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Modeling and Evaluation of Effective Factors on Thermal Islands with an Approach Based on Fuzzy Systems: A Case Study of Tehran

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Abstract

Urban heat islands are areas where urbanization and human activities have significantly increased the temperature compared to surrounding areas. The main goal of this research is to provide a simple, developable, and suitable analytical model to contribute to better management of urban services by predicting areas with the highest probability of heat islands and accurately estimating its factors. In this research, the fuzzy systems method has been used to determine the location of heat islands in Tehran, which is a new approach compared to other studies. First, all factors are identified, and then their analysis is assigned weights. Finally, by writing the law of fuzzy comparison, comparisons between layers are made. According to the modeling results, urban heat islands cause a 1.3 °C warming in summer and 1.4 °C in winter. The presence of urban heat islands has led to an increase in average O3 pollutants by about 0.5 ppb, average NO2 pollutants by about 2 ppb, and CO by about 40 ppb. By considering the coefficients of these factors and comparing model data, an accuracy of 78.6% was achieved. The final results indicate that regions 9, 10, 11, 17, and 18, as well as parts of region 21 in Tehran, have a very high possibility of heat islands.

Keywords: Spatial Data Analysis, Fuzzy logic, Urban thermal islands, Air pollution, Geographic Information System (GIS)

1- Introduction

An urban heat island refers to any area where humans have built structures and the temperature is significantly higher than surrounding areas [1]. Urban heat islands are one of the most important issues in the modern era, resulting from urban development and human industrialization [2]. The rapid growth of urbanization, particularly in metropolitan areas, leads to changes in land cover as agricultural land and forests are converted into residential areas. Various factors influenced by human behavior have caused thermal differences between cities and more remote areas, but the primary reason for the emergence of heat islands in cities is the heat generated by human structures within urban areas [3]. Since the beginning of human existence on Earth, there has been a relationship between humans and the environment, with both mutually influencing each other. To promote their well-being, human beings have modified the environment to suit their needs. As time has passed and cities have emerged, these environmental changes have become more significant, influenced by factors such as energy consumption, population density, latitude, and airflow patterns. While these changes have contributed to enhancing human well-being, they have also led to various global and regional issues, including air pollution, global warming, industrial

waste production, water pollution, and other environmental challenges. It is evident that air quality plays a crucial role in human health and overall quality of life. According to the World Health Organization, approximately seven million people worldwide die each year as a result of air pollution, with six million of these deaths occurring in Asia. The most common health issues associated with air pollution-related deaths include heart disease, arterial blockages, lung congestion, lung cancer, and respiratory infections in children. The importance of studying thermal islands becomes clear when problems arise in the world's major cities due to the increase in temperature. Several urban research studies have focused on land surface temperature variation due to the urban heat island effect [4, 5, 6]. Based on these studies, the dramatic development of urbanization and the increase of unbalanced urban industrial areas have caused a significant change in the urban structure, overshadowing urban environmental functions. Different research strategies, methods, and techniques have been used in previous studies. For instance, a study examining the thermal islands and their effects in the city of Santiago over ten years using Landsat satellite imagery concluded that in the southern parts of the city, there is less heat due to green space, intense vegetation, and wet soil type, resulting in a lesser effect of the thermal island phenomenon [7]. In a study conducted in Toronto, Canada, using satellite imagery, the impact of the thermal island phenomenon was investigated. The study concluded that there is a direct relationship between heat generated in the city and urban construction [8]. In a study of the thermal island phenomenon in Hong Kong, researchers concluded that the highest weight of the thermal island phenomenon is in the northern part of the city [9]. Another study examined the relationship between energy demand and the thermal island phenomenon, finding that this phenomenon intensifies with increasing energy consumption [10]. A detailed analysis of urban heat islands using Landsat satellite images and thermal sensors found that the highest rate of urban heat islands is in the eastern part of the city [11]. A study conducted in Nigeria identified changes in thermal islands over time, concluding that the intensity of thermal islands is directly related to air pollutants and inversely related to vegetation [12]. In China, a study found that the highest intensity of heat islands is in areas with high building density and population density [13]. Studies have shown that the high volume of heat generated by large urban structures, as well as human industrial resources and activities, are important reasons for the emergence of thermal islands. Field research and studies on thermal islands have found that the heat reflected by structures in the city is also a significant factor in the generation of heat and thermal islands. In urban spaces, a large number of existing human structures absorb large volumes of radiation and solar energy, storing heat energy in building materials. As a result, the albedo coefficient in urban areas is low due to the geometry and shape of passages, increasing the temperature in these areas [14]. Various studies have been conducted to reduce temperature and minimize the possibility of thermal islands. Results indicate that one strategy is to create more urban green space. Increasing the number of trees in the city, as well as using appropriate building materials and facades to not store the sun's energy, can help reduce the occurrence of thermal islands [15]. A study evaluated urban heat islands and thermal comfort in the city of Navida using space technology to study thermal islands and the factors influencing their formation [16]. Another study analyzed urban heat islands using local climate areas and the impact of dry land breezes [17]. A study entitled 'Methods of Recovery of Urban Heat Islands' examined the recovery of urban heat islands and various methods [18]. In an article entitled "Development of Vulnerability Index to Quantify the Effects of Urban Heat Islands with Air Pollution: A Camden Case Study" [19], it was found that there are more thermal islands in the city center and crowded areas, as indicated in another article titled "Identification of Urban Thermal Islands Based on the Environmental Approach" [20], which focused on a case study in Isfahan metropolis. Additionally, a study in Urmia showed that areas with vegetation and green space have fewer thermal islands [21]. A new method for the optimal selection of land cover-related indicators to identify urban thermal islands using remote sensing data concluded that areas with higher population density result in higher thermal islands in a city [22]. Another study on identifying factors affecting the formation of urban thermal islands emphasized that high vegetation reduces thermal islands [23]. A system designed for the summer quarter measured the concentrations of NO2, O3, and PM10 and compared the results with those of meteorological stations on Earth, showing high accuracy. This system found that high concentrations of these pollutants can trap heat in space, reduce wind speed on the ground, and increase the likelihood of thermal islands [24]. A study comparing urban and non-urban green space with surface temperature found that increasing urban green space reduces the likelihood of thermal islands [25]. Population size and urban population density were found to be directly related to rising urban temperatures in another study [26]. In a study on urban development, the

intensity of thermal islands was positively correlated with the size of the population and the density of the regional population [27]. Sustainability, specifically in reducing urban air pollution, was mentioned as a factor in reducing thermal islands [28]. Another study found that the temperature of the islands was highest at night and in high-pressure conditions [29].

Based on the literature review, it is necessary to study the efficiency of fuzzy systems and spatial information systems in illuminating surface temperature anomalies and understanding urban thermal islands for better management of energy resources and urban planning. The main objectives of this study are to identify thermal islands using a fuzzy systems approach, analyze the effect of coverage type and amount on urban thermal islands, determine the intensity of thermal islands and resulting temperature differences, and recognize the effects of urban thermal islands. The methodology presented here can help reduce the effects of urban heat islands in urban space management.

2- Methodology

2-1- Study area and Data

This study was conducted in Tehran, the largest city and capital of Iran, as well as the capital of Tehran province. Tehran has a population of 8,244,535 and is the 25th most populous city in the world. The city covers an area of 730 square kilometers and is located at 35°43′00.12″ north latitude and 51°24′00.00″ east longitude (Figure 1). The highest points in the north of the city reach about 2000 meters, while the southernmost points reach 1050 meters above sea level. In this study, air pollution data (SO2, O3, PM10, and SO2) was collected from the Tehran Air Quality Control Company, which has approximately 22 stations located in different areas of Tehran, every three hours. Additionally, data on rainfall, air pressure, temperature changes, and wind speed over the past 15 years were obtained from the Tehran Air Quality Control Company. It is important to note that this data was collected from active stations in Tehran, with an average sampling frequency of 4 hours every 15 years, resulting in a total of approximately 150,000 numerical values.

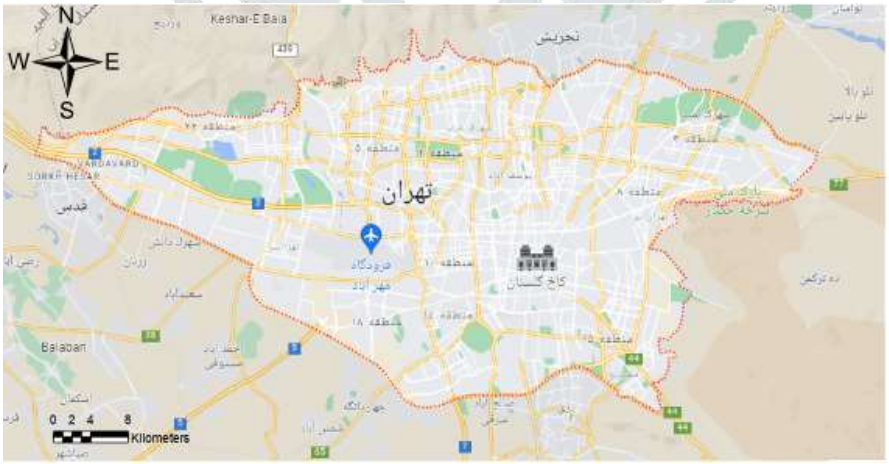


Fig 1: Figure of Tehran (OpenStreetMap)

2-2- Fuzzy logic system

2-2-1- Fuzzy logic

In this work, Fuzzy commands are presented as sentences with IF-THEN logic (IF x is A THEN y is B). Each command represents. the relationship between B, A, and the membership function μ_(A → B). According to the previous explanations, the relations between the two values of B and A can be expressed in terms of commonality, community, and complement as follows:

1. μ_(A → B) (x, y) = 1 - min [μ_A (x), 1 - μ_B (y)] (1-3)

2. μ_(A → B) (x, y) = max [1 - μ_A (x), μ_B (y)] (2-3)

3. μ_(A → B) (x, y) = 1 - μ_A (x) [1 - μ_B (y)] (3-3)

4. μ_(A → B) (x, y) = min [μ_A (x), μ_B (y)] (4-3)

5. μ_(A → B) (x, y) = μ_A (x) μ_B (y) (5-3)

A fuzzy inference can be represented as follows:

IF x is A THEN y is B

(x is A ^ ´) / (y is B ^ ´)

Reference: [30]

2-2-2 Combining fuzzy relations:

The two relations P and Q in the spaces (x, y, and z) can be combined and finally, a subset can be reached, which is shown as follows:

R (x, z) = P (x, y) O Q (y, z) (6-3)

The following two combinations in the above relation can show the degree of relationship between z and x:

1. Composition min - max

POQ (x, z) = {((x, z) ┤, max ├ [min¦y (μ_P (x, y), μ_Q (y, z))])} (7-3)

2. Product combinations - max

POQ (x, z) = {((x, z) ┤, max ├ [μ_P (x, y) * μ_Q (y, z)])} (8-3)

A mathematical formula for μ_POQ (x, z) can be proposed:

μ_POQ (x, z) = Sup¦ (y∈Y) (μ_P (x, y) * μ_Q (y, z)) (9-3)

Reference: [31]

2-3- Effective Parameters in the Formation of Thermal Islands

2-3-1- Climatic Conditions

The climate of an area, influenced by elements such as temperature and precipitation, can impact air pollution and the formation of thermal islands. For example, in Tehran, the center of the city experiences higher temperatures compared to the suburbs, which can contribute to trapping heat in the area. Rainfall also plays a crucial role in regulating temperature, with areas receiving less rainfall typically experiencing higher temperatures. Rainfall below 5 mm per day not only fails to purify the air but can also lead to increased pollution in the city.

2-3-2- Temperature

Temperature fluctuations, both spatially and temporally, are key factors in air quality changes. Solar radiation directly or indirectly provides atmospheric heat. The most significant temporal temperature changes occur daily and seasonally. Horizontally, the equator typically experiences the highest temperatures, with temperatures decreasing as we move towards the poles. Sunlight directly affects air temperature. By utilizing data from synoptic stations, a temperature layer was created for this study, dividing temperatures into four classes: low, medium, high, and very high.

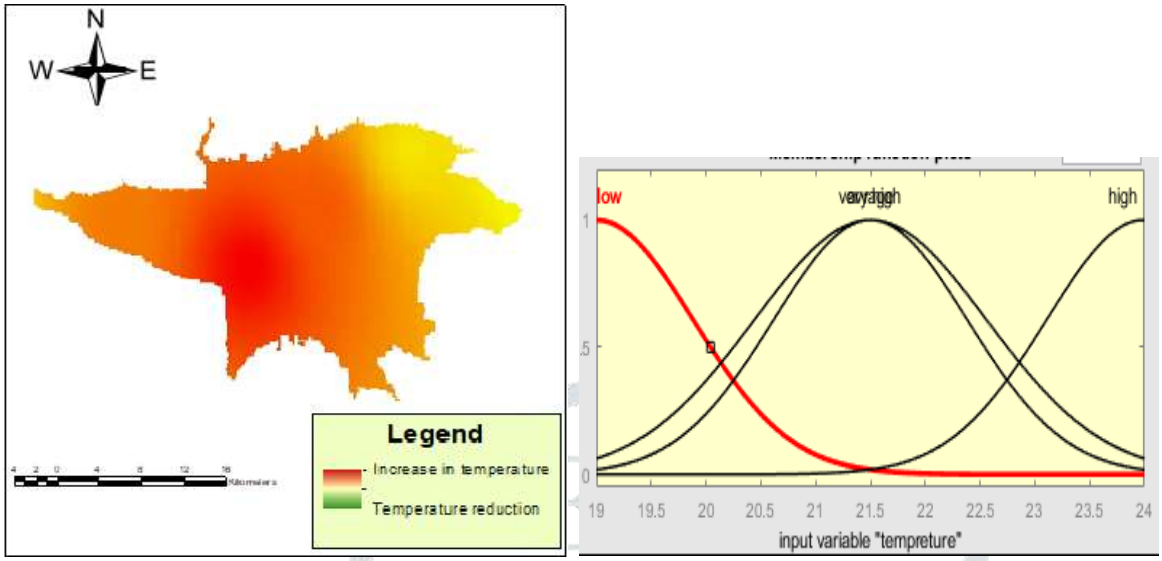


Fig 2: Estimated temperature layer of Tehran Fuzzy diagram and temperature classification

2-3-3 Rainfall

Rainfall is one of the most important and influential factors in air temperature. This parameter can be considered a negative factor affecting air temperature. When hot air rises into the sky, it carries water vapor up with it. As the water vapor ascends, it cools and condenses around fine dust particles in the air. Some of the water vapor freezes into tiny ice crystals, which then absorb the condensed water droplets. These droplets freeze further to form larger ice crystals, known as snowflakes, which eventually fall as snow. As the snowflakes descend, they encounter warmer air and melt into raindrops. In this study, the rainfall parameter was categorized into three classes: low, medium, and high (see Figure 3).

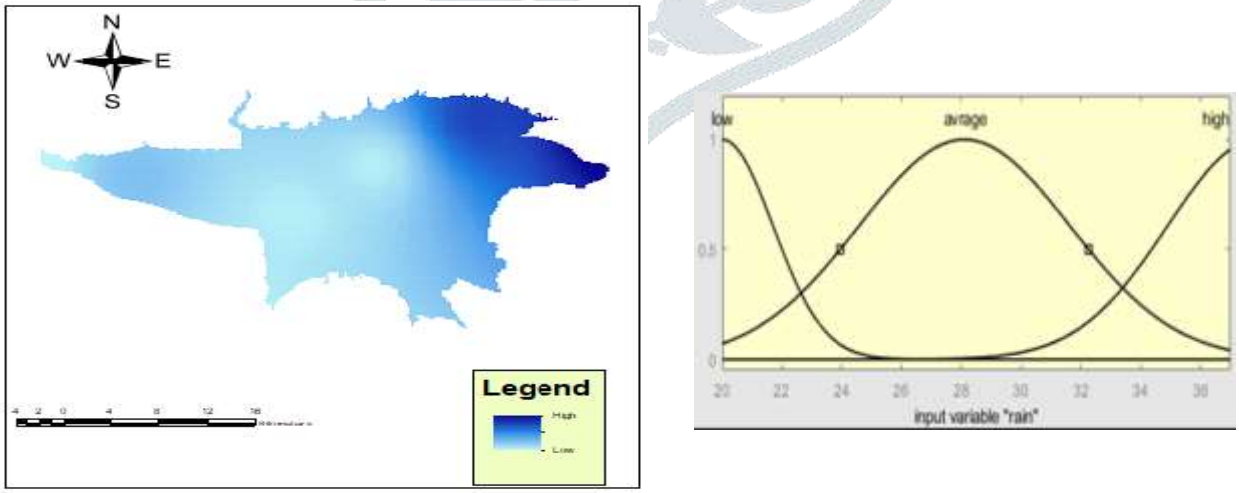


Fig 3: Estimated Rain layer of Tehran Fuzzy diagram and Rain classification

2-3-4- Wind

The wind is one of the elements that affect the weather and climate conditions of any region. The main cause of wind is changes in air pressure. Changes in air pressure, in turn, occur as a result of changes in temperature and air movement. Wind speed can play an important role in determining the temperature of the region. For example, if there is a high level of air pollutants in an area, the presence of pollutants can help increase the temperature in that area. However, if cool monsoon winds blow at high speed in that area, they can displace stable factors and move to another location. This prevents the accumulation of environmental factors in that area. In this study, wind for each point was divided into 4 classes: low, medium, high, and very high (Figure 4).

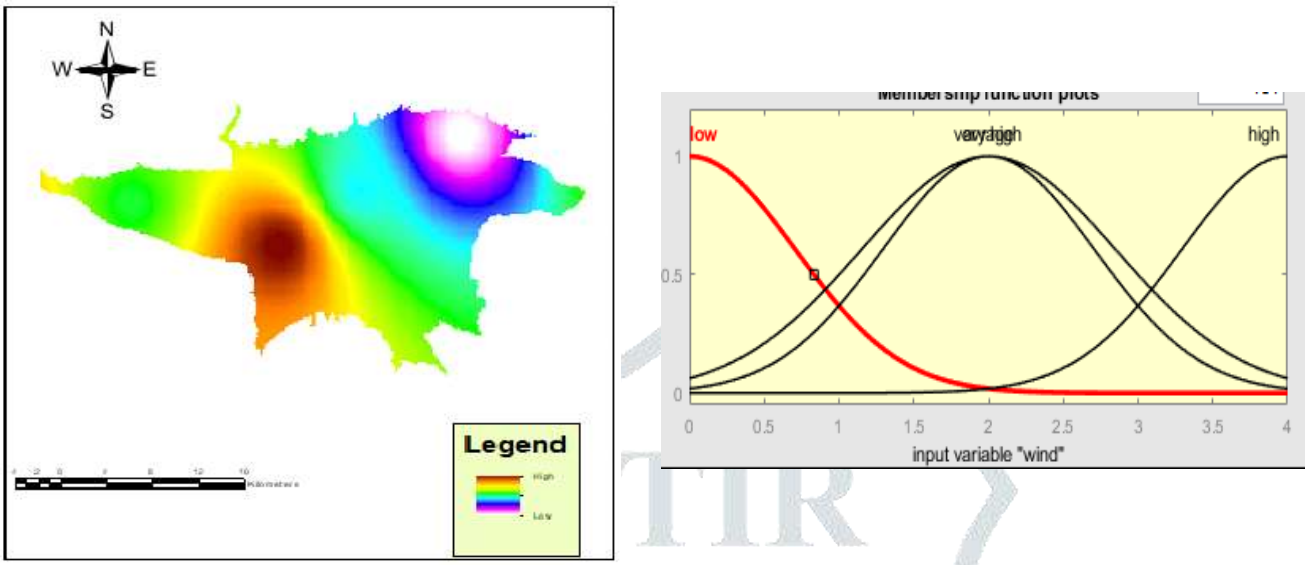


Fig 4: Estimated wind layer of Tehran Fuzzy diagram and wind classification

2-3-5- Population

The urban population is surprisingly affected by rising temperatures. The population living in an area indirectly contributes to factors that increase air temperature. The existing population can generate heat by increasing energy consumption. For example, each person uses various electrical devices to complete daily tasks. The use of these devices and their energy consumption leads to heat production. In this study, the population was divided into three classes: low, medium, and high (Figure 5).

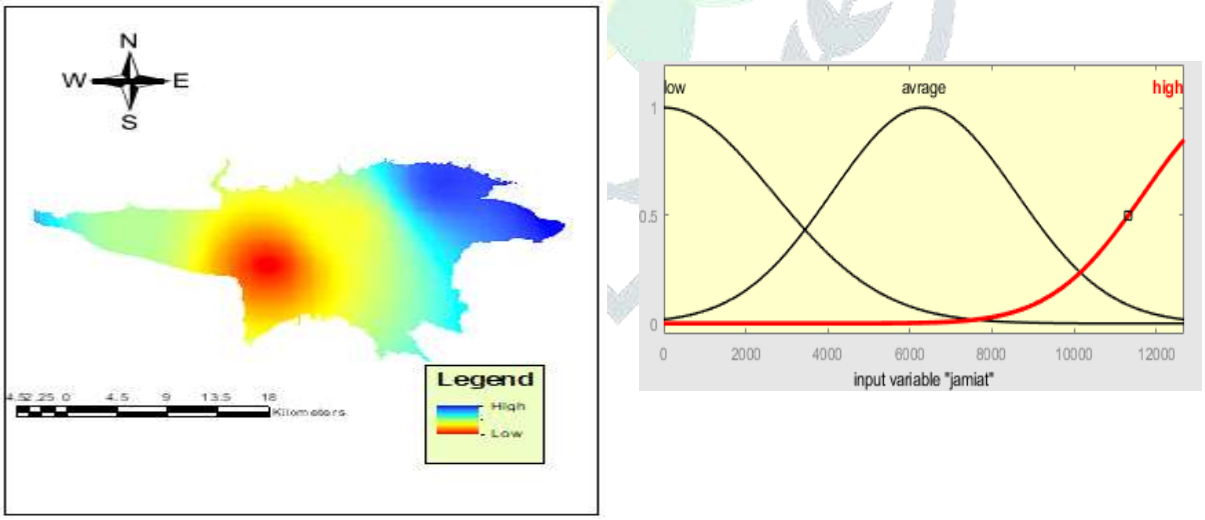


Fig 5: Estimated population layer of Tehran Fuzzy diagram and population classification

2-3-6- Streets and public thoroughfares

The presence of main streets plays a significant role in raising temperatures, as the traffic from vehicles on these roads produces greenhouse gases that contribute to increased air temperature. In this study, main streets were mapped and their distances calculated using the Euclidean distance method in the ArcGIS program, resulting in a raster output. It is expected that areas closer to main streets will experience higher temperatures. The distances from the streets were categorized into two classes: low and high (see Figure 6).

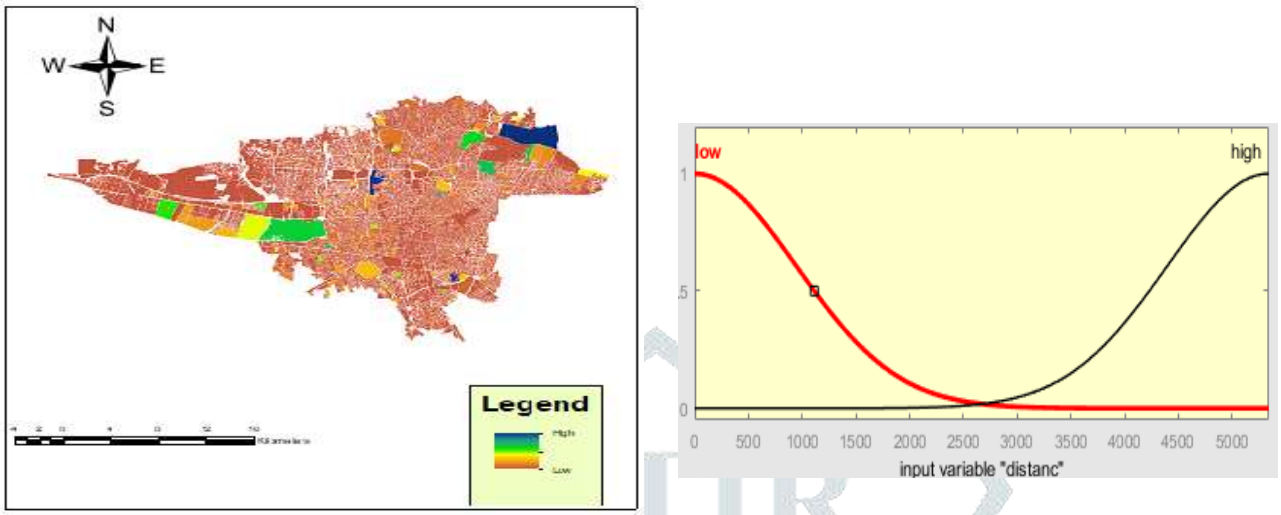


Fig 6: Estimated Streets and public thoroughfares layer of Tehran Fuzzy diagram and Streets and public thoroughfares classification

2-3-7- Air pollution

Today, the presence of air pollutants is one of the main factors contributing to the generation of ambient heat. There exists a direct relationship between the increase in the number of air pollutants in the atmosphere and the rise in air temperature. The Earth absorbs some of the sun's energy and reflects the remainder. During this process, the wavelength of light undergoes a change. Some gases present in the Earth's atmosphere absorb this radiation, which is primarily in the infrared range. Greenhouse gas molecules absorb infrared light to a greater extent than other gases. The absorption of energy by gas molecules leads to their movement and an increase in energy. This study investigates the effects of NO2, O3, PM10, and SO2 gases. The concentration of pollutants in this study was categorized into three classes: low, medium, and high (see Figure 7).

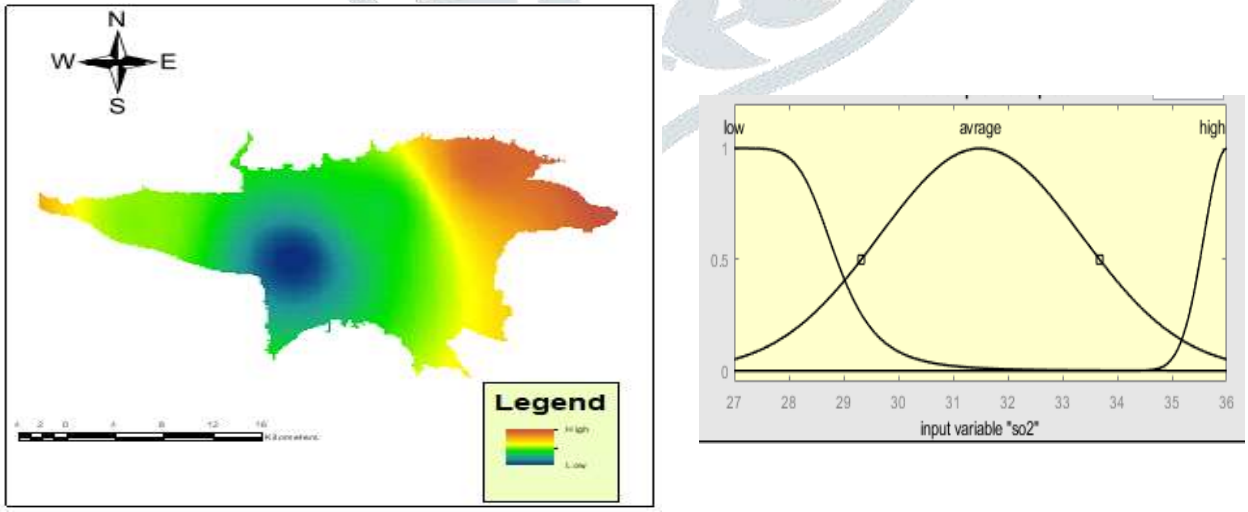


Fig 7: Estimated air pollution layer of Tehran Fuzzy diagram and air pollution classification

2-3-8- Air pressure

Another influential factor in determining the temperature of a region is air pressure. However, it should be noted that air pressure alone is not the only effective factor, as it is measured in conjunction with other factors. For example, if there are aggravating air temperature factors in an area, high air pressure in that area will help stabilize the situation. The presence of air pollutants and other factors is stabilized and undergoes fewer changes due to the high air pressure. Even the wind may not have the desired effect on these conditions. Conversely, if the temperature rise factors in an area are low, or if the temperature drop factors are high, the high air pressure in such

conditions stabilizes these factors and diminishes the effect of hot winds. Therefore, the effect of air pressure must be considered in conjunction with other factors. In this study, air pressure was divided into low and high classes (Figure 8).

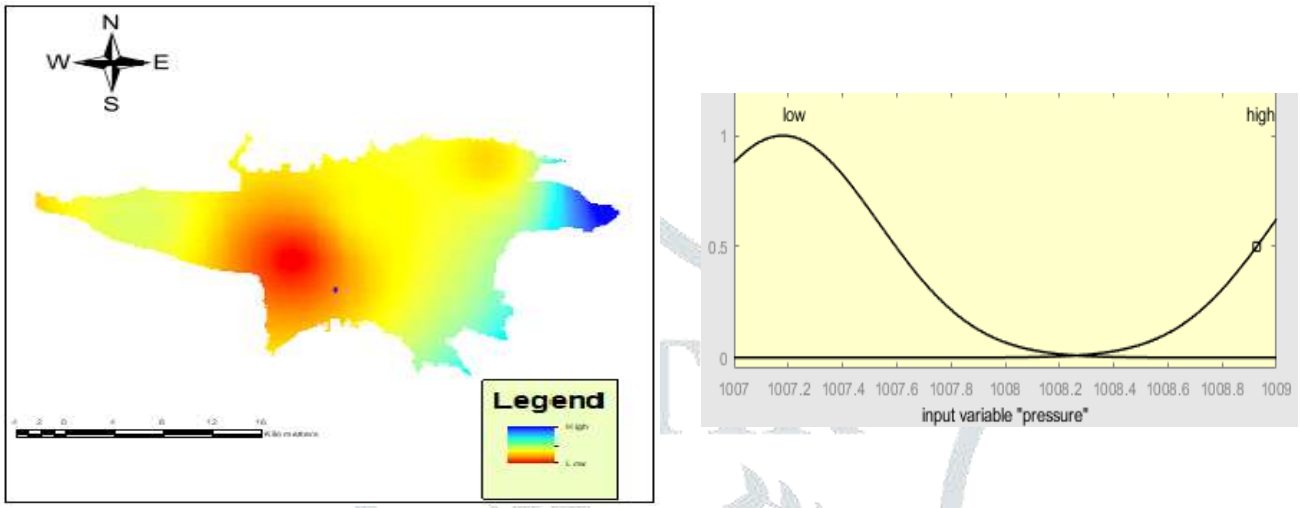


Fig 8: Estimated air pressure layer of Tehran Fuzzy diagram and air pressure classification

2-3-9- Height

Altitude is a factor that directly affects air temperature. In the troposphere, the lowest layer of the atmosphere, temperature decreases with increasing altitude. The troposphere itself is composed of smaller layers. The main difference between this layer and others in the atmosphere is the accumulation of water vapor in Earth's atmosphere. This layer is where many atmospheric phenomena related to humidity, which are key factors in weather conditions (such as clouds, rain, snow, fog, and lightning), occur. The heat source for the troposphere layer is the radiant energy from Earth's surface, so as altitude increases, temperature decreases. In this study, altitude was divided into two classes: low and high (see Figure 9).

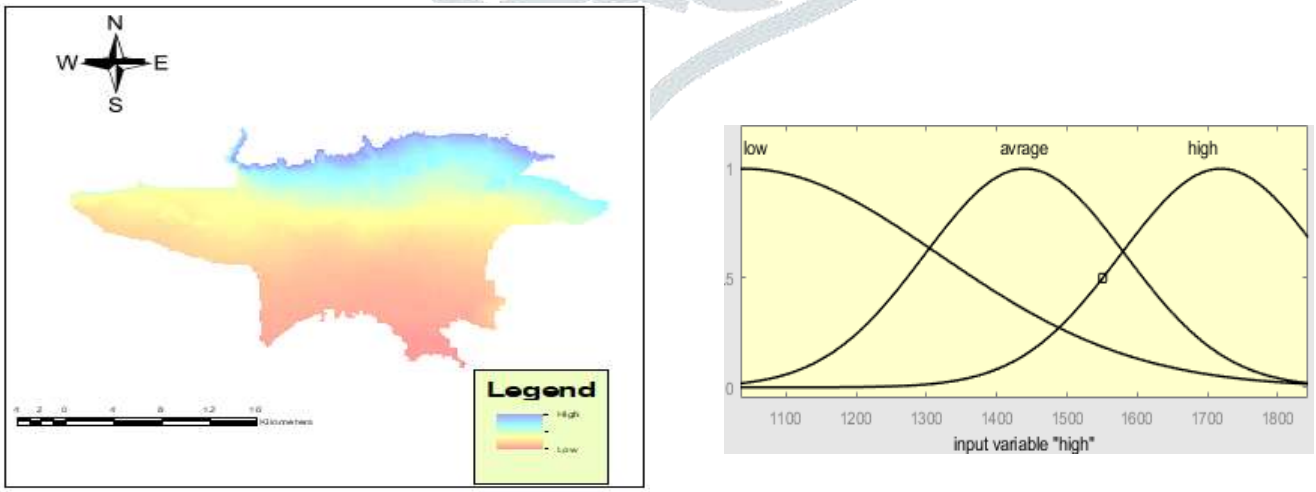


Fig 9: Estimated High layer of Tehran Fuzzy diagram and high classification

2-3-10- Green area

Trees in their biological communities are essential life-giving systems for humans, and vegetation serves as a crucial design element in enhancing the urban environment and improving the thermal comfort of open urban spaces in hot climates. Urban parks and tree-lined roads can greatly enhance the thermal environment for urban residents. Parks and green spaces within the city have the ability to alter the temperature and humidity levels, creating various microclimates. However, it is important to note that green areas tend to be cooler

than the residential areas located outside of the park. Most measurements taken within parks indicate higher average humidity levels and lower temperatures compared to the surrounding built-up areas. In this study, green space was categorized into three classes: low, medium, and high (see Figure 10).

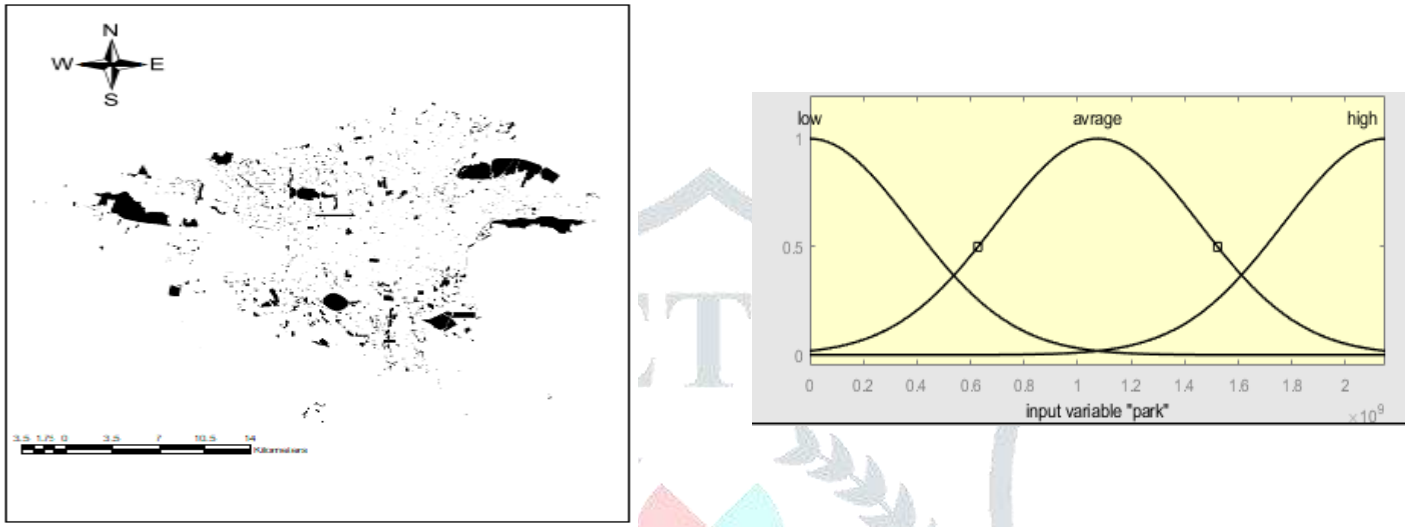


Fig 10: Estimated green area layer of Tehran Fuzzy diagram and green area classification

The relationship between different factors and the thermal island phenomenon is presented in Table 1.

Table 1: The relationship of each factor with the thermal island phenomenon.

Effects on urban temperature balance	Factors influencing the creation of heat islands
Positive effect	* Urban population's
Negative effect	* Urban green space
Positive effect	* Distance from main streets
Negative effect	*Rainfall
Depends on other factors	*Air pressure
Positive effect	* Temperature rise
Negative effect	*Wind blows
Negative effect	*Height
Positive effect	*Air pollution
Positive effect	SO2 gas's
Positive effect	O3 gas's
Positive effect	PM10 gas's
Positive effect	SO2 gas's

2-4- Define the membership function

According to the previous description in this section, membership functions must be defined for each parameter. In this research, the Gaussian function has been used as a membership function, with most values ranging from real numbers.

The Gaussian function is based on the number Neper and is named after Carl Gauss, a mathematician known for his research and applications in mathematics. The formula for the Gaussian function is F(x) = ae^((x - b)^

2 / 2c^2), where a, b, and c are real numbers. The value of c must be a real non-zero value. When a is positive, the function ranges over real numbers. In statistical and probability theories, the Gaussian function is also referred to as a normal density function due to its applications.

In the equation (2) = 1 / (σ√2π) e^(1 / 2 ((x - μ) / σ)²) f(x), μ = b and σ = c represent the mean and standard deviation, respectively.[41]

2-5- Gaussian membership function

Figure [11] appears an uncommon frame of Gaussian *MF (G (u))* can be seen within the condition down underneath three. Characterized by a central esteem m and a standard deviation *k >0*. The littler k is, the smaller the "bell" is. The work utilized within the past interface to draw Gaussian capacities employments a diverse K^1 parameter, the taking after Eq. (3). The mapping between both parameters is*:*

$$K^1 = \frac{1}{2k^2}$$

$$G(u) = e^{-\frac{(x-m)^2}{2k^2}}$$

where m appears as the center of separation from the beginning σ speaking to the width of the bend. *G (u)* encompasses an unobtrusive highlight, and there are no zero focuses at all. [42]

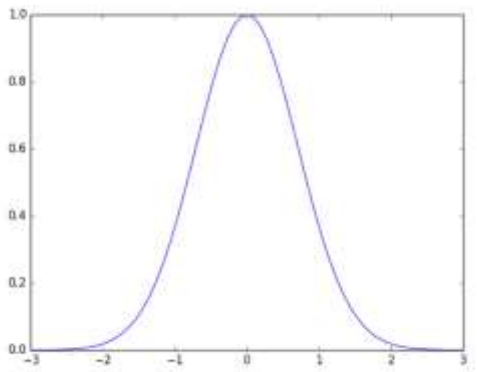


Fig 11: Gaussian membership function

If you don't have the Fuzzy Logic toolbox (and therefore do not have access to Gauss), in (Figure 12) we have a simple anonymous function to create a parameterized Gaussian curve. This demo got captured from the math work website. *x* is an array of x-values. *mu* is mean. *sig* is the standard deviation. The *amp* is the (positive or negative). *V o* is the vertical offset from baseline (positive or negative)

```
x = linspace(-5,25,100);
mu = 10;
sig = 5;
amp = 9;
vo = -5;
y = gaus(x,mu,sig,amp,vo);
% Plot gaussian
plot(x, y, 'b-', 'LineWidth',3)
% Add noise
yh = y + randn(size(y))*amp*.10;
hold on
plot(x, yh, 'ro','markersize', 4)
grid on
title(sprintf('Guassian with \\mu=%.1f \\sigma=%.1f amp=%.1f vo=%.1f', ...
    mu, sig, amp, vo))
```

Figure 12: Demo of Gaussian function

3- Results

3-1- Fuzzification

The fuzzy phase of this study incorporates inputs such as urban population, urban green space, distance from main streets, rainfall, air pressure, temperature rise, wind speed, height, air pollution, SO2 gas, O3 gas, PM10 gas, and SO2 gas. Our study concluded that the best functions for this analysis are the Gauss mf and tri mf functions. As a result, we decided to utilize both functions and compare the results. Additionally, each data point was categorized based on its importance, with some falling into categories of very good, good,

medium, and poor. Others were divided into three categories, while some were grouped into two categories. In Figures 12 and 13, we have two Gaussian diagrams showing the input categorized into four and three categories, respectively.

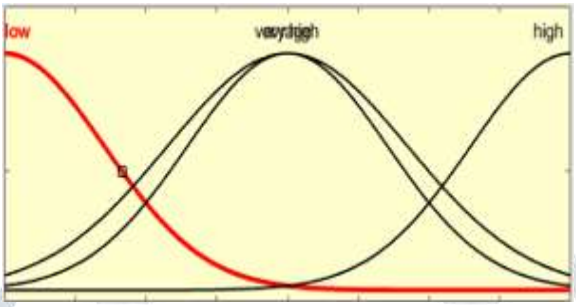


Fig 12: The curve of Gaussian with 4 categorize

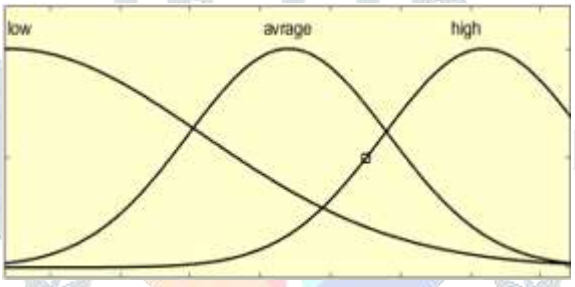
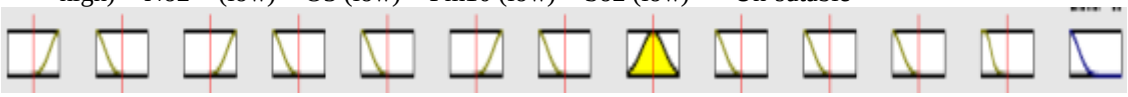


Fig 13: The curve of Gaussian with 3 categorize

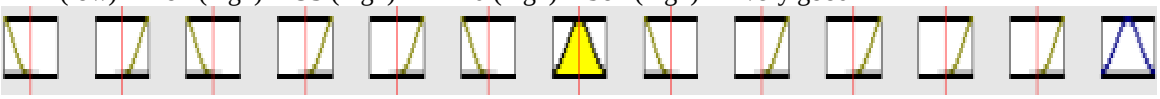
3-2- Fuzzy rules inference and defuzzification

This is the main and most important part of the research. At this stage, a logical relationship must be established between all available parameters. These relationships are the result of understanding each parameter and its effect on the creation of thermal islands as described earlier[43]. Based on the previous description, the relative impact of each parameter was determined. For example, if the temperature is high, wind speed is low, altitude is low, pollution is high, population is high, green space is low, rainfall is low, and air pressure is high, then an area has the potential for a heat island. Here is an example of 17 fuzzy commands out of 40 commands that are considered, along with the graph level of each command variable.

1) Distance (high) + population (low) + High (high) + Park (high) + Pressure (low) + Rain (high) + Temperature (low) + Wind (very high) + No2 + (low) + O3 (low) + Pm10 (low) + So2 (low) → Un-sutable



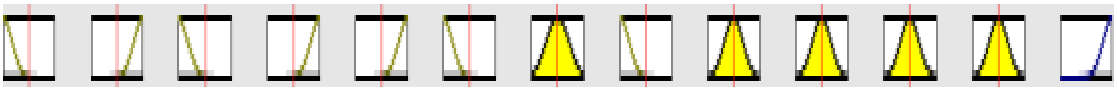
2) Distance (low) + population (high) + High (low) + Park (low) + Pressure (high) + Rain (low) + Temperature (very high) + Wind (low) + No2 (high) + O3 (high) + Pm10 (high) + So2 (high) → very good



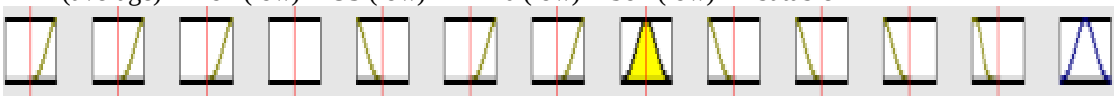
3) Distance (low) + population (high) + High (low) + Park (low) + Pressure (high) + Rain (low) + Temperature (very high) + Wind (average) + No2 (average) + O3 (average) + Pm10 (average) + So2 (average) → very good



4) Distance (low) + population (high) + High (low) + Park (low) + Pressure (high) + Rain (low) + Temperature (very high) + Wind (low) + No2 (average) + O3 (average) + Pm10 (average) + So2 (average) → good



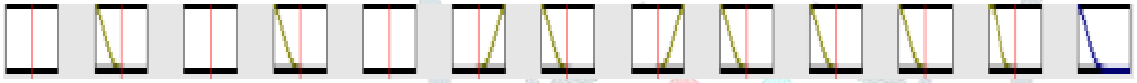
5) Distance (high) + population (high) + High (high) + Park (average) + Pressure (low) + Rain (high) + Temperature (high) + Wind (average) + No2 (low) + O3 (low) + Pm10 (low) + So2 (low) → sutable



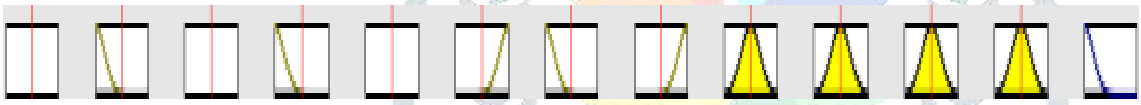
6) Distance (high) + population (low) + High (high) + Park (high) + Pressure (low) + Rain (high) + Temperature (average) + Wind (high) + No2 (low) + O3 (low) + Pm10 (low) + So2 (low) → Un-sutable



7) Distance (-) + population (low) + High (-) + Park (high) + Pressure (-) + Rain (high) + Temperature (low) + Wind (high) + No2 (low) + O3 (low) + Pm10 (low) + So2 (low) → Un-sutable



8) Distance (-) + population (low) + High (-) + Park (high) + Pressure (-) + Rain (high) + Temperature (low) + Wind (high) + No2 (average) + O3 (average) + Pm10 (average) + So2 (average) → Un-sutable



9) Distance (high) + population (average) + High (high) + Park (average) + Pressure (low) + Rain (high) + Temperature (high) + Wind (average) + No2 (low) + O3 (low) + Pm10 (low) + So2 (low) → sutable



10) Distance (-) + population (average) + High (-) + Park (high) + Pressure (-) + Rain (high) + Temperature (low) + Wind (high) + No2 (average) + O3 (average) + Pm10 (average) + So2 (average) → Un-sutable



In Figure 14, which is a three-dimensional model of the relationship between temperature and rainfall with the impact on the formation of the thermal island, it is clear that in conditions where the air temperature is low and precipitation reaches its maximum, there is the lowest possibility of occurrence of thermal islands. Conversely, in conditions where the temperature is high and rainfall is low, the space is more suitable for the formation of a thermal island. Also, the modeled relationship between population-temperature, temperature-pressure, and temperature-rain are shown separately in (Figure 14).

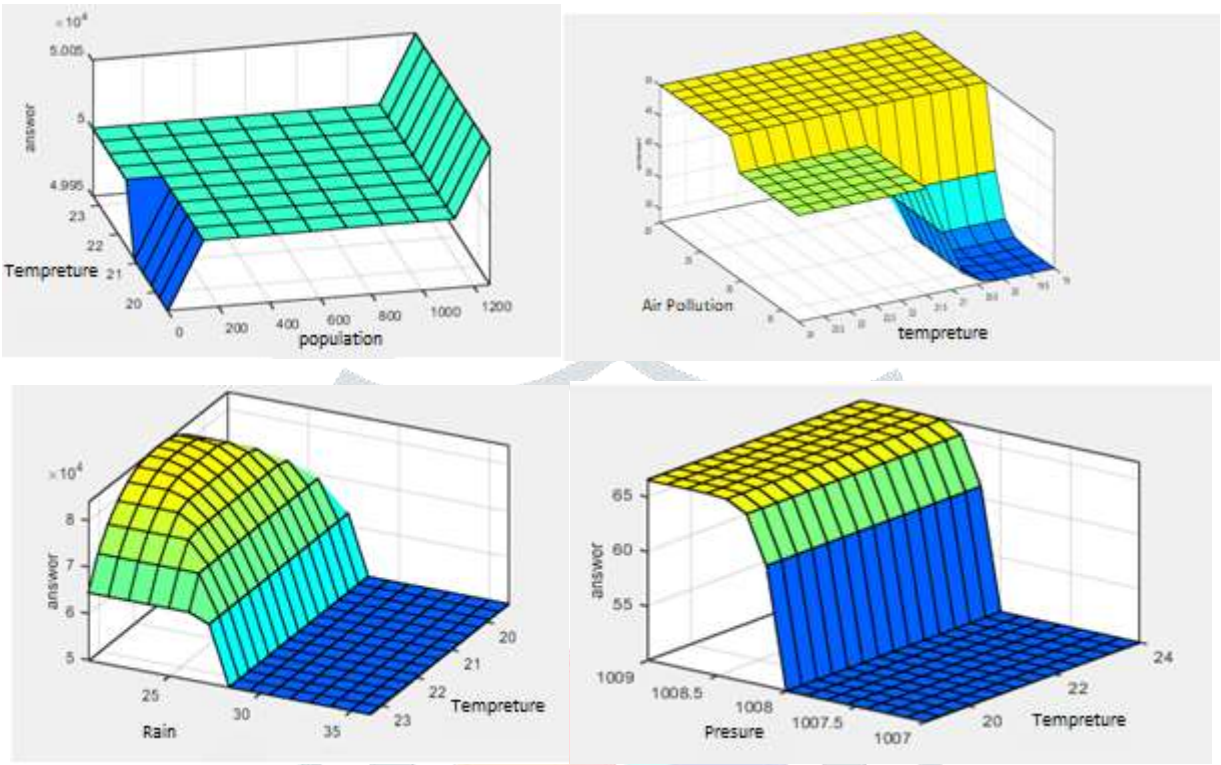


Fig (14): The modeled relationship between temperature-precipitation, temperature –population, temperature-rain, and temperature-pressure

3-3- Analysis membership function model

According to the results of this study, population indices of 20%, air pollution 17%, temperature 16%, green space 15%, altitude 10%, precipitation 11%, wind 8%, distance from streets 7%, and air pressure of 6% had the greatest effect on the formation of thermal islands in Tehran, respectively (Table 2 and Figure 14). It can be concluded that during the last 20 years, the mentioned parameters according to Table 2 have caused the formation of thermal islands in the city of Tehran.

It can be concluded that during the last 20 years, events such as vegetation loss, uncontrolled construction, population growth, declining rainfall, global warming, overuse of vehicles, unsustainable growth, the practice of factories, industries and the increase of pollutants resulting from them have played an important role in the formation of thermal islands in Tehran (Figure 15).

Table 2: The effect of indicators used in this study in terms of percentage by day and night.

The effect of parameters on the formation of thermal islands in Tehran (%)	Indicators
16%	Temperature
11%	Rainfall
8%	Wind
20%	Population
7%	Distance from the streets
6%	air pressure
10%	Height
15%	green space
17%	air pollution

As it was said before, due to the importance of two functions gauss mf and tri mf in this study, we decided to use both functions as calculation functions and the interesting thing was that the numerical value of each output in both functions was close to each other, which is Finally, it was decided that the numerical average of each parameter from both functions is determined as the final number of that parameter. The numerical value of each function is given in Table 3.

Table 3: Comparison of results from two membership functions gauss mf and tri mf

Parameters	Membership function name	Formula	The extent of the impact on the formation of thermal islands
Population	Gauss mf	$F(x) = ae^{\frac{-(x-b)^2}{2c^2}}$	%20
	Tri mf	$\mathbf{f(x)} = \begin{cases} (), & \mathbf{x < -a} \\ \frac{x-a}{b-a} & a < x > b \\ \frac{c-x}{c-b} & b < x > c \\ (), & x > c \end{cases}$	18%
Air pollution	Gauss mf	$F(x) = ae^{\frac{-(x-b)^2}{2c^2}}$	%17
	Tri mf	$\mathbf{f(x)} = \begin{cases} (), & \mathbf{x < -a} \\ \frac{x-a}{b-a} & a < x > b \\ \frac{c-x}{c-b} & b < x > c \\ (), & x > c \end{cases}$	17%
Green area	Gauss mf	$F(x) = ae^{\frac{-(x-b)^2}{2c^2}}$	%15
	Tri mf	$\mathbf{f(x)} = \begin{cases} (), & \mathbf{x < -a} \\ \frac{x-a}{b-a} & a < x > b \\ \frac{c-x}{c-b} & b < x > c \\ (), & x > c \end{cases}$	17%
Height	Gauss mf	$F(x) = ae^{\frac{-(x-b)^2}{2c^2}}$	%10
	Tri mf	$\mathbf{f(x)} = \begin{cases} (), & \mathbf{x < -a} \\ \frac{x-a}{b-a} & a < x > b \\ \frac{c-x}{c-b} & b < x > c \\ (), & x > c \end{cases}$	11%
Air pressure	Gauss mf	$F(x) = ae^{\frac{-(x-b)^2}{2c^2}}$	%6
	Tri mf	$\mathbf{f(x)} = \begin{cases} (), & \mathbf{x < -a} \\ \frac{x-a}{b-a} & a < x > b \\ \frac{c-x}{c-b} & b < x > c \\ (), & x > c \end{cases}$	5%
	Gauss mf	$F(x) = ae^{\frac{-(x-b)^2}{2c^2}}$	%7

Streets and public thoroughfares	Tri mf	$\mathbf{f(x)} = \begin{cases} (), & \mathbf{x < -a} \\ \dfrac{x-a}{b-a} & a < x > b \\ \dfrac{c-x}{c-b} & b < x > c \\ (), & x > c \end{cases}$	7%
	Gauss mf	$F(x) = ae^{\frac{-(x-b)^2}{2c^2}}$	%8
Wind	Tri mf	$\mathbf{f(x)} = \begin{cases} (), & \mathbf{x < -a} \\ \dfrac{x-a}{b-a} & a < x > b \\ \dfrac{c-x}{c-b} & b < x > c \\ (), & x > c \end{cases}$	8%
	Gauss mf	$F(x) = ae^{\frac{-(x-b)^2}{2c^2}}$	%16
Temperature	Tri mf	$\mathbf{f(x)} = \begin{cases} (), & \mathbf{x < -a} \\ \dfrac{x-a}{b-a} & a < x > b \\ \dfrac{c-x}{c-b} & b < x > c \\ (), & x > c \end{cases}$	15%
	Gauss mf	$F(x) = ae^{\frac{-(x-b)^2}{2c^2}}$	%11
Rain	Tri mf	$\mathbf{f(x)} = \begin{cases} (), & \mathbf{x < -a} \\ \dfrac{x-a}{b-a} & a < x > b \\ \dfrac{c-x}{c-b} & b < x > c \\ (), & x > c \end{cases}$	12%

3-4- Final output of the fuzzy map

As predicted, in the areas shown in Figure 15, where the aggravating factors of the thermal island phenomenon were at their maximum level, the likelihood of experiencing thermal island phenomena was highest. In some parts of the western regions, factors such as population density, higher temperatures, and lower winds contributed to the increased probability of this phenomenon occurring in these areas. The presence and growth of cities and urban heat islands have led to an increase in average O3 pollutants by approximately 0.5 ppb, average NO2 pollutants by around 2 ppb, and CO by about 40 ppb. By considering the coefficients of these factors and comparing the model data, an accuracy of 78.6% was achieved.

The final results indicated that in regions 9, 10, 11, 17, and 18, as well as parts of region 21 in Tehran, the likelihood of heat islands is very high. Moving from the central parts towards the southwest, a circular but lighter mass is observed compared to the southeast, indicating the possibility of thermal grains. Additionally, in a limited area moving towards the north from the center, a high probability of this phenomenon was observed. The least probable presence of a thermal island in Tehran is in the northeastern regions, where lower temperatures, population density, proximity to streets, and increased rainfall minimized the likelihood of this phenomenon occurring.

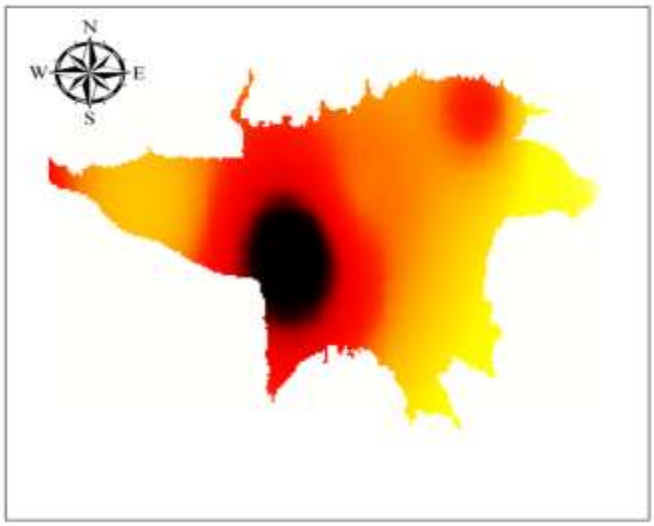


Fig 15: The final output of the fuzzy map

4- Discussion

In this study, the parameters of temperature, air pollution, and the population had the greatest impact on the emergence of heat islands, and air pressure, altitude, and the wind had the least impact on the emergence of heat islands. Of course, due to the low speed and the inappropriate direction of wind, it is expected that this parameter will have a low impact, and on the contrary, in the case of a parameter such as the increase in population in different regions due to the production of heat factors, a high impact of this parameter is expected. These findings are similar to those of previous studies [44], [45]. However, researches on the same topics have different results. For example, in the work of [46], similar to the result of this research, the temperature was one of the parameters that had the highest impact on the formation of heat islands. On the contrary, in the work of [47], the wind was one of the most influential factors in the formation of heat islands.

According to the evaluation methods of urban heat islands, the fuzzy approach in evaluating these islands has been a less commonly used new approach. Satisfactory results were obtained through the modeling process, and the accuracy of these results was confirmed by analyzing and comparing them with experts in this field. By comparing and analyzing the data between temperature and air pollution, we concluded that the effect of temperature is greater than pollution. The relationship between the two is direct, as the temperature increases after an increase in air pollution, perhaps due to the production of heat in ambient conditions by gases like So2 and Pm10. Additionally, comparing the results of air pollution and the population in certain blocks, we find that an increase in population in the blocks leads to an increase in heat and pollution.[49]. The regions with the highest population density were Regions 1, 2, and 3, while

the lowest population density was found in Regions 15, 16, 20, and 21. A comparison was also made between the results of rain-temperature, air pressure-temperature, temperature-air pollution, and population-temperature in relation to the response space. Interesting results were obtained, and a three-dimensional diagram is shown in Figure 14. For example, the relationship between temperature and rainfall in the emergence of heat islands shows that the behavior of rainfall before and after a certain amount is significantly different. If rainfall occurs before 29 ml, with average temperatures between 19 and 24 degrees Celsius, the likelihood of heat islands appearing is high. However, once the average rainfall exceeds about 29 ml, its impact diminishes. Even in different temperature intervals, the probability of heat islands appearing reaches a minimum. In this modeling, the relationship between temperature and air pollution with the response space yielded an interesting result. In Figure 14, the temperature-air pollution chart provides a detailed examination of pollution levels in relation to precipitation. The chart distinguishes between scenarios where rainfall is below or above 28 milliliters. When precipitation is less than 28 milliliters, the likelihood of heat islands is high, as expected. This indicates that rainfall below 28 milliliters is insufficient to counteract the effects of air pollution in the formation of heat islands. Conversely, when rainfall exceeds 28 milliliters and air pollution is low, the likelihood of heat islands is significantly reduced. Even in cases of high air pollution, precipitation plays a more significant role in mitigating the likelihood of heat islands than air pollution does. Furthermore, upon analyzing the three-dimensional graph of temperature-population and the response space, which indicates the probability of a heat island emerging, it is evident that once the population exceeds a certain threshold, it has a significant impact on the generation and retention of heat. To enhance the examination of population values in the three-dimensional diagram, they have been categorized into 6 blocks, allowing for a more detailed assessment and thorough analysis. Within this diagram, it is apparent that in the final block representing the highest population density, the likelihood of heat islands forming increases abruptly, regardless of the amount of temperature emitted by the sun. While this outcome was somewhat expected, the sudden shift is truly surprising. This suggests that in areas with the highest population density in Tehran, the production and retention of heat will experience substantial growth. This finding aligns with previous research conducted in Tehran, as seen in the works of [50], [51].

5- Conclusion

In this research, a model was developed to predict and identify thermal islands in Tehran using an approach based on fuzzy systems. The main goal of this research was to provide a simple, developable, and suitable analytical model for identifying and predicting urban heat islands. Understanding the impact and results of this research will help in better management of urban affairs.

Data related to air pollution, rainfall, air temperature, wind, population, green space, height, and distance from main streets were identified based on their positive or negative impact on the emergence of thermal islands. Fuzzy logic was developed considering Gaussian and Tri MF functions. Fuzzy rules and fuzzy inference blocks were defined based on the study conducted to identify the effect of each parameter and the input from experts in the field.

By comparing the data from AQCC stations with the results from Gaussian functions, the model achieved an accuracy of 78.6%. Challenges were faced in considering the impact of buildings on wind and calculating wind direction in presenting this model. By analyzing data separately for summer and winter seasons, it was found that thermal islands increase temperatures by 1.3°C in summer and 1.4°C in winter. Regions 9, 10, 11, 17, and 18 were identified as having the highest probability of thermal islands.

Declarations

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Ethics declarations

Conflict of interest

The authors declare no competing interests.

Authors' contributions

All authors read and approved the final manuscript.

Availability of data and materials

The data are available on request.

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