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The Subsurface Urban Heat Island Intensity in Enugu Urban, Nigeria

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Abstract: Urbanisation over the past hundred years has caused environmental and thermal influences underground; yet little knowledge exists about subsurface warming in Enugu, despite previous studies confirming the presence of urban heat island in the area. This study analysed the subsurface urban heat island intensity in Enugu urban, using secondary urban subsoil temperature data set that was sourced from the Nigerian Meteorological Agency over 21 years (2000-2020). With an application known as grid, the rural subsoil temperature data set was gotten by downscaling that of the urban which is 40 km away. The statistical technique employed was Welch's t-test. The study showed that the annual mean urban subsoil temperatures were generally warmer than that of the rural subsoil temperatures, with a mean difference or subsurface urban heat island intensity of 0.4°C. From the study, it was clear that the urban heat island effect occurred in the subsurface in Enugu, as it does above the ground. This study, to define urban and rural better, suggests that the use of the Local Climate Zone classification scheme should be considered in further research. A joint investigation of the three urban heat island categories in Enugu should also receive top priority in subsequent studies.

Keywords: Enugu, Subsurface, Urban Heat Island Intensity, Urbanisation, Welch's T-test

1. Introduction

Urbanisation over the past hundred years has caused environmental and thermal influences underground [1]. For Enugu urban, the city has witnessed remarkable growth in its urbanisation in recent years [2] and its population during the past few decades has almost tripled — with data aptly showing that there has been a 79.4% increase within two decades, changing from 464,514 in 1991 to 833,373 in 2011 [3]. This has resulted in a phenomenon known as urban heat island (UHI), which has been well documented for this location, particularly since 2009 (Enete [4] presented a detailed review). However, until now, little is known about its subsurface warming since most of these studies show the UHI as the temperature increase above the ground, focusing on surface air temperature (SAT) and land surface temperature. Modifications of surface covers also affect the subsurface temperature and the measured temperature profiles [5].

Studies have shown that urban environments can experience soil warming due to the UHI effect (Santos *et al.* [6], for example) and UHI intensity or "magnitude" [7, 8] is a key variable most often used to quantify UHI status [9, 10]. The subsurface UHI (SubUHI) is vertically different and its studies can be categorised into three layers following Zhan *et al.* [9]: shallow (<10 m), deep (10-100 m) and very-deep (>100 m). Several studies at the shallow layer [11-14], deep layer [15, 16] and very-deep layer [17, 18] all indicated several degrees temperature increase in the urban subsurface compared to its corresponding rural background.

The focus in this study is only on the shallow layer, without regard to the deep and very-deep layer respectively. Turkoglu's [11] measurements at depths of 5-50 cm in Ankara (Turkey) found that soil temperature between the city and rural area differ by 1.8-2.1°C. The one-year, comprehensive measurements of the soil temperature at 600 locations in Nanjing, China [12] was done at the 10-150 cm depths, and they found the urban soil 1.21°C higher than the rural soil. In another study in Nanjing [13], the measured results at eight depths (down to 3 m) revealed that the mean temperature under the urban concrete surface is 3.7°C warmer than that of suburban bare soil surface. In 2012, another study [14] was conducted still at Nanjing (down to 300 cm depth) and the data revealed that the urban soil temperature is 2.02°C warmer than the rural soil temperature. Generally, these magnitudes or intensities are typically (but not always) about 1-5°C, depending on the city and the depth of the measurement [8].

According to Shi, Tang, Gao, Liu and Wang [14], "with increasing pressure on space in urban areas, more and more urban engineered structures are transferred from the ground surface to underground soil". Hence, for sustainability, it becomes necessary to study the changes in soil temperature in urban environments [13]. Although progress has been made in this area, until now, there are few investigations on SubUHI compared to those of the surface or the air [8]. Currently, out of the three categories of UHIs (subsurface, surface and air or atmospheric), this is the only category where limited knowledge still exist in Enugu urban. It was because of this that the present study was conceived. Therefore, this study seeks to determine the SubUHI intensity (SubUHII) in Enugu urban.

2. Materials and Methods

2.1. Study Area

The study area is Enugu urban, which is the capital of Enugu State in Southeastern Nigeria. It is composed of Enugu East, Enugu North and Enugu South Local Government Areas (LGAs), and is bounded by various LGAs in the following directions: in the north by Igbo-Etiti and Isi-Uzo, south by Nkanu West, east by Nkanu East and west by Udi. It lies approximately within Latitudes $6^{0}21$'N and $6^{0}29$'N of the Equator and Longitudes $7^{0}26$'E and $7^{0}35$'E of the Greenwich meridian (Figure 1).

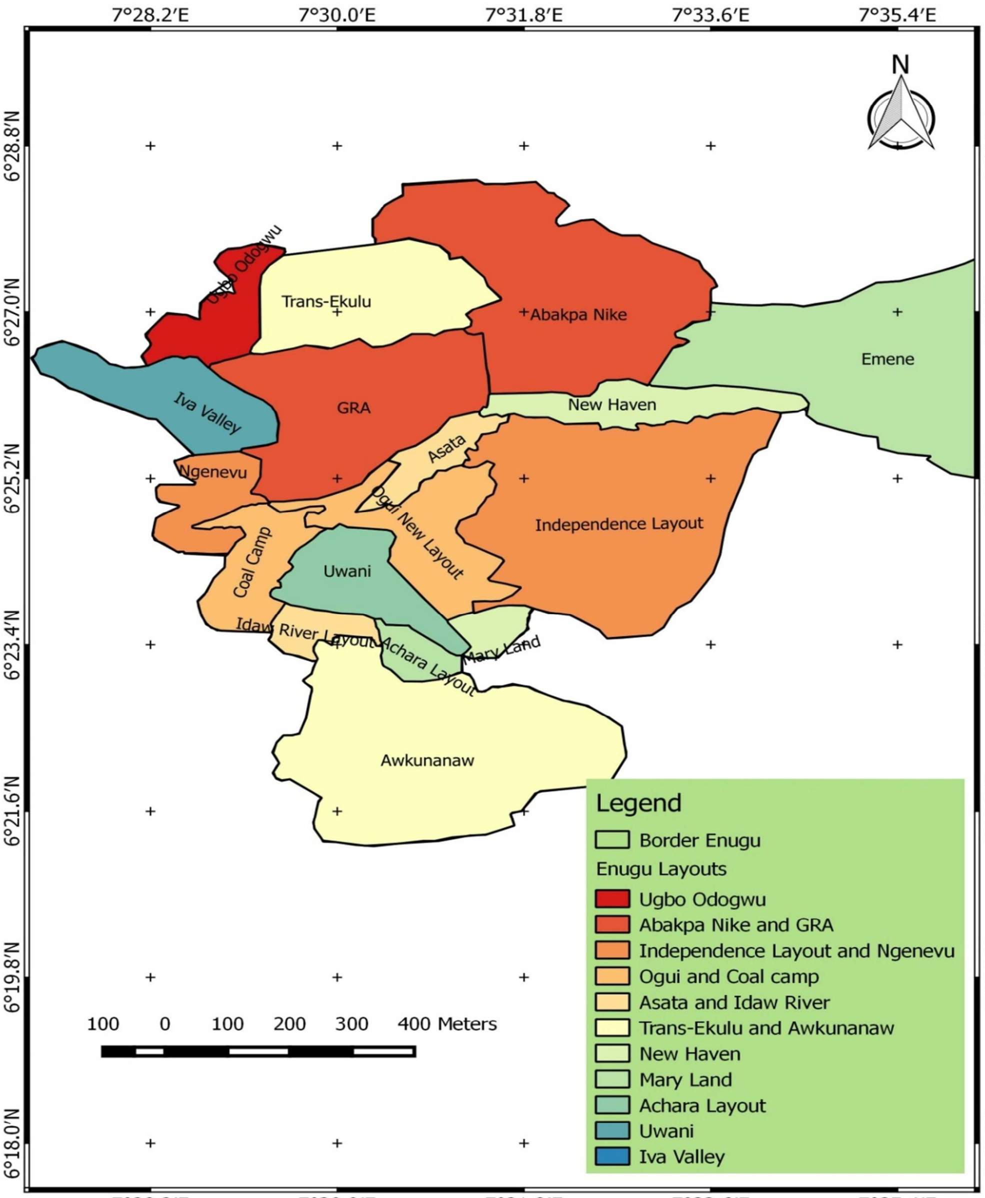

Figure 1. The wards in Enugu urban. (Source: GIS Lab, Department of Geography & Meteorology, NAU, Awka).

The past census figures confirm the growth of this city. Enugu urban had a population of 464,514 and 717,291 in 1991 and 2006 respectively as well as an estimated population of 833,373 in 2011 [3]. The city is an ideal location for this study; besides being the ninth most populous city in Nigeria [19], it is the largest city in Enugu State [2].

Enugu urban is located in the Tropical Rainforest zone that relates to the Tropical Wet and Dry (Aw) climate of the Köppen-Geiger-Pohl classification system [20]. The general relief comprises a gently undulating plain with low hills and steep valleys, creating a dual division of escarpment and lowland zones. It lies below 300 m northwest on the Cross River basin and is characterised by a dendritic drainage pattern that is dominated by two major river systems: the larger, Ekulu river system (northwards) and the Nyaba river system (southwards).

Human activities have reduced Enugu's vegetation from tropical rainforest to derived guinea savanna vegetation [19, 21], otherwise described as a "rainforest-savanna ecotone" [22], with a hydrologic ratio of less than 0.75 [23]. The city's well-developed transportation network plays an important role in stimulating production. It is an hour's drive from Onitsha, one of the biggest commercial cities in Africa, and takes two hours from Aba, another very large commercial city, both of which are trading centres in Nigeria [2].

2.2. Data Need

Soil temperature data sets over 21 years (at depths of 5, 10, 20, 30, 50 and 100 cm, respectively) were collected for urban and rural areas and examined. Even though the groundwater temperature exists as an alternative, the soil temperature was chosen as the subsurface temperature because it is more accessible and affordable [24, 25]. These depths were chosen because they are the depths at which soil temperatures are measured at the Nigerian Meteorological Agency (NIMET), Enugu (see Figure 2) and fall within the "shallow layer" definition given by Zhan *et al.* [9]. For this study, the rural area was used loosely to refer to the surrounding area. Unlike SAT, the soil temperature is not commonly available [26]. This informed the choice of the study's duration, which is considered suitable for this analysis. Records from 2000 to 2020 was selected for this study.

Figure 2. *Soil thermometers at NIMET, Enugu.*

The thermometers are spaced roughly 65 cm apart and arranged orderly to allow for easy reading of the soil temperature at six depths (from left to right): 5, 10, 20, 30, 50 and 100 cm. As the soil temperature increases, the mercury in the bulb extends and rises. When the soil temperature drops, the mercury shrinks and falls down the tube.

The annual soil temperatures across the six depths were averaged to obtain a single value to represent all the depths per year. Afterwards, the calculation of the difference or SubUHII was done (SubUHII: urban subsoil temperature − rural subsoil temperature).

2.3. Data Sources and Method of Collection

All the data sets used in this study were sourced from the NIMET headquarters in Abuja as secondary data. At the observatory unit of NIMET, Enugu, regular meteorological observations are provided, including soil temperatures that are collected every six hours (0000, 0600, 1200 and 1800 GMT) by the meteorological observers. A mercury-in-glass soil thermometer (Casella-London immersion) that is spaced at about 65 cm apart (Figure 2) was used to measure the soil temperature at 5, 10, 20, 30, 50 and 100 cm depth points, and recorded on "Form Met 113". The daily mean soil temperatures are calculated for each soil depth and averaged to get the annual mean required for this study. The rural soil temperatures were downscaled by NIMET; this was done 40 km away from the observatory unit using an application known as "grid" (Jimoh, personal communication, January 12, 2022). Further attempts to get more information about the workings of this application and the stepwise guide to using it were unfortunately declined.

2.4. Method of Data Analysis

Following the recommendation elsewhere [27], this study employed Welch's t-test. This test is also called the Welch-Satterthwaite test or unequal variance t-test. According to previous studies [27, 28], "convention is a weak justification for the current practice of using Student's t-test by default". The Welch's t-test is a modification of the Student's t-test that is more powerful than the Student's t-test whenever sample sizes and variances are unequal between groups and produces the same result when sample sizes and variances are equal [29]. Using this method, t' (Eq. 1) and the degree of freedom (df; Eq. 2 or Eq. 3) were calculated to test the null hypothesis (H_0) that states thus: "There is no significant difference between urban and rural subsoil temperatures in the past 21 years". This statistic has been used recently to study surface UHIs across East Africa [30] and it is available in practically all statistical software packages [27].

$$t' = \frac{(\bar{X}_1 - \bar{X}_2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (1)$$

$$df = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{n_1 - 1} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{n_2 - 1}} \quad (2)$$

$$df = \left[\frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{n_1 + 1} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{n_2 + 1}}\right] - 2 \quad (3)$$

where, t' : Welch's t, s_1^2 and s_2^2 : unpooled standard deviations (assumption: $s_1^2 \neq s_2^2$), $\bar{X}_1$ and $\bar{X}_2$: means of the two sets of data, n_1 and n_2: number of observations for each data set, df: degree of freedom, Eq. 3 is more accurate than Eq. 2 but the difference is negligible [31].

This inferential analysis was judged at a 5% (0.05) level of significance (denoted as α or alpha). The statistic had an associated probability value (p-value or abbreviated as "Sig."). If the p-value is less than or equal to the α ($p \leq 0.05$), then the H_0 will be rejected, implying that the result is statistically significant. However, if the p-value is greater than the α ($p > 0.05$), then the H_0 will be accepted. This will mean that the result is statistically nonsignificant.

3. Results and Discussion

Table 1 summarises the descriptive statistic while Table 2 provides Welch's t-test result (Welch's t is a Welch's F that applies to two groups).

Table 1. *Welch's t-test descriptive statistic.*

Subsoil Temperatures								
Grps	**N**	**Mean**	**SD**	**Std. Error**	**95% Confidence Interval for Mean**		**Minimum**	**Maximum**
					Lower Bound	**Upper Bound**		
U	21	30.062	.2617	.0571	29.943	30.181	29.6	30.8
R	21	29.633	.2415	.0527	29.523	29.743	29.2	30.3
Total	42	29.848	.3300	.0509	29.745	29.950	29.2	30.8

Table 2. *Welch's t-test result.*

Subsoil Temperature (°C)				
	Statistic[a]	**df1**	**df2**	**Sig.**
Welch	30.417	1	39.746	.000

a. Asymptotically F distributed.

From Table 2, Welch's t-test rejected the H_0 (since $p = 0.000 < 0.05$), thereby accepting the alternative hypothesis (H_1) which states that "There is a significant difference between urban and rural subsoil temperatures in the past 21 years". Inspection of the group means revealed that the urban subsoil temperature decreased steadily as movement is made towards surrounding rural areas (Figure 3), giving it a "downward-sloping" shape. And since the urban mean is larger (see Table 1 and Figure 3), the data fits the general opinion held by urban meteorologists and climatologists that urban centres tend to have a higher temperature than surrounding rural areas. Also, the mean difference is 0.429°C (that is 30.062 – 29.633) for the study duration and represent the SubUHII for Enugu.

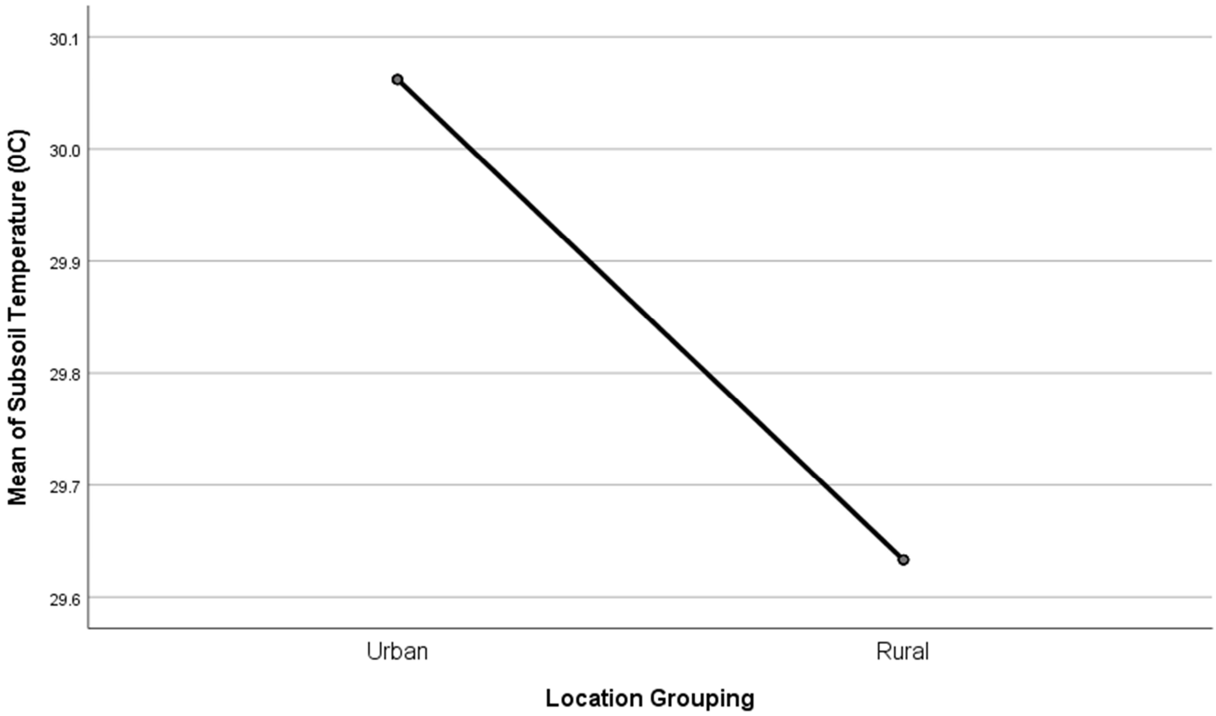

Figure 3. *Means plot of subsoil temperature.*

From Figure 3, the SubUHII of 0.4°C is less than the intensity of about 1.2-3.7°C reported in other studies focused on the shallow layer in Ankara and Nanjing. Turkoglu [11] reported it to be between 1.8 and 2.1°C in Ankara. For

Nanjing, it has been reported as 3.7°C [12], 1.21°C [13] and 2.02°C [14]. However, as pointed out in [8], SubUHII could depend on the city in addition to the depth of the measurement. Hence, this difference in result could be due to the dissimilar anthropogenic heat patterns in these cities.

4. Conclusion

This study showed that the annual mean urban subsoil temperatures were generally warmer than that of the rural subsoil temperatures, with a mean difference or SubUHII of 0.4°C. From the study, it was clear that the UHI effect occurred in the subsurface in Enugu, as it does above the ground.

However, it should be noted that this study had the problem of defining urban and rural. Although the rural-urban distinction is important, a consistent definition of urban and rural has not been agreed upon in scientific literature. And since only one meteorological station exists in the study area, unlike in the literature reviewed, the rural subsoil temperature was used loosely to refer to the surrounding area and the value gotten by downscaling that of the urban which is 40 km away. This downscaling was done using an application known as “grid”.

Based on this challenge, the present study suggests that the use of the Local Climate Zone classification scheme should be considered in further research. This scheme was proposed by Stewart and Oke [32] to standardise urban climate research by considering the physical properties of built (urban) and vegetated (rural) landscapes, making it applicable in cities all over the world. Also, since each of the UHI categories has been studied separately in Enugu, further study can be done to jointly investigate the three categories in the “Coal City”.

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