test) was used. The differences between Capelle (20.50), Oost (12.50), Ommoord (28.50), Delfshaven (36.50), and Spaanse polder (4.50) were statistically significant, H (4, n=40) = 39.000, p<0.001.

Table 2 Kruskal-Wallis test on ambient address density.

Test Statistics[a,b]

	ambientaddressdensity
Kruskal-Wallis H	39.000
df	4
Asymp. Sig.	<.001

a. Kruskal Wallis Test

b. Grouping Variable: neighborhood_recode

Subsequently, the temperature of the five neighborhoods was plotted over the eight-day observation period (Figure 4).

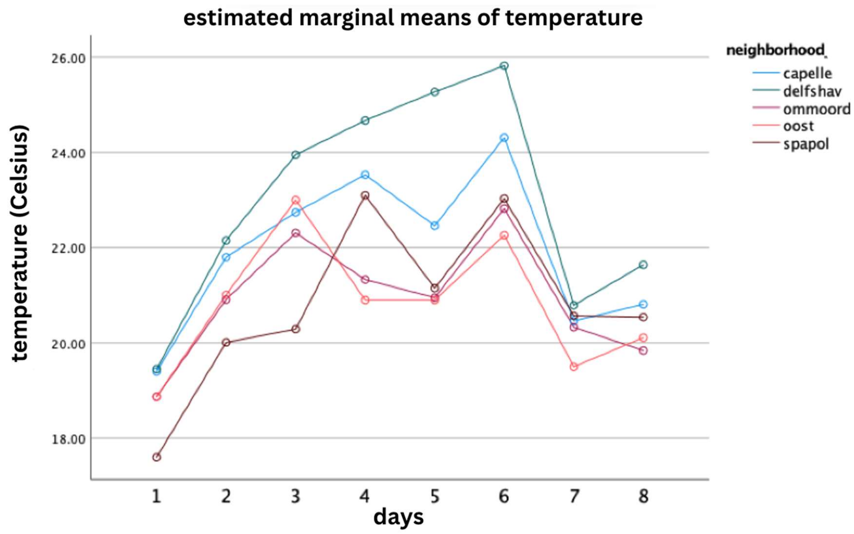

Figure 4 Graph of mean daily temperature at 8 days during the heatwave for each neighborhood.

On inspection, differences are visible. These were tested with a one-way ANOVA test (table 2). The one-way ANOVA test showed that the effect of neighborhoods on air temperatures was not statistically significant. F (4,35) = 2.513, p = 0.059. The results of the Shapiro-Wilk tests, Levene's test, and outliers test to meet assumptions for one-way ANOVA can be found in appendix D.

Table 3 one-way ANOVA test of the effect of neighborhoods on air temperature.

ANOVA

temperature

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	29.240	4	7.310	2.513	.059
Within Groups	101.822	35	2.909		
Total	131.062	39			

4.2 Hypothesis testing

Model 1 examined the association between AAD and air temperature in five neighborhoods (Capelle, Oost, Ommoord, Delfshaven, and Spaanse Polder). The average AAD was 2884.2 (SD = 1234.71) and the average temperature within the sample was 21.49 degrees Celsius (SD = 1.83).

Model 1: a simple linear regression of the effect of AAD on air temperature.

Linear regression of model 1 revealed a statistically significant model since F (1,38) = 8.665, p = 0.006. with an adjusted R^2 of 0.164. This suggests that AAD accounts for about 16.4% of the variance in air temperature among the sampled neighborhoods. The regression coefficient for AAD was found to be 0.001, implying that for an increase of one unit in AAD, the air temperature rises with 0.001 degrees Celsius. This effect is found to be statistically significant (t (38) =2.944, p = 0.006).

Table 4 coefficient table on linear regression of ambient address density on air temperature

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients			Correlations			Collinearity Statistics	
		B	Std. Error	Beta	t	Sig.	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	19.641	.681		28.860	<.001					
	ambientaddressdensity	.001	.000	.431	2.944	.006	.431	.431	.431	1.000	1.000

a. Dependent Variable: temperature

model 2: multiple linear regression for the influence of ambient address density on air temperature, including total water surface area as control variable.

To perform multiple linear regression for the influence of AAD on air temperature, several confounders were explored. For level of greenery, the map in Figure 2 shows that the percentage of greenery in the subject neighborhoods differs less than 10% between neighborhoods. Therefore, it can be argued that it is not a potential confounder. The number of vehicles ($t(35) = 0.045$, $p = 0.964$), total surface area ($t(35) = -0.740$, $p = 0.464$) and total water area ($t(35) = -4.179$, $p < 0.001$) are all statistically insignificant results (appendix E). Since none of the confounders were associated with AAD, this multiple linear regression model was not further pursued.

5. Discussion

This study investigated the effect of urban density on the urban heat island effect in Rotterdam by analyzing data on air temperature in a heatwave for five different neighborhoods with differing AAD. The analysis demonstrated a statistically significant effect of considerable impact: an increase of 1000 in AAD is associated with a rise of 1 degree Celsius. The findings of this study align with prior research as it suggests that higher urban density increases the UHIE (Li et al., 2020).

While model 1 has shown a significant effect, certain limitations should be considered. Firstly, the used dataset consisted of a small sample size and missed data on level of greenery. having an unmeasured confounder can reduce the internal validity of the study. The dataset offered AAD as measure for urban density, but in its definition AAD overlaps with other variables and may not give these enough weight. A logical link could be made by theorizing that a higher AAD would indicate a larger population density and larger surface area for a neighborhood, as there is more ‘room’ for more addresses. However, the AAD specifically focuses on the number of addresses and therefore may not always consider including aspects of urban density, such as traffic density. Another challenge with the dataset was the inability to perform repeated measures ANOVA. The air temperature could not be evaluated in a time series model due to challenges with analyzing time series in SPSS. This would have strengthened the power of the study.

Secondly, the microenvironmental factors that can influence the degree of heat retention per measurement station are important to consider. Their position towards the sun or their shelter from wind could bias the measurement results. However, since all weather stations were placed on rooftops within residential areas (see appendix A), their elevation was relatively consistent, and urban setting could be considered to therefore cause minimal variation. For future studies it may still be interesting to include the microenvironment of the weather stations to increase internal validity. This provides a more comprehensive picture of explaining the air temperature measurements.

Thirdly, the number of neighborhoods included in the study was limited, due to the dataset on air temperature from TU Delft. This influences the statistical power of the model. Neighborhoods with very low or high AAD, such as Centrum (6306) and Ridderkerk (1749) would have been very interesting to include. However, Centrum contained no data on air temperature during the heatwave and Ridderkerk was relocated during the measurement period. Moreover, neighborhoods such as Lansingerland would also be very interesting to include as they are located in the greater area of Rotterdam, which defines the boundary of the UHIE. Unfortunately, Lansingerland is not part of the municipality of Rotterdam and therefore data was not accessible. For future studies, researching the UHIE including boundaries or areas located just beyond the municipality borders could create an interesting contrast and increase the power of the analysis. This would help to explain the UHIE on a more comprehensive scale.

Lastly, even though there is a statistically significant effect between AAD and air temperature, it only explains 16.4% of the variation in air temperature. This is evident from figure four, where the temperature of Spaanse Polder deviates on Oost and Ommoord on day 3 and 4. These deviations could be explained by factors not accounted for by AAD that may influence air temperature such as traffic intensity, change in wind direction, or heat radiation from the cooling of offices, which only occurs on weekdays. Strikingly, temperatures drop on day five (a Saturday) in four of the five neighborhoods (less home-work traffic and no heat radiation from office cooling). The fact that temperatures rise on day six (a Sunday) illustrates that weekdays are only part of the explanation, and meteorological factors such as cloudiness and wind may play an important role. This suggest that future studies could provide more in-depth research on these factors. Moreover, the feasibility and efficacy of mitigating interventions for the UHIE should be the subject of future studies.

As this study shows the important effect of the urban density on air temperatures and therefore the UHIE, this bears implications for practice and policy. Improving urban planning is important for the wellbeing of Rotterdam citizens. Urban planning policies should give a higher priority to factors that are known to reduce heat such as increasing the level of greenery. Nevertheless, policies should apply a comprehensive approach to address multilevel interventions to combat the UHIE. Studies found that reflective surfaces, vegetation, and urban layout of buildings are all important strategies in reducing heat (Han et al., 2022). Dependent on climate characteristics of an urban environment, one aspect might be more influential than the other. Studies found that using reflective pavements for instance may be more influential in building morphology when the height to width ratio of buildings is lower (Qin, 2015). By combining these climate dependent factors together and considering the AAD, policies could create neighborhoods in Rotterdam that are a cooler place and more habitable to live in with ongoing climate change.

6. Conclusion

This study set out to determine whether urban density influences the UHIE in Rotterdam in a heatwave. The data included temperature measurements during a heatwave and the AAD of the city from five neighborhoods. To answer the research question: how does urban density influence the UHIE in Rotterdam in a heatwave? The results suggest that AAD has a significant effect on the air temperatures in a heatwave in Rotterdam. For future studies, it could be interesting to approach urban density on a comprehensive basis to include all of its aspects and provide a stronger result for the UHIE to identify its underlying causes. By adjusting policies towards these findings, citizens in Rotterdam can live in a cooler environment to protect their health.

References

Agache, I., Sampath, V., Aguilera, J., Akdis, C. A., Akdis, M., Barry, M., Bouagnon, A., Chinthrajah, S., Collins, W., Dulitzki, C., Erny, B., Gomez, J., Goshua, A., Jutel, M., Kizer, K. W., Kline, O., LaBeaud, A. D., Pali-Schöll, I., Perrett, K. P., . . . Nadeau, K. C. (2022). Climate change and global health: A call to more research and more action. *Allergy*, *77*(5), 1389–1407. https://doi.org/10.1111/all.15229

Al-Kodmany, K. (2012). The logic of vertical density: tall buildings in the 21st century city. *International journal of high-rise buildings*, *1*(2), 131-148.

Angel, S., Lamson-Hall, P., & Blanco, Z. G. (2021). Anatomy of density: measurable factors that constitute urban density. *Buildings and Cities*, *2*(1), 264–282. https://doi.org/10.5334/bc.91

Bakker, M. (2018). *Changing Suburban Neighbourhoods in Rotterdam: Densification and sustainable urban mobility in Prins Alexander in Rotterdam* (Master's thesis).

Centraal Bureau voor de Statistiek (CBS). (2022). *Bevolking; kerncijfers* [Data set]. https://www.cbs.nl/nl-nl/cijfers/detail/85318NED

Chen, T. K., Qiu, C., Schmitt, M., Zhu, X. X., Sabel, C. E., & Prishchepov, A. V. (2020). Mapping horizontal and vertical urban densification in Denmark with Landsat time-series from 1985 to 2018: A semantic segmentation solution. *Remote Sensing of Environment*, *251*, 112096. https://doi.org/10.1016/j.rse.2020.112096

Delft University of Technology. (n.d.). *Weather data from the Green Village field lab* [Data set]. TU Delft Weather Plots. https://weather.tudelft.nl/plots/

Ebi, K. L., Capon, A., Berry, P., Broderick, C., De Dear, R., Havenith, G., Honda, Y., Kovats, R. S., Ma, W., Malik, A., Morris, N. B., Nybo, L., Seneviratne, S. I., Vanos, J., & Jay, O. (2021). Hot weather and heat extremes: health risks. *The Lancet*, *398*(10301), 698–708. https://doi.org/10.1016/s0140-6736(21)01208-3

Gabriel, K. M., & Endlicher, W. R. (2011). Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. *Environmental Pollution*, *159*(8–9), 2044–2050. https://doi.org/10.1016/j.envpol.2011.01.016

Giridharan, R., Ganesan, S., & Lau, S. (2004). Daytime urban heat island effect in high-rise and high-density residential developments in Hong Kong. *Energy and Buildings*, *36*(6), 525–534. https://doi.org/10.1016/j.enbuild.2003.12.016

Han, D., Zhang, T., Qin, Y., Tan, Y., & Liu, J. (2022). A comparative review on the mitigation strategies of urban heat island (UHI): a pathway for sustainable urban development. *Climate and Development*, *15*(5), 379–403. https://doi.org/10.1080/17565529.2022.2092051

Hess, P. (2014). Density, urban. In *Springer eBooks* (pp. 1554–1557). https://doi.org/10.1007/978-94-007-0753-5_698

Hu, Y., White, M., & Ding, W. (2016). An Urban Form experiment on urban heat island effect in high density area. *Procedia Engineering*, *169*, 166–174. https://doi.org/10.1016/j.proeng.2016.10.020

KNMI - augustus 2022. (n.d.). https://www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/2022/augustus#:~:text=De%20maand%20werd%20gekenmerkt%20door,vaak%20onder%20invloed%20van%20hogedrukgebieden.

Li, Y., Schubert, S., Kropp, J. P., & Rybski, D. (2020). On the influence of density and morphology on the Urban Heat Island intensity. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-16461-9

Miao, C., Yu, S., Hu, Y., Zhang, H., He, X., & Chen, W. (2019). Review of methods used to estimate the sky view factor in urban street canyons. *Building and Environment*, *168*, 106497. https://doi.org/10.1016/j.buildenv.2019.106497

Mohajerani, A., Bakaric, J., & Jeffrey-Bailey, T. (2017). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Environmental Management*, *197*, 522–538. https://doi.org/10.1016/j.jenvman.2017.03.095

Morini, E., Touchaei, A., Castellani, B., Rossi, F., & Cotana, F. (2016). The impact of Albedo increase to mitigate the urban heat island in Terni (Italy) using the WRF model. *Sustainability*, *8*(10), 999. https://doi.org/10.3390/su8100999

Municipality of Rotterdam. (n.d.) https://www.rotterdam.nl/stadsprojecten

Mueller, K., Allstrom, H., Smith, D. J., Downes, E., & Modly, L. A. (2024). Climate change's implications for practice. *The Nurse Practitioner*, *49*(10), 30–38. https://doi.org/10.1097/01.npr.0000000000000230

Nieuwenhuijsen, M. J. (2021). New urban models for more sustainable, liveable and healthier cities post covid19; reducing air pollution, noise and heat island effects and increasing green space and physical activity. *Environment International*, *157*, 106850. https://doi.org/10.1016/j.envint.2021.106850

Nugroho, N. Y., Triyadi, S., & Wonorahardjo, S. (2021). Effect of high-rise buildings on the surrounding thermal environment. *Building and Environment*, *207*, 108393. https://doi.org/10.1016/j.buildenv.2021.108393

PDOK Viewer - PDOK. (n.d.). https://www.pdok.nl/pdok-viewer

Qin, Y. (2015). Urban canyon albedo and its implication on the use of reflective cool pavements. *Energy and Buildings*, *96*, 86–94. https://doi.org/10.1016/j.enbuild.2015.03.005

Ramírez-Aguilar, E. A., & Souza, L. C. L. (2019). Urban form and population density: Influences on Urban Heat Island intensities in Bogotá, Colombia. *Urban Climate*, *29*, 100497. https://doi.org/10.1016/j.uclim.2019.100497

Rijksinstituut voor Volksgezondheid en Milieu (RIVM). (2020). *Stedelijk hitte-eiland effect (UHI) in Nederland*. Atlas Natuurlijk Kapitaal. https://www.atlasnatuurlijkkapitaal.nl/stedelijk-hitte-eiland-effect-uhi-in-nederland

Rojradtanasiri, P., Tamura, J., & Kobayashi, M. (2024). Estimating ambient population density using physical features from GIS and machine learning: a study based on Japanese neighborhood. *Journal of Asian Architecture and Building Engineering*, 1–16. https://doi.org/10.1080/13467581.2024.2428262

Shahmohamadi, P., Che-Ani, A. I., Maulud, K. N. A., Tawil, N. M., & Abdullah, N. a. G. (2011). The impact of anthropogenic heat on formation of urban heat island and energy consumption balance. *Urban Studies Research*, *2011*(1). https://doi.org/10.1155/2011/497524

Stedelijk hitte-eiland effect (UHI) in Nederland. (n.d.). Atlas Natuurlijk Kapitaal. https://www.atlasnatuurlijkkapitaal.nl/stedelijk-hitte-eiland-effect-uhi-in-nederland

Van der Hoeven, F., & Wandl, A. (2018). Hotterdam: Mapping the social, morphological, and land-use dimensions of the Rotterdam urban heat island. *Urbani izziv*, *29*(1), 58-72.

Van Hove, B., et al. (2015). The impact of urban planning on UHI effects in the Netherlands. *Urban Climate, 14,* 213-223.

Vujovic, S., Haddad, B., Karaky, H., Sebaibi, N., & Boutouil, M. (2021). Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements. *CivilEng*, *2*(2), 459–484. https://doi.org/10.3390/civileng2020026

Wang, Y., Guo, Z., & Han, J. (2021). The relationship between urban heat island and air pollutants and them with influencing factors in the Yangtze River Delta, China. *Ecological Indicators*, *129*, 107976. https://doi.org/10.1016/j.ecolind.2021.107976

Ward, K., Lauf, S., Kleinschmit, B., & Endlicher, W. (2016). Heat waves and urban heat islands in Europe: A review of relevant drivers. *The Science of the Total Environment*, *569–570*, 527–539. https://doi.org/10.1016/j.scitotenv.2016.06.119

Yang, L., Qian, F., Song, D., & Zheng, K. (2016). Research on Urban Heat-Island Effect. *Procedia Engineering*, *169*, 11–18. https://doi.org/10.1016/j.proeng.2016.10.002

Zacharias, S., Koppe, C., & Mücke, H. (2014). Climate change effects on heat waves and future heat Wave-Associated IHD mortality in Germany. *Climate*, *3*(1), 100–117. https://doi.org/10.3390/cli3010100

Zhao, L., Oppenheimer, M., Zhu, Q., Baldwin, J. W., Ebi, K. L., Bou-Zeid, E., Guan, K., & Liu, X. (2017). Interactions between urban heat islands and heat waves. *Environmental Research Letters*, *13*(3), 034003. https://doi.org/10.1088/1748-9326/aa9f73

Appendix

Appendix A:

Pictures of weather stations

Figure 5 Photo of weather station Spaanse polder

Figure 6 photo of weather station Delfshaven

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Figure 7 photo of weather station Oost

Figure 8 photo of weather station Ommoord

Figure 9 photo of weather station capelle

Appendix B

Name and corresponding coordinates of weather stations and their corresponding CBS neighborhood

Table 5 weather stations and corresponding locations and neighborhoods

Name weather station (TU Delft)	address	coordinates	Neighborhood name (CBS)
Delfshaven	Watergeusstraat 230, 3025HX, Rotterdam	51.90506, 4.44618	Delfshaven
Capelle	Gemaal Reigerlaan, 2903TS, Capelle aan den Ijssel	51.92746, 4.58506	Middelwatering-Oost
Oost	Ringvaartweg 152, 3065AE, Rotterdam	51.92530, 4.54767	‘s-Gravenland
Ommoord	Fioringras 2, 3068PE, Rotterdam	51.95842, 4.54745	Ommoord
Spaanse Polder	Groothandelsmarkt 154, 3044HE, Rotterdam	51.93245, 4.41623	Spaanse Polder

Appendix C

Definitions of variables included in the dataset that were not included in final regression but were used in analysis to determine potential confounders:

Total surface area is determined by using total surface area, which is defined as the sum of water surface area and land surface area. For **water surface area**, bodies of water are included when they are wider than six meters and larger than one hectare. For this, the land use data from 2017 is used as well. **Number of vehicles** includes all motor vehicles (including personal cars, business car and motoric two-wheelers) that were registered on January 1st are included. Important to note is that only vehicles that are licensed with insurance to participate in traffic are registered in the database.

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Appendix D

Testing assumptions of one-way ANOVA

Normal distribution assumption:

Shapiro-wilk tests are performed to determine normal distribution of temperatures per neighborhood. The distribution of air temperature for Capelle W (8) =0.981, p=0.969 is statistically insignificant. Delfshaven's air temperature distribution is statistically insignificant since W (8) =0.946, p=0.669. the distribution of air temperature in Ommoord W (8) =0.981, p=0.969 is statistically insignificant. The distribution of air temperature in Oost W (8) =0.964, p=0.846 is statistically insignificant. The distribution of air temperature in Spaanse Polder W (8) =0.910, p=0.351 is statistically insignificant. Based on this outcome, it is shown that the air temperature is normally distributed, and the assumption is met.

Table 6 normality tests for neighborhood temperature distributions.

Tests of Normality

	neighborhood_recode	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
temperature	capelle	.128	8	.200*	.981	8	.969
	delfshav	.166	8	.200*	.946	8	.669
	ommoord	.124	8	.200*	.981	8	.969
	oost	.194	8	.200*	.964	8	.846
	spapol	.204	8	.200*	.910	8	.351

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Homogeneity assumption:

Levene's test for homogeneity of variances was found to be met, as F (4,35) = 1.553, p=0.209 is statistically insignificant. Therefore, the assumption of homogeneity of variances is met.

Table 7 Levene's test for homogeneity of variances on temperature measurements.

Tests of Homogeneity of Variances

		Levene Statistic	df1	df2	Sig.
temperature	Based on Mean	1.553	4	35	.209
	Based on Median	1.492	4	35	.226
	Based on Median and with adjusted df	1.492	4	31.002	.229
	Based on trimmed mean	1.559	4	35	.207

Outliers assumption:

Figure 10 shows a boxplot on the temperature measurements for the subjected neighborhoods; visual inspection shows that no outliers are present within the boxplot. This means that the assumption is met.

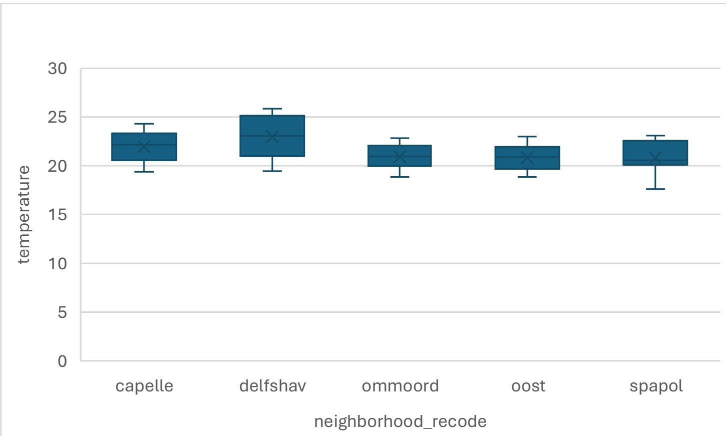

Figure 10 boxplot on outliers in sample per neigborhood.

Appendix E

Testing confounders for the effect of AAD on air temperature gave the following results. Linear regression of potential confounders independent variable was performed to determine their confounding factor. For total surface area, the dependent variable was used as well. As can be seen in table 8 and 9, the effect is statistically insignificant between number of vehicles (t (35) =0.045, p=0.964) and total water area (t (35) =0.560, p=0.579) with AAD. Total water surface area is statistically significant since (t (35) =-4.179, p<0.001) with AAD. However, in table 11 the results show a statistically insignificant effect (t (35) =-0.740, p=0.464) between total surface area and AAD. Since all results are statistically insignificant, the potential confounders are not included in the model as covariates.

Table 8 coefficient table to test for the potential confounder number of vehicles on ambient address density.

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	Correlations Zero-order	Correlations Partial	Correlations Part	Collinearity Statistics Tolerance	Collinearity Statistics VIF
1	(Constant)	2873.169	313.312		9.170	<.001					
	vehicles	.003	.062	.007	.045	.964	.007	.007	.007	1.000	1.000

a. Dependent Variable: ambientaddressdensity

Table 9 coefficient table to test for the potential confounder water surface area on ambient address density.

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	Correlations Zero-order	Correlations Partial	Correlations Part	Collinearity Statistics Tolerance	Collinearity Statistics VIF
1	(Constant)	2981.949	263.241		11.328	<.001					
	totalwatersurfaceareaha	-.680	1.214	-.090	-.560	.579	-.090	-.090	-.090	1.000	1.000

a. Dependent Variable: ambientaddressdensity

Table 10 coefficient table to test for the potential confounder total surface area and ambient address density.

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	Correlations Zero-order	Correlations Partial	Correlations Part	Collinearity Statistics Tolerance	Collinearity Statistics VIF
1	(Constant)	3461.310	214.162		16.162	<.001					
	totaltotalsurfaceareaha	-8.413	2.013	-.561	-4.179	<.001	-.561	-.561	-.561	1.000	1.000

a. Dependent Variable: ambientaddressdensity

Table 11 coefficient table to test for the potential confounder total surface area and air temperature.

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	Correlations Zero-order	Correlations Partial	Correlations Part	Collinearity Statistics Tolerance	Collinearity Statistics VIF
1	(Constant)	21.668	.381		56.809	<.001					
	totaltotalsurfaceareaha	-.003	.004	-.119	-.740	.464	-.119	-.119	-.119	1.000	1.000

a. Dependent Variable: temperature