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Urban Climate Analysis with Remote Sensing and Climate Observations: A Case of Morogoro Municipality in Tanzania

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Abstract

Rapid urbanization is threatening sustainable development of urban areas in Tanzania. Among the risks of rapid urbanization are Urban Heat Island (UHI) effect and climate change. While this has been noted, it is not known to what extent these risks are being realized in fast growing urban areas like Morogoro and other areas of similar geographic and climatic conditions. Therefore a study was conducted to assess the influence of urbanization on UHI and climate in Morogoro Municipality using remote sensing and climate data. Landsat imageries acquired in 1990, 2000 and 2015 were used to assess the change of impervious surface for the year 1990 to 2015 using a Classification and Regression Tree (CART). Radiant surface temperature and normalized difference vegetation index (NDVI) were derived from thermal band and reflectance bands respectively. Mann-Kendall test was used to analyze climate data for trends. Results revealed an increase of impervious surface (built up areas) from 9 km^2 in 1990 to 48 km^2 in 2000 and 82 km^2 in 2015; which is associated with UHI. UHI was not apparent in 1990, but was apparent in 2000 and 2015 with the temperature rise of 1.08˚C and 1.22˚C respectively. A linear relationship between radiant surface temperature (T_B) and percent Impervious Surface (ISA); and between T_B and NDVI it revealed that NDVI is better indicator of variations in T_B dynamics than percent ISA. Mann-Kendall test indicated a significant increasing trend in mean annual maximum temperature. The results imply that increasing ISA coupled with vegetation degradation has contributed to temperature rise and change. Consequently, Morogoro Municipality residents are likely to suffer heat stress due to rapid urbanization. It is recommended that education on the use of reflective surfaces should be given to the residents; and an effective master plan that protects vegetation should be in place.

Keywords

Radiant Temperature, Impervious Surfaces, Urban Heat Island, Random Forest Algorithm, Mann-Kendall Test

1. Introduction

Urbanization is the increase in the population of urban areas versus rural areas [1]. In Tanzania this is largely caused by rural to urban migration and re-classification on new urban areas [2]. This trend is increasing exponentially in Tanzania [3], having risen to 29.1% in 2012 compared with 5.7% in 1967 [3]. Similar to other Sub-Saharan countries, the challenge to urbanization in Tanzania is that it doesn't occur concurrently with the economic growth and development transformation that support it [4]. The consequence is the highest level of urban poverty in the world which is characterized by unequal access to decent housing, high proportion of urban poor living in slum, lack of basic urban services such as access to sanitation, clean water, energy, and solid waste disposal [5]. This poses risks of social instability, risks to infrastructure, health and climate change in urban areas of Tanzania [6].

Urbanization also exerts influence on microclimate by transforming the landscape from natural cover types to increasingly impervious urban land [1], and through human activities that produce emissions of heat, water vapor and pollutants. The outcome of this change can cause temperature in urban areas to be higher than in surrounding non-urbanized areas, an effect called Heat Island [1]. Heat island plus above mentioned risks of rapid urbanization threaten sustainable development of urban areas in Tanzania. In essence, sustainable development aims at promoting economic and social wellbeing, while protecting the environment [7].

To have a sustainable development of human settlements in Tanzania, the National Human Settlements Development Policy was formulated in 2000 [8]. However, current efforts in implementation of the policy are not sufficient to ensure sustainability of urban areas development. In Morogoro Municipality, 65% of population lives in unplanned and un-serviced settlements [9], and climate variability has caused an increase of waterborne diseases due to deterioration of water quality; and a decline of crop production [10] [11]. Shortage of water caused by rapidly growing population, coupled with increasing urban poverty, makes Morogoro Urban more at risk of not meeting sustainable development [9]. Moreover, as urbanization contributes to global warming, Urban Heat Island (UHI) will for sure influence the sustainable development [12].

To better illustrate the urbanization and its impacts on urban climate, remote sensing data have been widely used in urban heat islands investigation as well as for urban climatology research [1] [13]. In this study, remote sensing and geospatial techniques tools were used to study land surface processes and their interactions with the atmosphere in Morogoro Urban. The thermal characteristic of

Morogoro Urban was identified from infrared radiative surface temperature. The surface temperature is of prime importance in understanding urban climatology as is a measure of the state of energy exchange at the surface, thus combines the influences of a number of processes that occur at the surface. The analysis also included the historical climate information to find the degree of association between the temperature variables.

It is envisaged that knowledge generated from this study will help in formulation of strategies for mitigation of global warming and Urban Heat Island effect for sustainable development of Morogoro Urban, and other developing cities in Tanzania as the urbanization characteristics are similar. Moreover, the study avails in filling a knowledge gap for Climate Change adaptation in Urban Areas of East Africa [14].

2. Materials and Methods

2.1. Description of the Study Area

Morogoro Urban District has an area of about 260 square kilometers, and is located between longitude 37˚34'52"E and 37˚45'25"E and between latitude 6˚38'56"S and 6˚55'8"S in Morogoro Region (Figure 1). Morogoro Region is

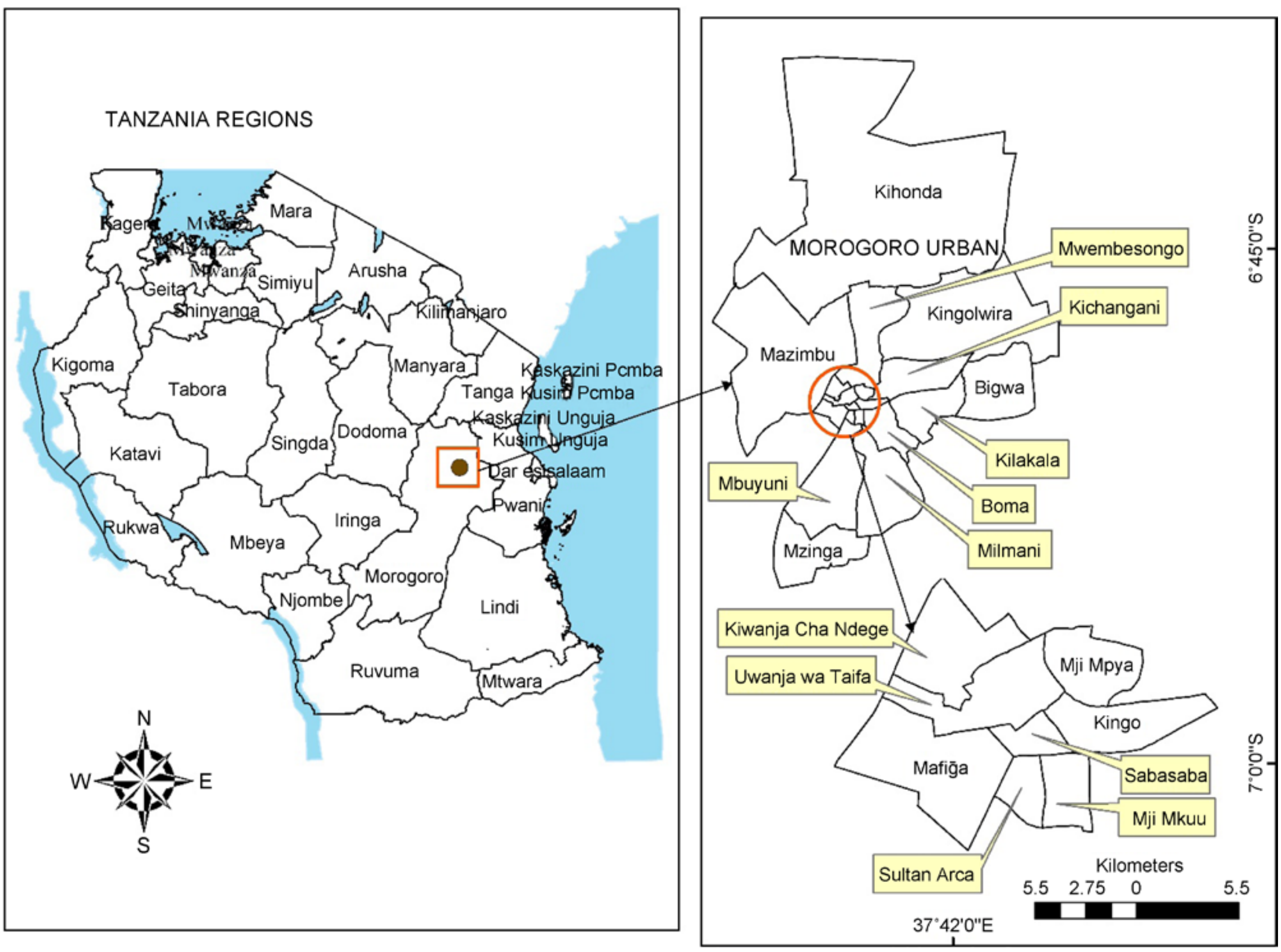

Figure 1. Morogoro municipality.

among the regions with the highest level of urbanization in Tanzania [15], and Morogoro Municipality ranked fifth after Dar Es Salaam, Mwanza, Mbeya and Arusha City Councils [16]. The District has an average minimum and maximum temperature of 16˚C and 33˚C respectively. The average annual rainfall ranges between 821 - 1505 mm [17]. The current population size is about 315,866 [18] compared to 227,921 in 2002 [19] and 117,601 in 1988 [20]. The main economic activities include industries, subsistence and commercial farming, small scale enterprises and trade.

2.2. Methods

Mapping Impervious Surfaces and Land Surface Temperature Estimation

Landsat TM and ETM+ digital imagery with path/row 167/65 covering the study area were acquired and analyzed for three time periods, 1990, 2000 and 2015. The key image analysis procedures include image acquisition, mapping impervious surfaces, accuracy assessment and land surface temperature estimation.

Landsat image acquisition

Table 1 presents Landsat imagery used in the study. The imageries were obtained from Earth Explorer (earthexplorer.usgs.gov). To avoid the effects of seasonality, all images were acquired during the dry season. Moreover, the choice of the imageries was done in consideration of the cloud cover and images with minimum cloud cover were selected. The 2012 image was used to fill gaps in image 2015. These two images (2012 and 2015) had gaps, as they were captured when Scan Line Corrector (SLC) of Landsat ETM+ was off. The Mosaicking tool in ERDAS Imagine software was used to gap-fill the 2015 image. The 2012 image was chosen for gap filling as the gap phase statistic between the images was highest (100%). Moreover, ground-truthing points were collected by a hand held GPS to guide mapping of impervious surfaces and for accuracy assessment.

Table 1. Landsat images used in the analysis of land cover changes.

Image	Date of acquisition	Season	Cloud cover (%)
Landsat TM	24.10.1990	Dry	12
	07.07.2000	Dry	2
Landsat ETM+	08.07.2012	Dry	2
	17.07.2015	Dry	3

TM = Thermatic Mapper, ETM = Enhanced Thematic Mapper plus.

Image pre-processing

Landsat data were preprocessed from Digital Number to at-satellite reflectance (for six reflective bands) and at-satellite radiance temperature (thermal bands after being resampled to 30 m using the nearest neighbor algorithm) following approach described in [21] and in Landsat 7 User's handbook (Equations (1), (2) and (3)).

$$L_\lambda = \frac{\left(LMAX_\lambda - LMIN_\lambda\right)}{\left(QCALMAX - QCALMIN\right)} * \left(QCAL - QCALMIN\right) + LMIN_\lambda \quad (1)$$

where: L_λ = spectral radiance at the sensor's aperture

$QCAL$ = quantized calibrated pixel value in DN

$LMIN_\lambda$ = spectral radiance that is scaled to $QCALMIN$

$LMAX_\lambda$ = spectral radiance that is scaled to $QCALMAX$

$QCALMIN$ = minimum quantized calibrated pixel value (corresponding to $LMIN_\lambda$ in DN

$QCALMAX$ = maximum quantized calibrated pixel value (corresponding to $LMAX_\lambda$ in DN

$$\rho_p = \frac{\pi * L_\lambda * \mathrm{d}^2}{ESUN * \cos\theta_s} \tag{2}$$

where: ρ_p = unitless planetary reflectance

L_λ = spectral radiance

d = Earth–Sun distance

$ESUN_\lambda$ = mean solar exo-atmospheric irradiances

θ_s = solar zenith angle.

Radiance values from band 6 were converted to radiant surface temperature by the following equation

$$T_B = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} \tag{3}$$

where: K_2 = calibration constant 2 (1260.56 and 1282.71 for TM and ETM+ respectively)

K_1 = calibration constant 1 (607.76 and 666.09 for TM and ETM+ respectively)

L_λ = spectral radiance

T_B = at-satellite brightness temperature.

Also, normalized difference vegetation index (NDVI) was derived from reflectance bands using the equation in [22]. NDVI is among most widely useful features for differentiation of vegetation and non-vegetation in urban areas [23]; and it has been used to study urban climate change associated with urbanization [24].

Mapping impervious surfaces

A Classification and Regression Tree (CART) was implemented using the random forest algorithm in R-software to classify the Landsat imagery into land use/land cover maps. The regression tree algorithm produces rule-based models for prediction of continuous variables based on training data. Random forest creates many decision trees based on input layers and then classifies a pixel using the decision trees based on training data [25]. Training data of impervious surfaces were created in QGIS by digitizing vector polygons in Landsat imagery guided by Google Earth (SPOT 5). Training data were restricted to the 2010 National Forest Resources Monitoring and Assessment (NAFORMA) land cover classes.

After classification, classes outside impervious surfaces were masked out by reclassifying the classes to 0% impervious. The impervious class (Built up) was reclassified to 100% impervious. Also, different percentage categories of impervious surfaces were determined based on Wards boundaries. Thereafter, post-classification method was used to estimate the change in impervious surface that have occurred between 1990 and 2000 and between 2000 and 2015 periods. Moreover, Zonal Statistics tool in QGIS evaluated mean temperatures in impervious and non-impervious classes for 1990, 2000 and 2015 years. Zonal Statistics tool summarize a raster layer within specified features. In this study, input raster layers were Radiant surface temperature layers, and specified features were impervious and non-impervious polygons for respective years.

Accuracy assessment

Accuracy of the Landsat-derived impervious surface estimates was assessed using field points and high spatial resolution SPOT 5 image by stratifying random sampling, wherein 246 reference points was used for validation. Error matrix (also called confusion matrix) was used to evaluate the accuracy (**Table 2**). The overall accuracy of classification reached 86.6% and the Kappa coefficient was 0.66 (66%). This was accepted as the overall classification accuracy was above the recommended target of 85%, with relatively even levels of accuracy for all classes [26].

Table 2. Error matrix.

Ground/Map	Impervious	Non Impervious	Totals	Producer's accuracy
Impervious	45	6	51	88%
Non Impervious	27	168	195	86%
Totals	72	174	246	
User's accuracy	62%	95%		

Climate data analysis

The study utilized historical climate data for the period from 1981 to 2012 (32 years) obtained from Tanzania Meteorological Agency (TMA), Morogoro Station to investigate Climate Change in Morogoro Municipality. Mean annual maximum temperature data was analyzed by Mann-Kendall test in order to determine monotonic trend over time as per equations described in [27]. Mann-Kendall test is a nonparametric statistical test widely used with environmental time series, as it is less sensitive to outliers and most robust for discovering trends in time series for which there may be missing observations [27] [28]. One advantage of using nonparametric test is that the data need not conform to any particular distribution [27]. R software was used to carry out the statistical Mann-Kendall test. In addition, linear trend line was plotted to compare results obtained from the Mann-Kendall test.

3. Results and Discussion

Impervious surface and T_B changes

The land cover maps indicate an increase of impervious surface (built up areas) from 1990 to 2015. The impervious surface was 9 km^2 in 1990, 48 km^2 in 2000 and 82 km^2 in 2015 (**Figure 2**). By visually inspecting the maps, it was found that the expansion of impervious surface is more in Kihonda Ward. Mean Temperature (T_B) for impervious, non-impervious and difference between T_B in impervious and T_B in non-impervious for three dates are presented in **Table 3**. In 1990, an Urban Heat Island (UHI) was not apparent, while, in 2000 and 2015 UHI was apparent wherein 1.22˚C temperature difference in 2015 was the strongest UHI effect in Morogoro Urban. The spatial extent of UHI in 1990, 2000 and 2015 indicates that urban development is increasing the temperature of Morogoro Urban. The impervious surface emits and reflects more of solar radiations hitting the earth surface, which influences the urban temperatures and causing Urban Heat Island [29] [30].

UHI effect could be a reason for climate variability in Morogoro Urban, as [10] found that the climate is varying. The increasing UHI effect is likely to lead to discomfort of Morogoro Urban residents, as [31] stated that urban citizens are likely to suffer heat wave impacts more often due to UHI effect. The implications

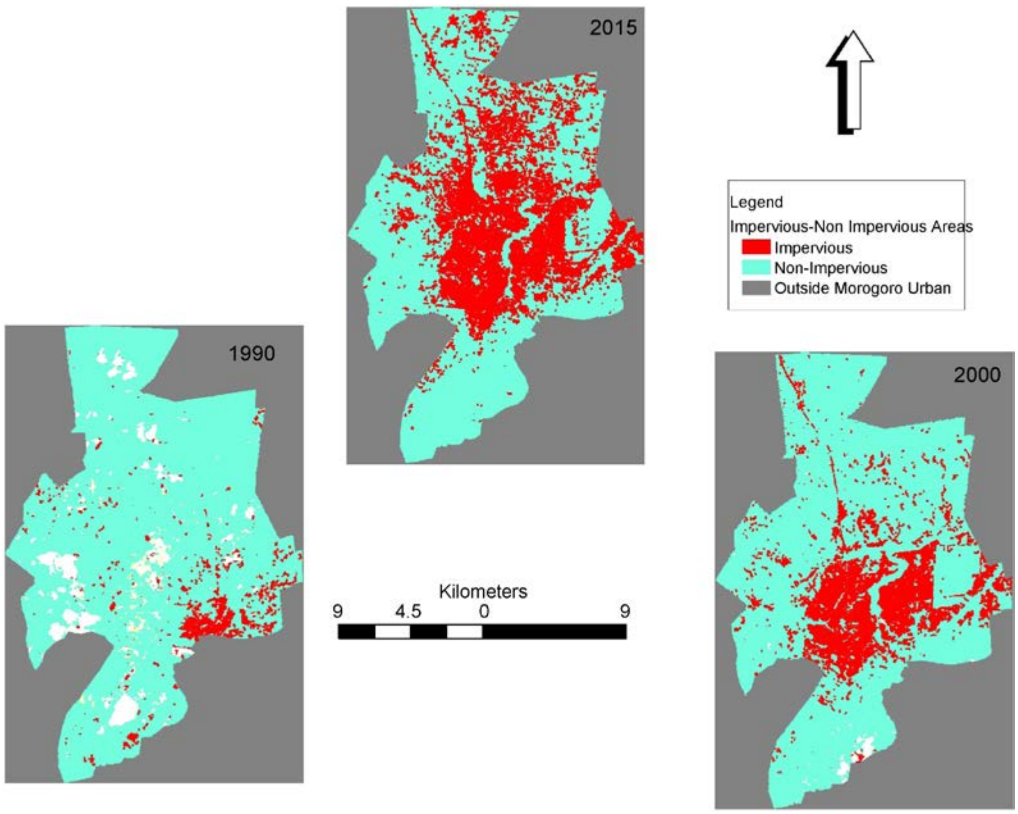

Figure 2. Impervious surfaces for year 1990, 2000 and 2015.

Table 3. Mean temperature of impervious and non-impervious surfaces and its difference.

Years	Mean Temperature (T_B)		ΔT
	Non-impervious	Impervious	
1990	303.24	302.46	−0.78
2000	297.33	298.41	1.08
2015	300.66	301.88	1.22

of increasing UHI effect is that there is a need of having effective master plan as stated in the National Human Settlements Development Policy in order to mitigate UHI effect and ensuring sustainable development. Moreover, there is a need for educating Morogoro Urban residents on the use of light colored surfaces which reflect more sunlight and absorb less heat for adaptation of UHI effect. The use of reflective surfaces is among strategies used to mitigate UHI effect in sustainable cities [32] [33].

Radiant Surface Temperature (T_B) relationships to percent impervious surface and NDVI

To further understand the impact of urbanization on T_B, the study investigated the links between T_B and percent Impervious Surface Area (ISA), and between T_B and NDVI for Morogoro Urban in 2015 using 100 randomly selected points. Figure 3 shows T_B values associated with different percent ISA in Morogoro Urban. The linear regression of the points indicated a weak positive linear relationship between T_B and percent ISA with a coefficient of determination value of $R^2 = 0.06218$ ($R = 0.25$), F-statistic = 6.498, and p-value = 0.01235. In contrast, the linear regression of the points between T_B and NDVI indicated a moderate inverse linear relationship with a coefficient of determination value of

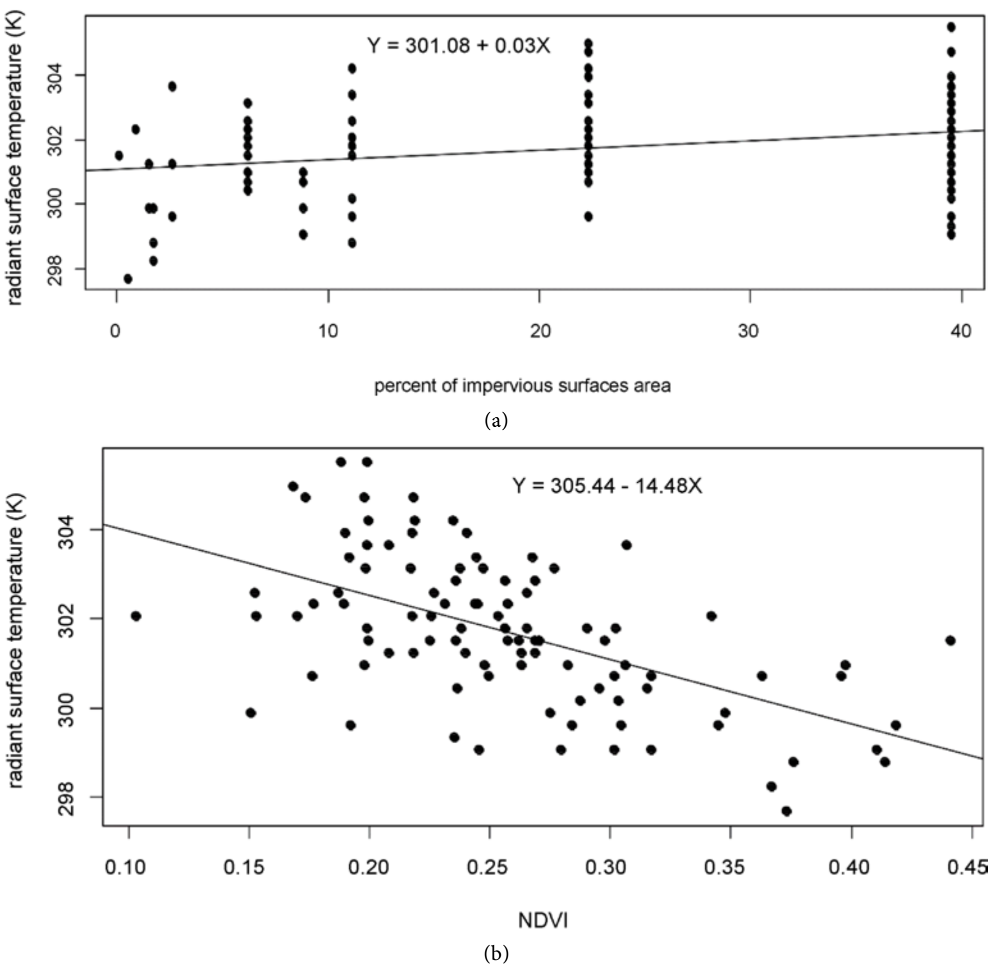

Figure 3. (a) & (b) Relations between percentage impervious surface area, NDVI and T_B.

$R^2 = 0.3177$ ($R = -0.56$), F-statistic = 45.64, and p-value = 1.02e−09. P-value of these relationships proven results was statistically significant at the significance level of 0.05. These linear relationships suggest that the variability of T_B in Morogoro Urban is more explained by NDVI than percent ISA. This suggests NDVI to be a better indicator of variations in T_B dynamics than percent ISA in Morogoro Urban. NDVI has been used traditionally in thermal remote sensing studies as the major indicator of urban climate, because vegetation absorbs sunlight energy which is used during photosynthesis [34].

Climate data analysis

Results of trend analysis using Mann-Kendall test (**Table 4**) indicate presence of statistically significant increasing trend in mean annual maximum temperature. This is also portrayed in (**Figure 4**) that shows a linear increasing trend in mean maximum temperature at a rate of 0.03˚C per year equating to temperature rise associated with increase of 1% of 2015 impervious surface (**Figure 3(a)**). The increase of 0.03˚C per year implies that mean maximum temperature has increased by 0.96˚C during 1981-2012. A study by [7] also found that the trend of temperature in Morogoro Municipal to be increasing; wherein annual average temperature increased from 21.78˚C in 2002 to 25.10˚C in 2009.

Overall, the study provides knowledge on the influence of urbanization (Built-up areas) on the urban climate. This knowledge is useful for UHI effect,

Table 4. Results of the Mann-Kendall test for max temperature data.

Mann-Kendall Statistic(s)	Kendall's Tau	Var(S)	*p*-value (two sided)
213	0.412	4137	0.00098

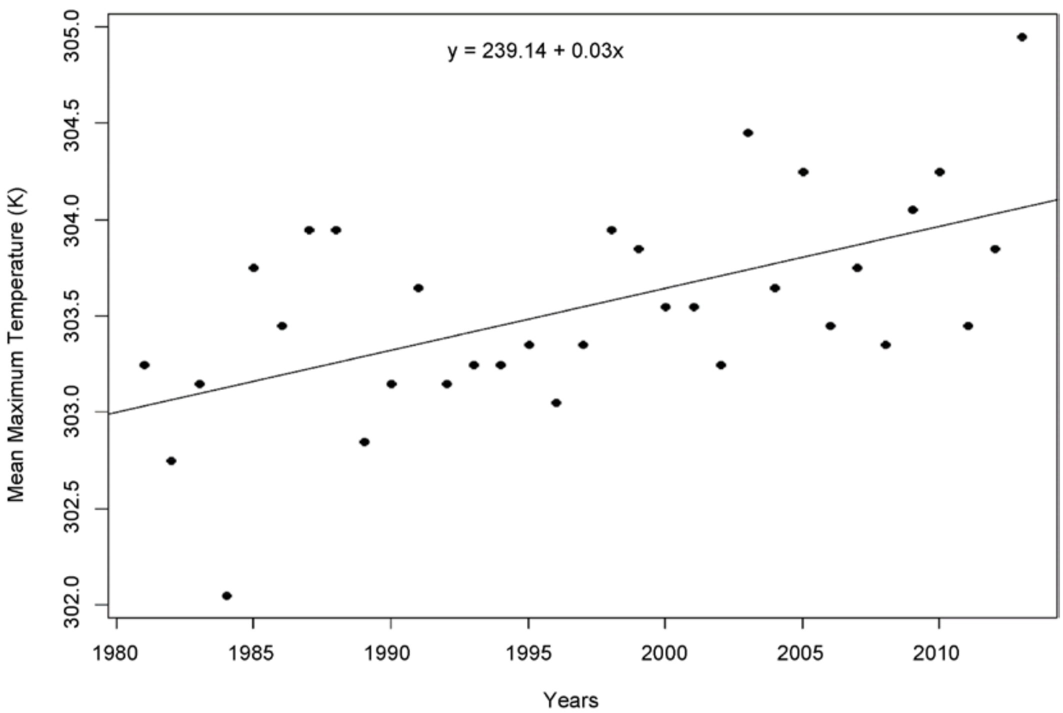

Figure 4. Mean maximum temperatures for Morogoro Urban.

Climate change adaptation and mitigation in other developing cities of East Africa as well. Moreover, the study provides knowledge that will help in monitoring of urban climate in other urban areas in East Africa for generation of more knowledge, as the study covered only Morogoro Municipal.

4. Conclusions

The impervious surfaces have increased in Morogoro Urban from 9 km^2 in 1990 to 82 km^2 in 2015. The increase of impervious surface (built up area) has contributed to Urban Heat Island effect in Morogoro Urban. Also, different percent of impervious surface has effects on radiant surface temperature within the Morogoro Urban. Higher percent of impervious surface is correlated with higher mean radiant surface temperature.

The study also revealed that radiant surface temperature has negative correlation with NDVI within the area; and NDVI has greater influence to radiant surface temperature than impervious surfaces. Therefore, NDVI is better than percent impervious surfaces for UHI studies in Morogoro Urban.

The long term impact of increasing impervious surfaces coupled with vegetation degradation could modify climate condition in Morogoro Urban, as revealed by the increasing trend of mean annual maximum temperature of 0.03˚C per year during 1981 to 2012. It is recommended that education on the use of light colored surface reflects more of solar radiation and absorbs less heat should be given to Morogoro Urban residents for adaptation to UHI effect; and effective master plan that protects natural environment and vegetation should be prepared in order to mitigate UHI effect and achieve sustainable urban development.

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