

Assessment of Urban Heat Islands Using Remotely Sensed Data

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Abstract

Thermal infrared satellite sensor images are widely used for assessing the thermal urban environment as well as for identifying the Urban Heat Islands (UHI) in highly urbanized areas. In this study, the relationship between urban growth and UHI in the megacity of Istanbul was investigated using the Landsat 5 TM satellite sensor data and temperature recordings obtained from the meteorological stations within and around the city of Istanbul. Using the thermal band of the Landsat 5 TM images, the spatial distribution of the warmer surfaces in the urban environment are identified and matched with the urban surface characteristics together with the land use/cover distribution. Three Landsat 5 TM satellite sensor images obtained 25 September 1987, 18 July 1997, and 28 June 2007 were used. UHI boundaries were extracted from the classified thermal band of these satellite sensor images. Images were also classified to form the link between radiances, surface temperatures, and land use characteristics particularly for the urbanized areas. The results of the study indicated the expansion of urban sprawl in the city that further corresponded to growth in thermal radiation of land surface in high-density areas. This fact is mainly due to unplanned and uncontrolled urbanization that has occurred in the last three decades.

Keywords: Istanbul, Landsat TM 5, Remote Sensing, Urbanization, Urban Heat Islands (UHI).

Uzaktan Algılanmış Veriler Yardımıyla Şehir Isı Adalarının Değerlendirilmesi

Özet

Uydu görüntülerinin ısı (termal) bandları yoğun şehirleşmiş alanlarda, şehir ısı adalarının tanımlanmasının yanı sıra şehirlerin ısı çevrelerinin değerlendirilmesinde de yaygın olarak kullanılmaktadır. Bu çalışmada, oldukça büyük bir şehir olan İstanbul'da da şehir ısı adaları ile şehirleşmedeki büyüme arasındaki ilişki Landsat 5 TM uydu verileri ve İstanbul'un etrafındaki meteorolojik istasyonlardan elde edilen sıcaklık verileri kullanılarak irdelenmiştir. Landsat 5 TM' nin ısı bandı kullanılarak, şehir çevrelerindeki daha sıcak yüzeylerin mekansal dağılımı tanımlanmış ve arazi kullanımı/örtüsü dağılımı ile birlikte şehir yüzey karakteristikleri ile ilişkilendirilmiştir. Çalışmada, 25 Eylül 1987, 18 Temmuz 1997 ve 28 Haziran 2007 tarihinde elde edilen üç Landsat 5 TM uydu görüntüsü kullanılmıştır. Şehir ısı adalarının sınırları bu görüntülerin termal bandları sınıflandırılarak belirlenmiştir. Görüntüler aynı zamanda özellikle şehir alanlarındaki radyans, yüzey sıcaklığı ve arazi kullanımının karakteristiği arasındaki ilişkinin saptanması için sınıflandırılmıştır. Bu çalışmanın sonuçları şehir içindeki yerleşim alanlarındaki yoğun artışın, yerleşim alanlarındaki yüzey sıcaklığının artmasının temel nedeni olduğunu göstermiştir. Bu etkinin ana sebebi son 30 yılda ortaya çıkan plansız ve kontrol edilemeyen şehirleşmedir.

Anahtar Kelimeler: İstanbul, landsat 5 TM, şehirleşme, şehir ısı adaları (UHI), uzaktan algılama.

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INTRODUCTION

Since 1950 there has been a huge worldwide increase in the percentage of population living within cities. Approximately 59% of the world's population currently lives in urban areas, and this figure is further expected to increase especially in the developing countries where the fraction of the population that lives in cities is comparatively lower than the developed countries. In the near future, it

is expected that the global rate of urbanization will increase the world urban population up to 67% by 2030, as urban agglomerations emerge and population migration from rural to urban/suburban areas continue.

Population of the urban areas has increased rapidly in Turkey within the past three decades due to migration from the rural sites towards to the urban areas. While the Turkish

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metropolitan population was approximately 16.2 % in 1927, it increased to 65% in 2000 and it reached 70.5 % in 2007 (Kaya and Curran 2006, Kaya 2007). The population of Istanbul was 680.857 in 1927, 5.475.982 in 1985, 9.260.438 in 1997, and 12.573.000 in 2007 (Seker et al. 2008, Anonymous 2009). The population of Istanbul in the year of 2007 is almost 18% of whole population of Turkey.

Urbanization is defined as the development of cities and suburban areas due to population growth leading to major changes in land use/cover in accordance with human activities. Population growth in urban areas results in the use of more impervious land in the construction activities (Doygun and Ilter 2007, Deniz et al. 2008). Thermal remote sensing has been used widely for establishing the relationship between urbanization and climate (Arnfield 2003, Voogt and Oke 2003). The natural cooling effect of shading and evapotranspiration decreases when the vegetation is reduced due to human activities. Furthermore, artificial land surface changes resulting from narrower streets and taller buildings will reduce surface air flow; this phenomenon is called “canyon effect”. Heat generation and pollution as a result of such human activities are the main sources of temperature increase in urban areas. These factors make the urban atmosphere warmer than its surroundings commonly called an Urban Heat Island (UHI).

A number of factors contribute to the occurrence and intensity of heat islands; these include weather, geographical location, time of day and season, and city form and functions (Oke 1982, Oke 1997). The heat island is an example of unintentional climate modification when urbanization changes the characteristics of the Earth's surface and atmosphere (Voogt 2000, Ezber et al. 2007). The main cause of the Urban Heat Island is the modification of the land surface through urban development with the use of materials that effectively retain heat. As population increase, they tend to modify a greater area of land and have a corresponding increase in the average temperature (Rail 2007). Urbanization, on the other hand, negatively effects the environment due to pollution modifying the physical and chemical properties of the atmosphere, and the soil surface. UHI, considered to be a cumulative effect of all these impacts, is defined as the rise in temperature of any man-made area as seen

in Figure 1.

There are three types of heat islands: canopy layer heat island (CLHI), boundary layer heat island (BLHI), and surface heat island. The canopy layer is the heat island below the roof tops in the space between buildings (Mills 2007). Above the urban canopy layer lies the urban boundary layer, which may be 1 kilometer (km) or more in thickness by day while shrinking to hundreds of meters or less at night. It is the BLHI that forms a dome of warmer air extending downwind of the city. Heat island types differ by their shape, temporal characteristics, and some of the physical processes that contribute to their development.

A number of satellite-based studies using thermal infrared imagery have been carried out (Chen et al. 2006) since satellite sensor data provides a dense grid of almost instantaneous temperature measurements over a city thus, permitting visualization of spatial relationships between temperature patterns and urban land use including infrastructural features. There is no comprehensive study till now, on the urban heat island using medium resolution sensors supported by sufficient ‘in situ’ air and surface temperature measurements for statistical analysis of climatologically processes (Nichol et al. 2009). There is an important relationship between land use/cover changes and UHI density (Chen et al. 2006, Baek et al. 2011). Defining this relationship is of utmost significance regarding land use/cover planning. In this study, the relationship between the growth of UHI and increase of urbanized area are in parallel to the population increase as investigated for the period of 1987 to 1997 and 1997 to 2007, using the 6th band of the Landsat 5 TM satellite sensor images on the Istanbul Metropolitan area.

MATERIAL AND METHODS

Study Area and Data Utilized

In this study, Istanbul was selected as the study area (Figure 2), as it is the most crowded city of Turkey located between Asia and Europe with a population that has nearly doubled in 20 years between 1980 and 2000. For the period between 1990 and 2000, the population growth rate of Istanbul was 29.64% for urban and 81% for rural regions of the city. The population is expected to reach 20 million by 2030 (Anonymous 2009). The Bosphorus, a 30-km strait that connects the Black Sea to the Sea of Marmara, is considered

to form a boundary between Europe and Asia, where settlements are located on both sides of the southern half of the strait. The north of the city towards the Black Sea is mostly covered by protected forest patches, and the expansion of the city in that direction is mostly confined to the banks of Bosphorus. The most densely populated parts of the city are located in the northern part of the Marmara Sea. In this study, thermal remote sensing techniques are applied to examine the urban climate in Istanbul for the 10-year periods from 1987 to 1997 and 1997 to 2007.

Three Landsat 5 TM satellite images dated 25 September 1987, 18 July 1997, and 28 June 2007 were used as the remotely sensed data in the study. These three satellite sensor images were acquired at 10:29 a.m. Temperature recordings belonging to the same dates of the satellite sensor images that were provided from the meteorological stations of Istanbul are used. Unfortunately, data from the years 1987 and 1997 belonged to 6 conventional meteorological stations that recorded only the daily average temperatures. Thus, these values could not be compared with the images. The number of meteorological stations increased from 6 to 20 in Istanbul after 2006. Some of Meteorological stations belong to the National State Meteorological Works and some to Automatic Weather Observation Stations (AWOS) under the Istanbul Greater Metropolitan Municipality. The automatic weather observation stations that record the temperature in Istanbul every 2 seconds were set up in 2006. The names of the meteorological stations, temperature data obtained from these stations on 28 June 2007 10:30 a.m. together with the calculated radiance values and Digital Number (DN) representing the stations are listed in Table 1.

Land Use/Cover Classification

In the first step, bands of 1, 2, 3, 4, 5, and 7 of the Landsat 5 TM satellite sensor images were classified to extract the urbanization boundaries in Istanbul for 10-year periods between 1987 to 1997 and 1997 to 2007. ISODATA (Iterative Self-Organization Data) the uncontrolled classification algorithm was used for each of the satellite sensor images. In order to differentiate the urban class from the others, 30 layers were selected for further classification. These layers are merged and the numbers of layers were decreased to 7 main classes urban, roads, bare soil and agricultural land, forestry, water, sand,

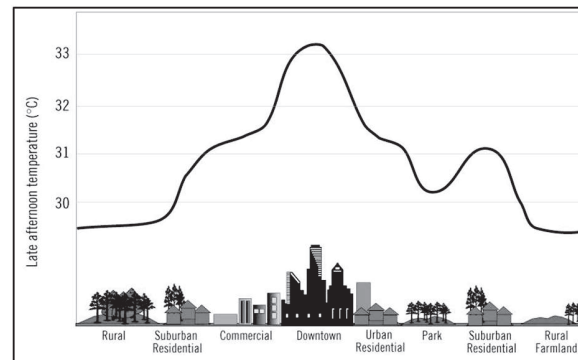


Fig. 1. Profile of urban heat islands (Sailor 1998).

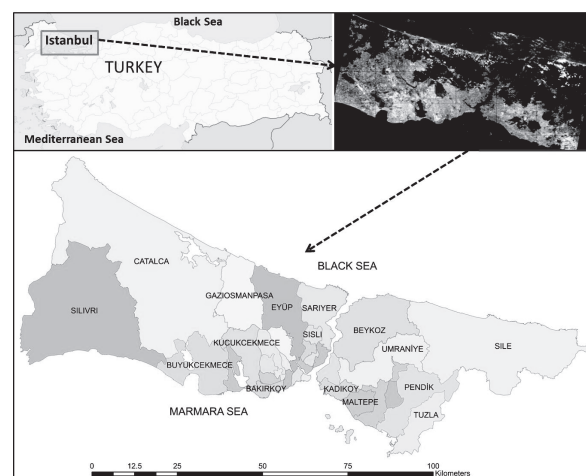


Fig. 2. The study area

Table 1. Meteorological Stations, temperatures, radiance, and digital number.

Meteorological Stations	Land Surface Temperature (°C)	Radiance (W/m ² . sr.µm)	Digital Number
Catalca	27,0	9,58	153
Gebze	33,1	10,94	173
S. Gokcen Sirport	33,0	10,91	169
Kandilli Rasathanesi	34,0	10,91	173
Istanbul University	32,7	10,89	175
Ataturk Airport	32,0	10,84	174
Kumkoy	28,3	9,68	146
Kamiloba	30,1	10,39	166
Hadimkoy	29,6	10,23	163
Goztepe	31,1	10,12	161
Kartal	32,8	10,45	164
Cavusbasi	30,5	10,28	164
Omerli	30,5	10,12	161
Buyukada	31,2	10,33	163
Olimpiyat	31,5	10,45	164
Aksaray	32,2	10,67	167
Terkos	27,9	9,51	141
Akom	30,8	10,23	163
Samandira	32,1	10,55	163
Sile	28,9	9,78	154

and cloud.

Conversion to Spectral Radiance

The digital numbers of the thermal band were

converted into radiance values for each of the investigated years using the following formula (Chen et al. 2006).

$$\text{Radiance} = \text{LMIN} + ((\text{LMAX} - \text{LMIN}) / (\text{QCALMAX} - \text{QCALMIN})) * (\text{QCAL} - \text{QCALMIN}) \quad (1)$$

where,

Radiance, (Watts / m².ster.μm),

LMIN, minimum spectral radiance at QCAL

LMAX, maximum spectral radiance at QCAL

QCALMAX=255

QCALMIN=1 (given in the header file of the 6th bands of the used Landsat 5 TM images)

QCAL=Digital Number (DN)

The thermal infrared bands of the Landsat TM images belonging to the years of 1987, 1997, and 2007 were classified using the density slice algorithm. The ranges used in this classification were kept to a minimum as much as possible in order to identify the areas representing heat. The areas with the highest temperature in all 3 images are shown in red (Figure 5). Such areas within the boundaries of urban cities are named as UHI. Only temperature data of the year 2007 obtained at the time of satellite passing the area are compared with the radiance values calculated for the image. This process was not done for the years of 1987 and 1997. Radiance values of the thermal images belonging to the year of 2007 are associated with temperature data provided from the meteorological stations which are also given in Table 1.

RESULTS AND DISCUSSION

Aerial information of land use/cover classes obtained from the classification of the images for the different years is given in Table 2. According to the results, bare soil, agricultural land, and forestry land decreased whereas, urban and sand areas together with roads increased. Although the 2007 image was a bit cloudy, urban areas have not been affected. Classification results of the images and thermal bands are given in Figure 3 and Figure 5, respectively. The aerial values and land use changes for every 10 year interval were determined accordingly. The urban boundaries were also extracted from the classified images and are displayed in Figure 4. In this figure grey, dark grey, and white colors represent the urban boundaries obtained from the classified images for 1987, 1997, and 2007 respectively. Changes in the urbanized area are given in Table 3, and the corresponding changes in the urban, forestry, and bare land and agricultural

areas were presented in Figure 7. In this figure, only 3 classes which have the highest temporal changes in the 20 year period are displayed. In the thermal band classification and the UHI, which mostly occurred in 2007 in the urbanized areas, is represented with the dashed line. The relationship between the urbanization and the UHI was displayed with the urban boundaries of Istanbul obtained from the images belonging to 1987, 1997, and 2007 and is marked with a continuous line on the thermal classification of the images (Figure 5).

Parallel to the increase in urban areas, the frequency and magnitude of the UHI may increase. The impacts of UHI range from local to global scales. Some of these impacts are; human health risks, release of more greenhouse gases, air pollution, and higher costs of water and energy use. Most greenhouse gas emissions which have the serious contribution to global climate change arise from urban areas (Anonymous 2012). Even though, the UHI themselves are not responsible for global warming because they are considerably small scaled phenomena, they still have to be taken into consideration.

During the last 20 years in Istanbul, while the urban areas have increased, forest, bare land and agricultural areas have sharply decreased. As indicated in Table 3, the urban area difference increased to 268.16 km² between 1987 and 1997, 156.75 km² between 1997 and 2007, and 424.91 km² between 1987 and 2007. Moreover, the growth rate of the city was 82.3% between 1987 and 1997, 26.4% between 1997 and 2007, and 130.4% between 1987 and 2007. The urban area of Istanbul has almost doubled in the past two decades from 1987 to 2007. Two major centers of urban heat islands were found in Istanbul. One is located southwest of the Bosphorus, and the other one is located at the southeastern region of the city. The major finding of this study is the expansion of urban areas that cause growth in thermal radiation of land surface in highly dense areas. This is most probably due to the rapid unplanned and uncontrolled urbanization within the last two decades.

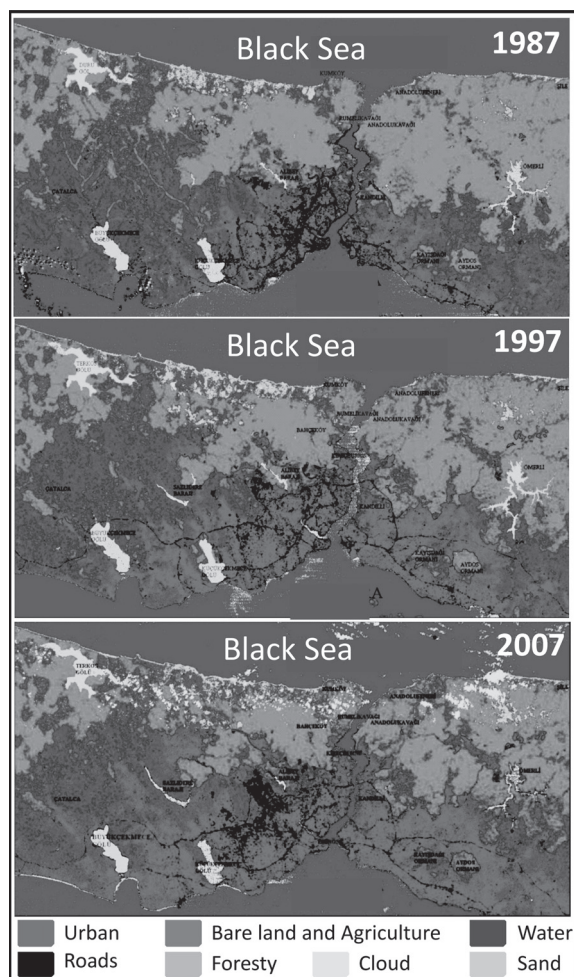
In the urbanized boundary of Istanbul in 1987, a relatively small and negligible UHI was observed. In 1997, parallel to the increase in the urbanized area, the UHI has also increased and several UHI were discovered over the city. In the year of 2007, due to the significant increase in the urbanized area

Table 2. Classification results (Surface coverage of years 1987, 1997, and 2007).

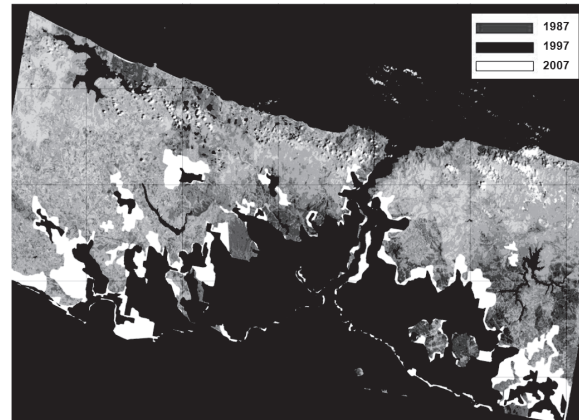
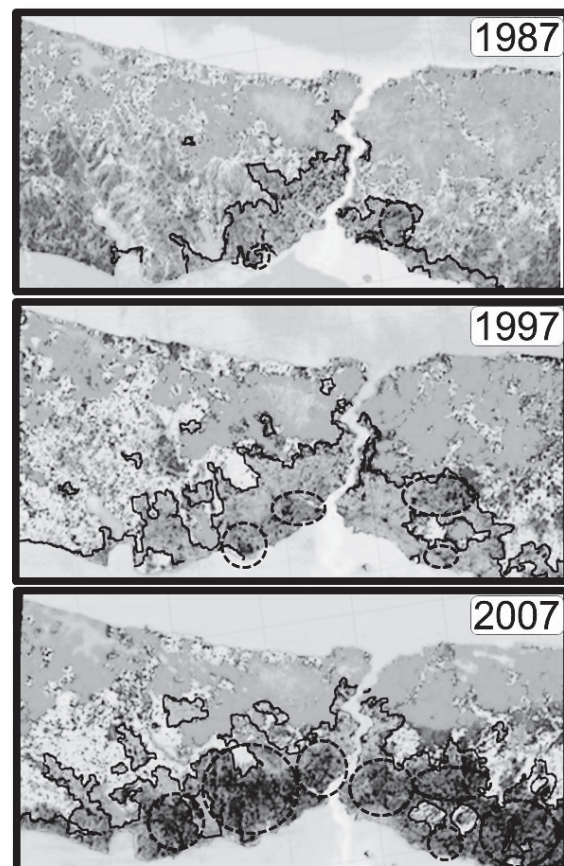
Land use classes	1987 (km ²)	1997(km ²)	2007(km ²)
Urban	325,96	594,12	750,87
Roads	90,79	101,83	133,64
Bare land and Agriculture	1587,78	1437,74	1348,52
Forestry	1640,62	1493,94	1398,88
Water	1532,81	1538,34	1442,96
Sand	52,33	73,31	103,32
Cloud	8,97	0,00	61,09
TOTAL	5239,28	5239,28	5239,28

Table 3. Changes in urban area between 1987, 1997, and 2007.

	1987–1997	1997–2007	1987–2007
Urban area difference	268,16 km ²	156,75 km ²	424,91 km ²
Growth (%)	82,3 %	26,4 %	130,4 %

**Fig. 3.** Classification results of Landsat 5 TM images.

of Istanbul, urban boundaries have been extended and a great amount of bare land and agricultural areas have been converted to urbanized areas. As a result of this expansion, some of the forestry areas, especially those located in the northern part of the

**Fig. 4.** Urban boundaries obtained from classified Landsat 5 TM images for the years 1987, 1997, and 2007.**Fig. 5.** Classification results of the thermal bands and urban heat islands.

city have been seriously affected and even partly destroyed. Also during the period of 1997 and 2007, a lot of high rise buildings were constructed in the center of the city. Due to these reasons, the UHI have sharply increased and have been found over both sides of the city by means of using the thermal bands of the satellite sensor image taken in the year

2007. If the urbanization still continues to increase, the UHI amount will also increase in the future.

The relationship between the radiance values and temperature were examined, and a linear correlation with a satisfactory compliance has been obtained and displayed in Figure 6. For this calculation, the geographical coordinates of each station and corresponding radiance value of the thermal band was used. The correlation of radiance values and temperature data was calculated as high as 88 % with the formula: $y = 0.2246x + 3.3896$ as seen in Figure 6.

The population of the study area increased to approximately 12.5 million in 2007 due to a migration from the rural parts of the country. Thus, the urban land increased to 750.87 km² from 325.96 km² in 1987. As observed from the findings, not only the population in the urban areas increased, but also the boundaries of the urban areas expanded. This study highlights the Urban Heat Islands in parallel to increase in both population density and urban sprawl. Correlation of temperature data with simultaneously taken Landsat 5 TM images of 2007 was achieved. The resulting correlation refers to 88% compliance. Similar findings are recommended for utilization by urban planners to decrease Urban Heat Islands.

CONCLUSIONS

In this study, Landsat 5 TM satellite sensor images of Istanbul were used to present the rapid growth of the city and UHI which occurred over the city due to this significant urban sprawl. It was demonstrated that UHI can be detected using the thermal band of the satellite images together with meteorological data. Classifications of the thermal bands have shown that UHI adhere to urbanization. In this study, the coefficient of determination between the recorded data supplied by the meteorological stations and the satellite estimated

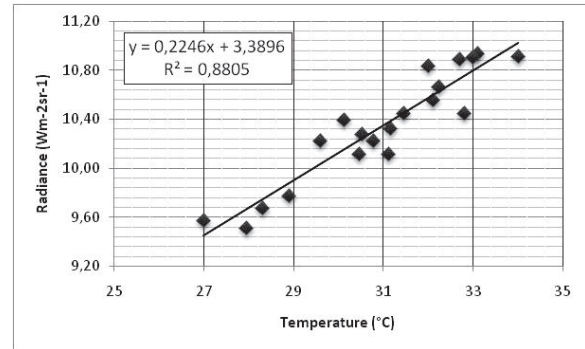


Fig. 6. The relationship between radiance and the temperature in 2007.

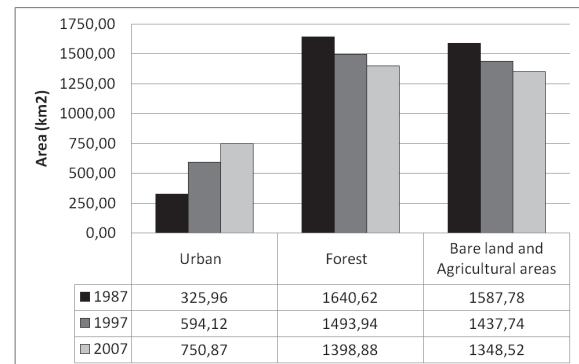


Fig. 7. Significant changes in urban, forest, and bare land and agriculture classes in the year of 1987, 1997, and 2007.

temperatures were calculated as high as 0.88 in 2007. This outcome indicates that UHI can be defined with high accuracy.

Communities can take a number of steps to reduce the heat island effect, such as; planting trees which not only help to shade cities from incoming solar radiation, but also increase evaporation, which decreases the air temperature and increases the vegetation cover. The concrete and asphalt of the cities increase runoff, which decreases the evaporation rate and thus also increases temperature.

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