Environmental Justice: A Case Study into the Heat Vulnerable Neighborhoods of Philadelphia

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Studies have shown that low-income communities and communities of color are more likely to live in neighborhoods experiencing multiple environmental burdens and disproportionate vulnerability to the impacts of climate change in American cities. The practice of redlining in Philadelphia, Pennsylvania has caused environmental injustice in ways that might not have been obvious at that time however there are neighborhoods that are still affected by this practice. These areas have the lowest median household incomes, lowest life expectancies, and highest population of African American people compared to the rest of the city. The main objective of this research is to map the heat vulnerable neighborhoods in Philadelphia and suggest ways to mitigate urban heat island. Mapping heat vulnerability shows the areas that are more susceptible to the exacerbating effects of heat. The research began with mapping factors that determine vulnerability, such as heat exposure, access to green space/tree coverage, median household income, life expectancy, and race. Mapping these indicators allowed the vulnerable neighborhoods to be pinpointed. The most vulnerable neighborhoods chosen were Tioga and Carroll Park. To conduct a better analysis the least vulnerable neighborhood, Chestnut Hill, was chosen to compare to. Further, overlaying the Homeowners Loan Corporation redlining map to find out that the "hazardous" neighborhoods overlap with the most vulnerable neighborhoods. To continue the analysis with simulations, Rhino and Grasshopper (Ladybug Tools) were used to quantify the urban heat island indicators such as Direct Sun Hours, Universal Thermal Climate Index (UTCI) and Heat Stress Hours in both public spaces and streets. In summary, this research proposes design interventions, including strategies of adding greenery, to mitigate the urban heat island effect. The simulations showed that the neighborhoods that are the most heat vulnerable would have to drastically change their environment to mitigate the urban heat island.

BACKGROUND

Due to accelerated climate change, heat has significantly impacted society, including a rise in heat-related deaths, for many cities nationally and internationally. The effects of heat are even exacerbated in cities because of the urban heat island (UHI) effect. Urban heat island is the phenomenon that outdoor temperatures within a city are higher than temperatures in outlying areas of cities. According to the Environmental Protection Agency (EPA), the difference in temperature between the city and the suburbs can be between 1-7°F.[1] Studies have found that people of color and people living below the poverty line face disproportionate harm from urban heat exposure. As the poorest major city in the USA with a 25.7% poverty rate, Philadelphia has a large proportion of residents with limited financial capacity to cope with rising temperatures, as well as a rapidly aging housing stock, which is not built to withstand extreme heat. Other issues include underfunded schools, prevalent racism in the workforce and a reluctance to change and growth.[2] These issues, compounding with the effects of redlining, reinforce a system that allows the poor to get poorer while the rich get richer. Philadelphia has a long-standing extreme heat response program; however, as climate projections for Philadelphia indicate greater frequency, intensity, and duration of extreme heat events, interventions need to continuously evolve.

Historic Redlining

Redlining was a historic practice throughout the United States that started in the 1930s and 1940s. This practice was created by the Home Owners Loan Corporation (HOLC) which was founded in 1933 through the Home Owners Loan Act. Between 1933 and 1935, bonds were given to people to help with mortgage relief during the Great Depression.[3] The HOLC map that was created showed the areas that were "best" to lend money to versus where it was "hazardous" to lend money. See Figure 1. This practice quickly became racist when the "best" neighborhoods were the areas that were in-demand, up-and-coming, and housed white "professional men". In contrast, the "hazardous" neighborhoods were places where "infiltration" had already occurred. The "hazardous" neighborhoods were areas where the majority of Black or African American people lived, who at the time were considered "undesirable people."

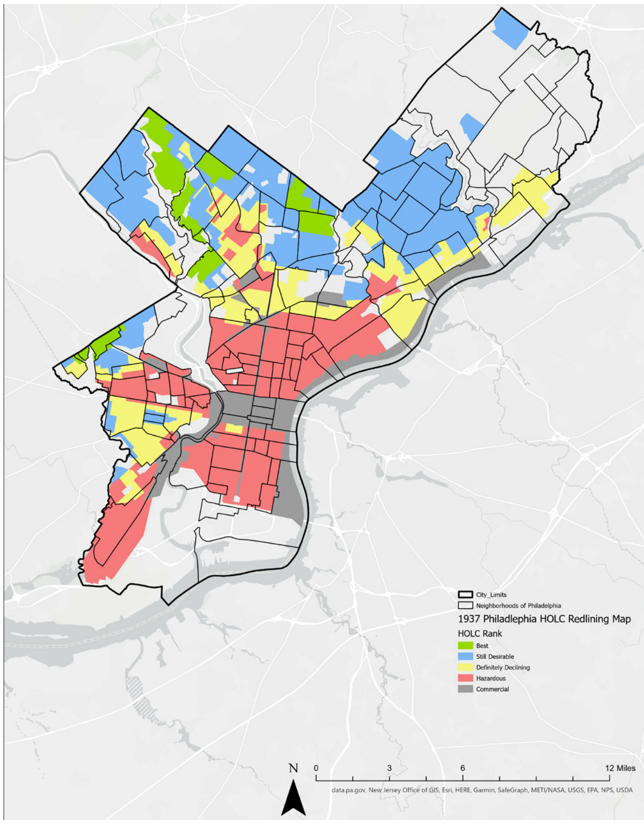

Figure 1. This map shows the redlined neighborhoods from the 1939 Homeowners Loan Corporation. Image credit to Author.

This practice allowed the gaps of not only race, but also incomes. The neighborhoods in the "best" areas usually had a higher median household income over the neighborhoods in the "hazardous" areas.

Heat Vulnerability Index

To find the areas that will be affected by urban heat island the most, an index has to be created. The Heat Vulnerability Index (HVI) contains different quantifiable factors that have a connection to urban heat island that will show where the affected areas are. Some indexes include income, access to healthcare, race, and tree canopy. The results of these show where the areas are the most vulnerable to the heat.

Necessity of Research

Although redlining was found to have impacted current racial segregation in Philadelphia in terms of economic and social equity, very few studies have looked into the environmental inequity that has occurred. Along with the environmental inequities there has not been the use of modeling and simulation software to propose mitigation techniques. These techniques are evolving rapidly and should be introduced into the city planning and development realm to provide more equity in the pinpointed vulnerable areas.

RESEARCH METHODS

Universal Thermal Climate Index

The Universal Thermal Climate Index (UTCI) describes the physical comfort of the human body under different climate conditions.[4] This does not just take temperature into account, but also incorporates humidity, wind, and radiation. This would be similar to the concept of a "feels like" temperature versus the actual temperature. There are 10 UTCI stress categories that range from extreme cold stress to extreme heat stress. This research incorporates data of how many hours an area experiences strong heat stress to extreme heat stress (a three, four, or five on the UTCI scale).

Data Collection and Mapping Analysis

The data for this research was collected through several different means. The primary sources used for the research consisted of the United States Census Bureau data for Philadelphia County at the tract level, the HOLC Redlining Map from 1939, the Heat Vulnerability Index Map that the City of Philadelphia created, and various maps from Pennsylvania Spatial Data Access (PASDA) and Open Data Philly. After collecting the different data sets, it was brought into ArcGIS Pro to begin the analysis. Maps were created for heat exposure (See Figure 2), Median household income, race, life expectancy, green spaces and tree canopies, Philadelphia neighborhoods, and the HOLC Redlining Map. The previously stated maps were chosen because they are the determining factors for vulnerability. Areas that have hot temperatures, low median household incomes, low life expectancy, a high population of people of color, and have low access to green spaces and tree canopies are considered vulnerable in this research. This information was mapped and analyzed, producing a comprehensive view to find the neighborhoods that are the most vulnerable in Philadelphia, PA.

Urban Heat Island and Mitigation Analysis

Modeling the most vulnerable Philadelphia neighborhoods was the start of the urban heat island simulations. This was conducted by utilizing Rhino 6 with the Ladybug Tools plug-in. Modeling the streets, tree canopy and buildings gave a base for the analysis. Through the Grasshopper scripting and Ladybug tools plug-in there was a list of inputs needed to run the analysis. The inputs were for both the buildings and the current environment of the area. The building inputs consisted of floor-to-floor heights, program types, age, and whether they have vegetation on them. For the environment inputs, there were tree canopy, street material, traffic flow, grass areas, and the weather data from the Philadelphia International Airport. This created a microclimate of the neighborhoods to run a deeper analysis. Analyzing the weather data from the

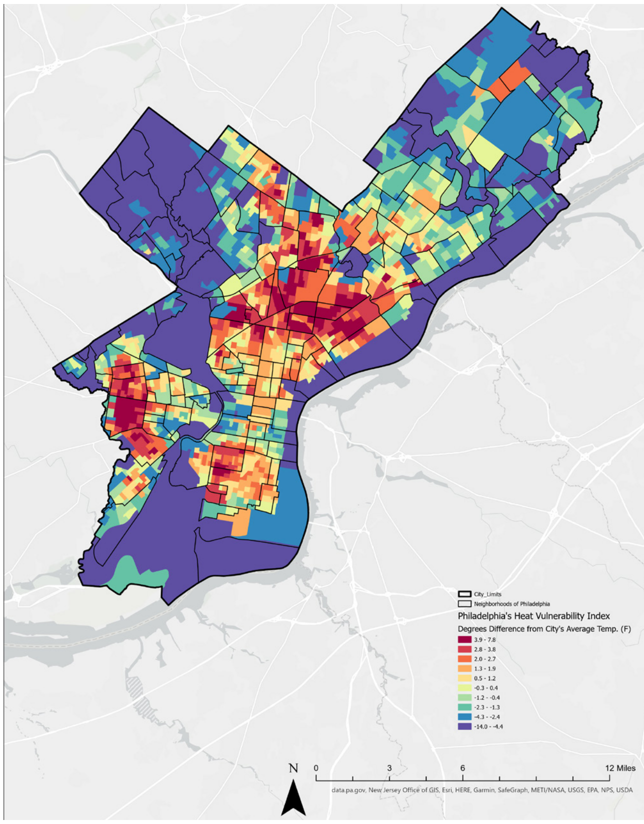

Figure 2. This map shows the average temperature difference between Center City Philadelphia and the outskirts. Image credit to Author.

airport, the average hottest week was determined and the week of July 15 to July 21 between 10:00 am- 4:00 pm was the analysis period for all the neighborhoods that were pinpointed through the analysis.

ANALYSIS AND FINDINGS

Mapping Heat Vulnerability and Results

This phase of the research determined two neighborhoods that were considered heat vulnerable in Philadelphia by using the vulnerability indexes stated prior to the mapping analysis. Starting with the heat exposure map from the City of Philadelphia, the neighborhoods (21 in total) that were in hottest zones (between 2.0- 7.8-degree difference of the average city temperature) were highlighted while the others were removed from the analysis. Next, with those neighborhoods highlighted, the median household income map was overlaid. The neighborhoods that were found to have an overlap between heat and low income (less than $48,000 per year) were kept, leaving 19 neighborhoods. Overlapping the racial breakdown of the city, next the neighborhoods that had a high population of Black or African American residents were kept in the analysis because they are more likely to have heat related medical emergencies (12 remaining).[5] Following that, overlapping the areas that have a lower life expectancy (72 years and younger) allowed the number of neighborhoods for analysis to be brought down to 9.

The last map that was overlaid was the green spaces and tree canopy. See Figure 3. This analysis showed neighborhoods that, while hot, have access to green space. After adding the last overlay, the analysis ended with 5 neighborhoods in Philadelphia. From the five neighborhoods, one neighborhood, Carroll Park, on the west side of the Schuylkill River (a river that splits Philadelphia in half) and one neighborhood, Tioga, in comparable size on the east side of the river were chosen for the analysis. This allowed for two different analyses since the 4 neighborhoods on the east side were in the same vicinity. In the two neighborhoods chosen a 3-block area was selected due to computer hardware limitations. After performing this analysis to find the most vulnerable neighborhoods, it was run in the opposite manner to find the least vulnerable neighborhood for a comparison of the results of the simulations. The least vulnerable neighborhood in Philadelphia was found to be Chestnut Hill in the northwestern part of the city. After finding the most and least vulnerable neighborhoods, the 3-block areas from each were exported into Rhino to perform the simulation.

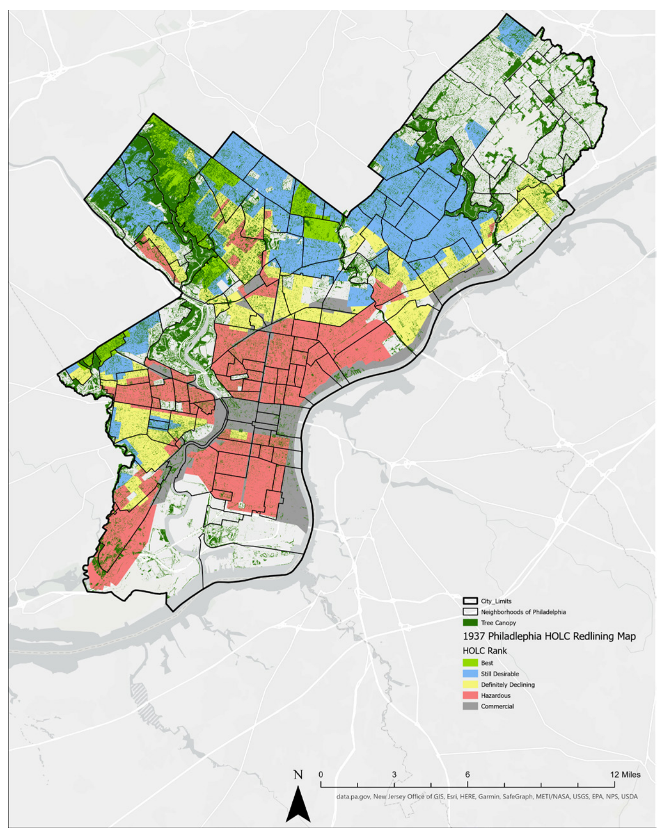

Figure 3. This map shows the redlined neighborhoods with the tree canopy layered on top as a result of the analysis. Image credit to Author.

Neighborhood Simulations and Results

After choosing neighborhoods and blocks, the urban heat island analysis was conducted. First, the blocks were modeled in Rhino, the buildings were extruded, curb lines were created into street surfaces, and tree canopies were made into surfaces. Next, the geometries were brought into Grasshopper to use the Ladybug Tools plug-in. The simulations that were run were direct sun hours (on the streets and the parcels), heat stress hours, and the UTCI. As determined before, the analysis period for the simulations was July 15 to July 21 from 10:00am to 4:00 pm. This was to ensure that it was analyzing the hottest time of the hottest week without having a skewed result due to the typical temperature drop in the evenings.

Existing Conditions

The first simulation conducted was the urban heat island temperature. This created the microclimates that allowed the rest of the simulations to be run. To start, a simulation of the existing conditions was run. The starting UTCI temperature was 101.20°F (38.44°C) in Tioga, 101.10°F (38.38°C) in Carroll Park, and 100.92°F (38.28°C) in Chestnut Hill. These temperatures will act as the baseline for the subsequent simulations. The next simulations run were the direct sun hours on the street and parcels of the 3-block areas.

The direct sun hours simulation analyzes the amount of time that the chosen neighborhoods experience a certain amount of direct sunlight. In the Tioga neighborhood, the direct sun hours for the street were 40.32 while the sun hours for the parcels were 22.90. In Carroll Park, the streets experience 45 direct sun hours while the parcels experience 26.3 hours. Chestnut Hill experiences significantly less direct sun hours, with 25.26 direct sun hours on the streets and 12.33 direct sun hours on the parcels.

For the heat stress simulation, each area was analyzed for the number of hours that the temperature would be so high that it would be high enough to cause heat stress on its residents. The time constraint was removed for this analysis, so the full 24 hours were simulated from July 15th to July 21st. The analysis

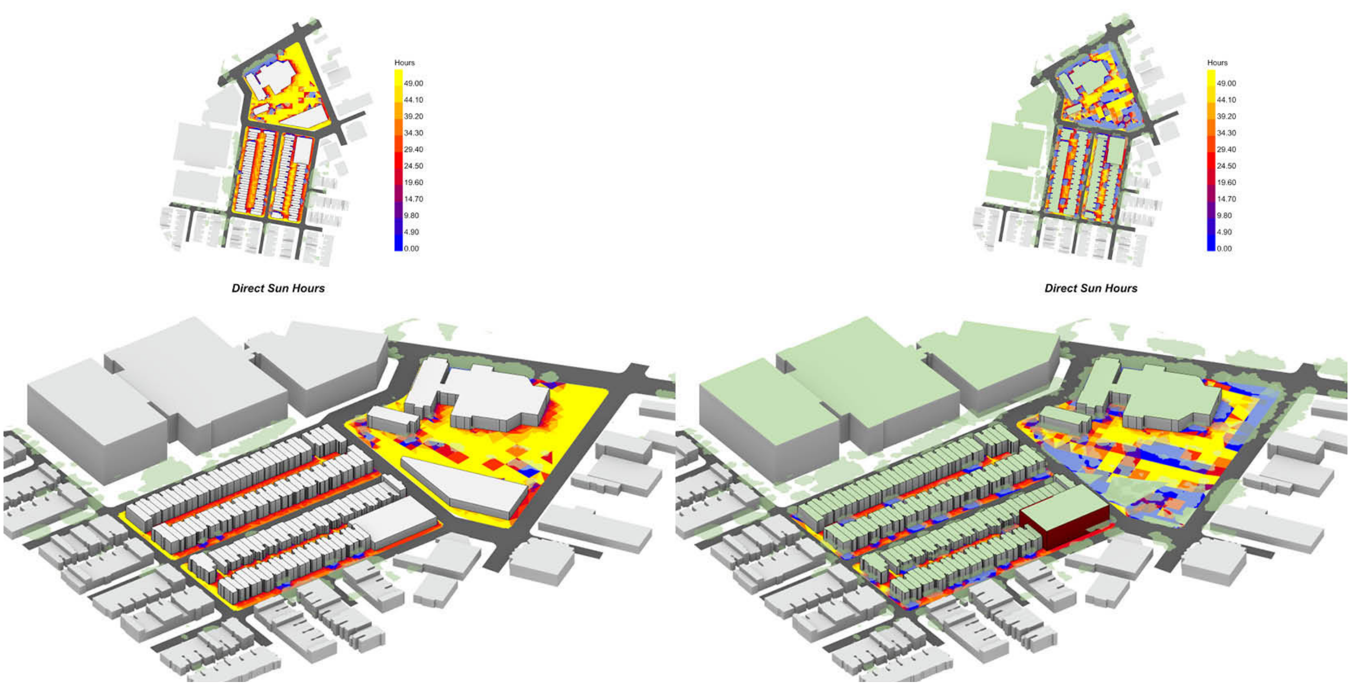

Figure 4. This image shows the before and after of using Rhino and Grasshopper to simulate the mitigation of the direct sun hours . Image credit to Author.

filtered for hours that were between strong heat stress and extreme heat stress. The existing conditions for Tioga had 78 hours of high heat stress, Carroll Park had 75 hours, and Chestnut Hill had 75 hours. Although these results do not have a significant difference, it is to be remembered that the analysis was done on a 3-block scale and that it only represents a small part of the neighborhoods.

These simulations supported the notion that the neighborhoods that were mapped were heat vulnerable. This starts to quantify the issue of urban heat island so that it can be seen as a direct impact on the people in the neighborhoods.

Proposed Conditions

The proposals were created by running the same analyses, but with more tree canopy, grass in places it was not before, and adding green roofs. See Figure 4. The proposals mentioned were hypothetical to evaluate the program and were pushed to see how much of a difference could be found between the existing and proposed. In Tioga, tree coverage increased from 35% of the area to 91% while Carroll Park had an increase from 9% to 31%. Chestnut Hill's tree canopy stayed at its current coverage at 65%. For grass coverage, Tioga increased from 5% to 60% while in Carroll Park it increased from 45% to 68%. Chestnut Hill's grass coverage stayed at its existing value of 39%. These drastic increases led to only a slight change in the temperatures, but a meaningful change in direct sun hours.

Running the urban heat island simulation with the proposed site improvements lowered the UTCI temperature to 100.92°F (38.28°C) from 101.20°F (38.44°C) in Tioga and to 100.99°F (38.32°C) from 101.10°F (38.38°C) in Carroll Park. In Tioga the hours of strong heat stress went down from 78 hours to 75 hours, while in Carroll Park it stayed at 75 hours. However, the hours of direct sunlight went down from 22.90 hours to 17.21 hours on the parcels in Tioga and in Carroll Park it went down from 26.3 hours to 20.3 hours.

This research has shown that drastically increasing the tree canopies and grass coverage just barely makes the heat vulnerable neighborhoods comparable to the least heat vulnerable neighborhood. This indicates that the interventions cannot be just at a block scale, but rather the whole neighborhood to see the true magnitude of the proposed alterations. See Figure 5.

CONCLUSION

In conclusion, the analysis found that the most vulnerable neighborhoods are in the areas that were considered to be "hazardous" in redlining terms. Tioga and Carroll Park had the highest temperature, lowest median household income, highest population of Black or African American residents, lowest life expectancy, and low percentage of tree canopy. The area that was determined to be the opposite of that was Chestnut Hill, which was used to compare to when running the simulations. After running the simulations, it was found that the most vulnerable neighborhoods, Tioga, and Carroll Park, were definitely hotter than the least vulnerable neighborhood, Chestnut Hill, and to even make them comparable the percentages of tree coverage and grass coverage would have to increase drastically.

RESEARCH LIMITATIONS AND FUTURE WORK

Timing of Research

Conducting this research in a short amount of time and during the winter months did not allow for a complete analysis of the experience in the neighborhoods. The research was based on the models and simulations from Grasshopper and various plug-ins. Given more time, there would have been analysis in the field during the summer months to experience firsthand each of the chosen sites to see what the actual feel of the neighborhoods were like, and it would have provided the opportunity to know the actual age and conditions of the buildings in the neighborhood. Lastly, it would also give time to interview the residents of the neighborhoods to find out about their experiences during the summer months. This experiential analysis would allow for a more personal mitigation proposal that the people of the neighborhood could help create. Also, the shortened research time limited the use of other vulnerability factors such as asthma rates and access to healthcare facilities. This would have allowed for an even more thorough mapping analysis.

Programs Used

The Ladybug Tools plug-in used to simulate urban heat island and the mitigation techniques does not account for the real nature of the environment. For example, when using the tree coverage, it only accounts for the shade that the tree provides. It does not consider how large the tree is, what type of tree it is, and how the trees process CO_2. This limitation only allows for a general simulation of how shade helps mitigate heat. Also, the plug-in does not account for the habits of humans with energy consumption, such as the use of HVAC systems, and how that can affect a neighborhood. Lastly, the Ladybug Tools plug-in is extremely taxing on a computer's processing power which is why a 3-block area was chosen to run the simulations. This was done knowing that if this project were scaled up there would be a greater difference in the results in temperature and heat stress hours since the larger scale interventions are more effective than just a small area.

Future Work

This research will continue with expansion to different cities within the United States. Running this same process and analysis throughout, will give cities a starting place in their urban heat island mitigation efforts. Starting the mitigation efforts in the hottest neighborhoods allows for environmental equity to lower urban heat island. This research also aims to promote community engagement. The timing did not allow for it this time; however, it should be included in the future plans and developments.

	Tioga		Carroll Park		Chestnut Hill
	Simulation Inputs				
	Existing	Proposed	Existing	Proposed	Existing
Tree Coverage	35%	91%	9%	31%	65%
Grass Coverage	5%	60%	45%	68%	39%
	Simulation Outputs				
	Existing	Proposed	Existing	Proposed	Existing
UTCI	101.20°F (38.44°C)	100.92°F (38.28°C)	101.10°F (38.38°C)	100.99°F (38.32°C)	100.92°F (38.28°C)
Sun Hours (Parcels)	22.90 Hours	17.21 Hours	26.30 Hours	20.30 Hours	12.33 Hours
Sun Hours (Streets)	40.32 Hours	32.08 Hours	45.00 Hours	42.50 Hours	25.26 Hours
Heat Stress Hours	78 Hours	75 Hours	75 Hours	75 Hours	75 Hours

Figure 5. This is a chart summarizing the findings from the simulations. Image credit to Author.

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