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Quantification urban heat island (UHI) using the local climate zone classification (LCZ): A case study in Constantine

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Abstract

The number of issues assigned to the risks of urban warming has highlighted the extremely problematic nature of this phenomenon that affects the local climate characteristics of urban areas. In this context, city planners are strongly solicited to consider climatic information in their process of design. The use of classification schemes, such as Local Climate Zone (LCZ) is adapted for this type of application. This contribution aims, through the use of the newly developed climate scheme -called LCZ -, to give a better understanding and more objective assessment of the atmospheric Urban Heat Island (UHI) phenomenon in Constantine (Algeria). The three-step procedure of LCZ workflow has been followed in the case study area, to classify the landscape into fragments that are homogeneous in terms of urban characteristics and thermal features. Urban form parameters have been calculated so as to build LCZ types in the study Area. Two measurement campaigns were carried out using fixed stations; to investigate screen-height air temperature distribution inside two LCZ (LCZ5 ''open mid-rise'', LCZ2 ''compact mid-rise). Results showed that air temperature intensity has mainly demonstrated a small daily gap and higher night-time amplitude in urbanized LCZ types.

Keywords: Constantine; Local Climate Zone (LCZ); Urban Climate/Urban Heat Island (UHI)

1. Introduction:

Cities represent the most significant human environment, both in terms of the physical artefacts and socioeconomic activities associated with the processes of urbanization [1]. The physical presence of cities has a direct corollary of local disturbances in all types of exchanges (radiative, thermal, aerodynamic…) between the surface of the ground and the atmosphere, generating a specifically urban climate. Urban areas modify their climate [2]; these modifications include increasing temperature, changing wind speed, cloud cover and solar irradiances [3]. The iconic manifestation of the altered urban climate is the positive thermal anomalies associated with urban air temperature. This feature has received widespread attention in the environmental science, used to reflect microclimatic changes in urban zones, broadly recognized as Urban Heat Island (UHI).

The concept of UHI describes the excess warmth of the urban atmosphere compared to the rural surroundings [4]; it is best visualized as a dome of stagnant warm air over the heavily built-up areas of the city [5].

Conventionally, UHI intensity is interpreted and expressed on the basis of synchronous screen-height air temperature values differences between samples stations representing urban and rural areas.

The physical explanation of the existence of the thermal gap is given by the difference in surface energy budget between urban and rural areas. Four urban surface parameters have been reported in the literature [6,7] as determined in the genesis of UHI: urban morphology, urban coverage, urban materials and urban metabolism. However, the role played by particular factors vary from city to city, with respect to differences in geographical location, overall size, number of inhabitants and more [8].

This anomaly has several practical effects (positive or negative) depends on the city's macroclimate. In relatively cold climates or seasons, heat islands convey many benefits to energy savings in buildings, outdoor thermal comfort of citizens, road maintenance and more. On the other hand, in hot cities or hot season, urban context is a critical scale owing to significant environmental, energetic and sanitary implication such as public health, energy consumption and outdoor air quality. The number of problems allocated to the risks of urban heat island has highlighted the extremely problematic nature of this anomaly that affects the specific climate of cities. That is why it is necessary today, to increase our knowledge about the subject, to provide solutions that will reduce their harmful effects.

In the literature of urban climate, theoretical and experimental studies of UHI are very abundant [9].

Observational data (in-situ ground-based, fixed or mobile) has been widely applied and recognized as an effective data source to investigating this phenomenon [10]. Through time, however, methodologists have raised concerns about the authenticity with which this data (UHI information) have been gathered and reported [11].

The conventional approach that evaluates the UHI by comparing urban with rural observations has been dissected by several researchers [12-14], who have highlighted significant gaps in the existing theoretical aspects. The root of these gaps is argued to urban climatology's longstanding paradigm for space classification, the Urban (U) –Rural (R) dichotomy [13]. The use of these simplistic descriptors (U-R) has given researchers a simple framework to separate the effects of the city and country on local climate [7].

I.D. Stewart in a systematic review and scientific critique of our background research of observational UHI [11], evaluated a sample of 190 studies between 1950 and 2007, based on criteria of experimental design and communication. The study is concluded with discouraging outlook as the majority of the published UHI magnitude are not scientifically defensible. Weaknesses identified include a lack of experimental control, inappropriate choice of sites, definition of UHI magnitude is not given, inadequate exposure of sensors, failure to adequately document the sites. From these problems arose the need for a protocol that makes heat island observation more credible and reliable. For this reason, scientists have developed landscape classification in order to study the relationship between urban fabric and local climate. In the state of art, we count as referent the systems of Auer [15], Ellefsen [16], Davenport [17]. But it is Tim Oke [6] who has advanced towards a universal system; the urban climate zone (UCZ), which has been adopted by the World Meteorological Organization (WMO). Currently, Stewart and Oke over these systems to create a more detailed and more universal method called "Local Climate Zone (LCZ)" [7].

A Local Climate Zone is defined as an area with a minimum diameter of 400 m which demonstrates both uniform features in terms of urban morphology, land use, urban material and urban metabolism and a characteristic screen-height temperature regime under calm and clear sky [7]. LCZ classification has 17 categories; all are presented in a clear and standardized format "Datasheet", based on quantitative and qualitative descriptions [7]. Each LCZ has a unique climatic behavior [18], from which is derived a standardized definition of the UHI magnitude that is expressed more objectively by comparing inter-zone thermal reactions. The LCZ scheme provides a research base for UHI studies and standardizes worldwide discussions of urban temperature observations.

The LCZ system was initially designed for establishing a common protocol for observational studies of urban temperature, in order to standardize their exchange at the global level. For this, the method is being validated in different cities around the world, Onitsha (Nigeria) [19], Dublin (Ireland) [1], Köchi (India) [20], Nancy (France) [18] and Singapore [21]. The protocol is adapted to other problems. It is an applicable tool in urban spatial mapping [22,23]. It can also support simulation studies [24,25], providing an urban database, for the development and application of numerical models. This scheme provides a foundation for the development and installation of urban meteorological station networks [26,27]. Recently, the local climate zone framework has been proposed in support of the World Urban Database and Access Portal Tools (WUDAPT)[1] initiative.

Urbanization in Algeria has been rapid since the independence (1962s). According to the latest census, it has been found that urbanization rate reached 63% in 2008 and this number will likely rise to 80% by 2025.

The spectacular urbanization process, often poorly or not at all controlled, have generated complex issues and made urban management extremely difficult. It has significantly changed the morphology and local climate

[1] http://www.wudapt.org/

conditions in urban area. A serial of environmental problems, especially the increase in temperature, is seriously affecting on life of urban residents. The average temperature increase in Algeria is of the order of 1°C to 2°C, with a decline of 12% of rainfall between 1990 and 2005 (National Organization of Meteorology - ONM)[2]. Because of this, it is important to understand the urban morphology and its impact on the local thermal environment.

The present study aims to apply the newly developed LCZ classification scheme in Constantine (In the east of Algeria), in order to quantify the intra-urban air temperature variations across test field site, under typical summer weather. This system has been tested all over the world, especially in developed countries. The idea behind this work is to adopt this approach in a developing country, with all its problems of urban planning and environment.

2. Materials and Methods

2.1. Site description

Constantine, with a total area of about 1 297.2 Km², is located in the North-Eastern part of Algeria, between 36°17'N of latitude and 6°37'E of longitude (Figure1). The site is characterized by an exceptionally rugged soil, marked by juxtapositions of high plain and hills, where the elevation ranges from sea level to over 694 meters. Constantine has a semi-arid climate marked by a long period of summer drought, ranges from 5 to 6 months. According to ONM, the relevant annual averages for the climatological period (1980-2014) are as follows: air temperature is 34.5°C in July and 2.7°C in January; relative humidity is 67.17% and precipitation is 517.08 mm.

As one of the fastest growing cities in Algeria, Constantine is a populous city with about 939 000 inhabitants (based on 2008 national census)[3]. It has undergone rapid urbanization and changes in its physical landscape over the last 50 years, resulting in serious urban environmental problems including the tendency of raising average temperature.

According to meteorological data from ONM, the mean annual air temperature of Constantine has been rising since 1972.

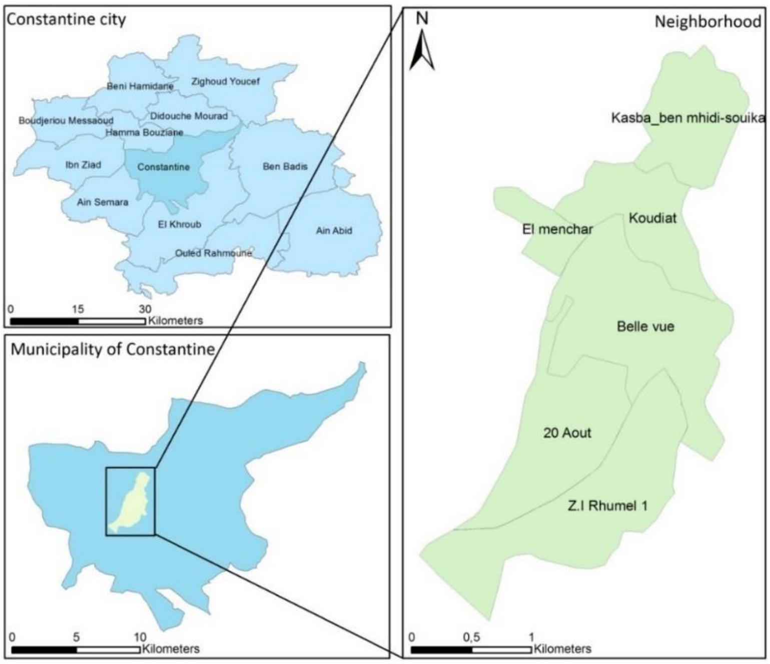


Figure 1. Localization of the area under study.

[2] https://www.meteo.dz/

[3] https://www.ons.dz/spip.php?rubrique43

2.2. Study design

In this research, the process adopted into LCZ building was developed and tested in the area presented in figure 1. It was based on the guideline developed by Stewart and Oke [7].

- Step 01: Collect site metadata

Metadata refers to the state of the urban context around a particular measurement site. Of the sample of literature reviews [11], three quarters of it failed to provide sufficient metadata to describe site conditions (gives only qualitative description). This makes it difficult to interpret this anomaly reliably. To filing this gap, LCZ inventors provide ten measurable physical parameters that have been reported in the literature as determining in the genesis of UHI (Table 1).

As part of this work, seven out of ten parameters (related to urban form: SVF, AR, BSF, ISF, PSF, H, Z0) are used to construct LCZs. The three parameters related to urban function (Surface albedo, admittance and anthropogenic heat) were not determined due to the lack of input data for urban materials and anthropogenic activities.

Table 1
Zone properties of LCZ system [7]

Type of properties	
Geometric, surface cover	Thermal, radiative, metabolic
Sky view factor (SVF)	Surface admittance
Aspect ratio (AR)	Surface albedo
Building surface fraction (BSF)	Anthropogenic heat flux
Impervious surface fraction (ISF)	
Pervious surface fraction (PSF)	
Height of roughness elements (H)	
Terrain roughness class (Z0)	

Researches have demonstrated the possibility of constructing LCZs using only the seven selected indicators [18,20]. To collect metadata, several methods have been proposed in the literature, including approaches using remote sensing data [28] and GIS methods [29,30].

In response to the lack of sufficiently detailed spatial data and the lack of basic information in the case of this work, alternative sources were used, including satellite images, topographic maps, published tables of values' properties, field visits.

- Step 02: Define the thermal Source area:

The second step is to choose - for each LCZ - the appropriate site for the installation of weather stations, which are used to determine the thermal effects of surface properties. The source area represents the field of view of the sensor; its dimensions are difficult to specify, but approximately, its diameter does not exceed a few hundred meters for temperature measurements at 2 m height [6].

Researchers used circles with different spatial resolution: 500 m, 250 m, 200 m, 100 m [6,19,21,22]. Oke and Stewart [7] argued that it has 100 m radius for densely built-up areas and 200 m radius for open lands areas. As part of this work, the calculation of the seven quantitative indicators selected in the previous step is carried out in a diameter of 200 m around the installation point of the thermal sensor. Source areas have been built according to the requirements addressed by Lecomte *et al.* [18] and Stewart and Oke [31].

- Step 03: Select the Local Climate Zone:

The final step is to find a correlation between the values of the surface parameters observed in each urban site (previous step) and the metadata of the LCZ types, proposed in the guideline, presented in form of data sheet. Intervals suggested represent, according to F. Leconte [32], the approximate limits within which the values of the collected urban indicators are included.

The purpose of this step is to select the appropriate LCZ category, which best fits the measurement site under study, among the seventeen LCZ proposed in the classification system (Figure 2).

The production of the LCZ map of the field study was based on theoretical segmentation of the area. According to the LCZ framework, type of landscape (building or plant), height of objects and density of objects are the three aspects for logical division [33]. Thus, three information layers were produced, each representing a classified map of the study area in one of the preceding criteria. The LCZs are obtained by the superposition of the three layers.

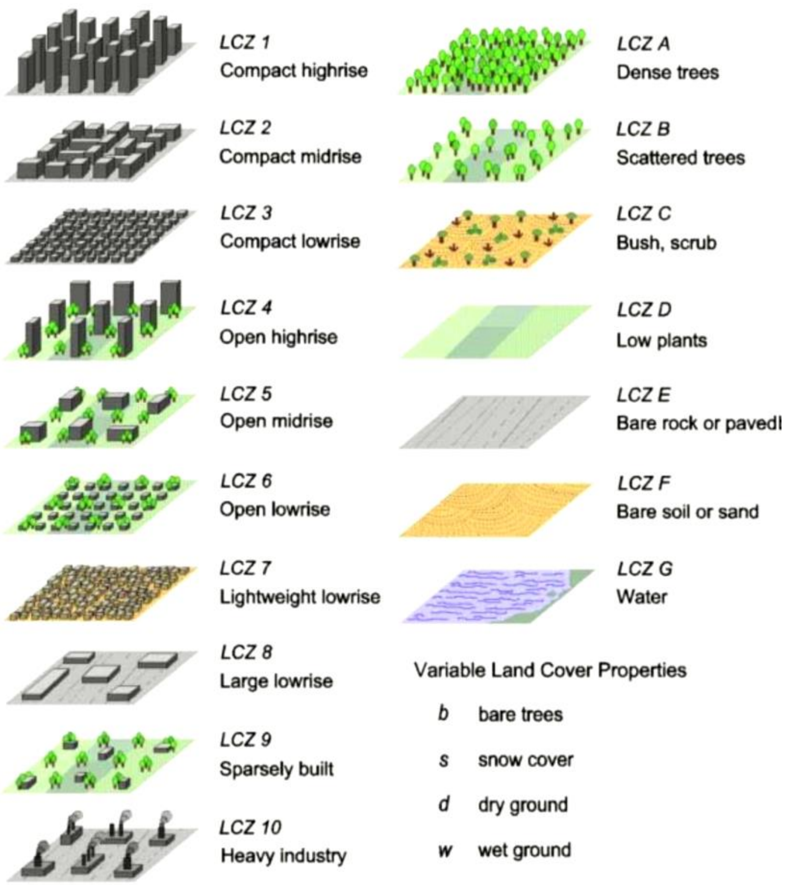


Figure 2. Local climate zone scheme. Source: [7]

2.3. Protocol measurement to quantify UHI (Fixed Recording Stations):

Meteorological data has traditionally been carried out via in-situ approach, using fixed or mobile weather stations. D. Stewart highlights the importance of time control during UHI measurement, to avoid confusion between urban-induced heat islands and time-induced heat islands [11]. For this reason, we chose the fixed measurement approach that, unlike the mobile methods, allows to measure temperatures synchronously. Our experimental proposes to carry out in-situ monitoring in two local climatic zones: LCZ_2 and LCZ_5, in order to study and compare the climatic characteristics of these environments. The two source areas, as well as the coordinates of the observational points, are shown in figures 3 and 4.

- The First point: LCZ_2 “compact mid-rise”: Lat: 36°21'44.33"N, Long: 6°36'22.44"E
- The second point: LCZ_5 “Open mid-rise”: Lat: 36°20'36.09"N, Long: 6°36'8.99"E

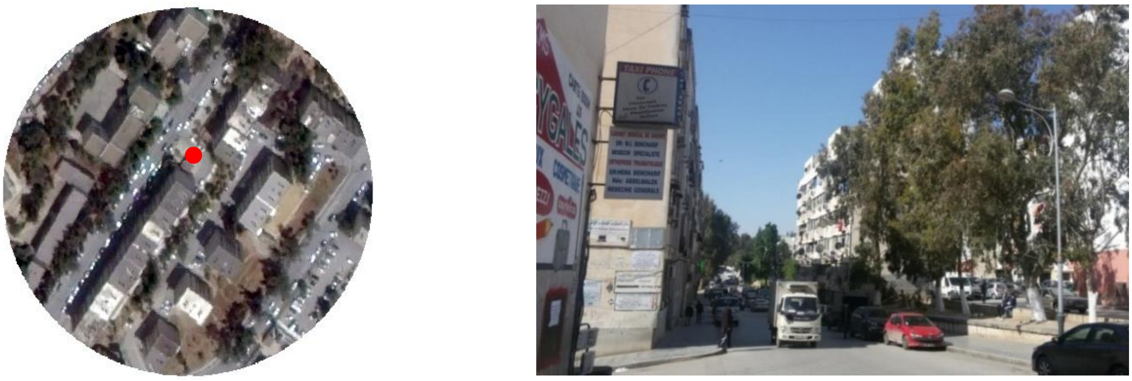
Temperature, relative humidity and wind speed of the two sample locations were measured using manual weather station LM-8000 with an accuracy of ± 0.2°C. Before the measurement, the equipment used (fixed stations) benefited from the same conditions in terms of temperature and relative humidity (put in the same room away from light for days) in order to decrease the margin of errors on the site. The recommendations for the installation of measuring instruments proposed in the protocol of T. Oke [6] were also followed:

- Measurements were taken at a standard height of 1.5 meters above ground;
- We took care to ensure that each station was naturally ventilated and was not excessively sheltered by obstacles;
- Stations are placed away from walls of buildings (>1m) and trees likely to distort the measure (not influenced by drafts and shadows).

Data acquisition took place over a 3-day period in August 2016 (hot and sunny summer days). For reasons of security, measurement period was from 7 am to 12 pm, realized simultaneously at both sites, set at a recording interval of one hour.

a b

Figure 3. (a) Airborne view of LCZ_2; (b) Street view in LCZ_2



a b

Figure 4. (a) Airborne view of LCZ_5; (b) Street view in LCZ_5

2.4. Measurement conditions

Our measurements have been performed under standardized meteorological conditions described in [6,18,22] as follows: calm and light winds, clear sky in the hours preceding the monitoring, no significant precipitation on the days of measurement and in the previous 24 hours.

The climatic context in which the measures are taken is: an average air temperature of 35.1°C; a relative humidity of 40.8%; wind speed is less than 6 m/s at 10 m high. Also; the topography of Constantine has been taken into account. The difference in altitude between the two monitoring points is in the range of 30 to 40 m. This altitude does not lead to any significant change in air temperature measurements [18,31].

3. Results and discussion

Using the classification procedure described above, we compiled a spatial distribution maps of LCZ sample sites for the selected study area figure 5. The cartography allows to characterizing representative samples of the main urban forms found in the investigated site. Only nine of LCZ (over the seventeen existing classes of LCZ) have been distinguished, seven of which belong to build types, while two LCZ belong to the land-cover types.

The survey of the existing LCZ typologies relevant for the area under study showed that the historical core and its narrow environment form “Compact" areas of medium height. The “Open set” is the most frequent type of development in the rest of the region of interest (low to medium height). Given the chosen site (urbanized), undeveloped areas are minimal. In addition to LCZ_B type characterized by scattered trees, there are still landscapes representing by bare soil (LCZ_F).

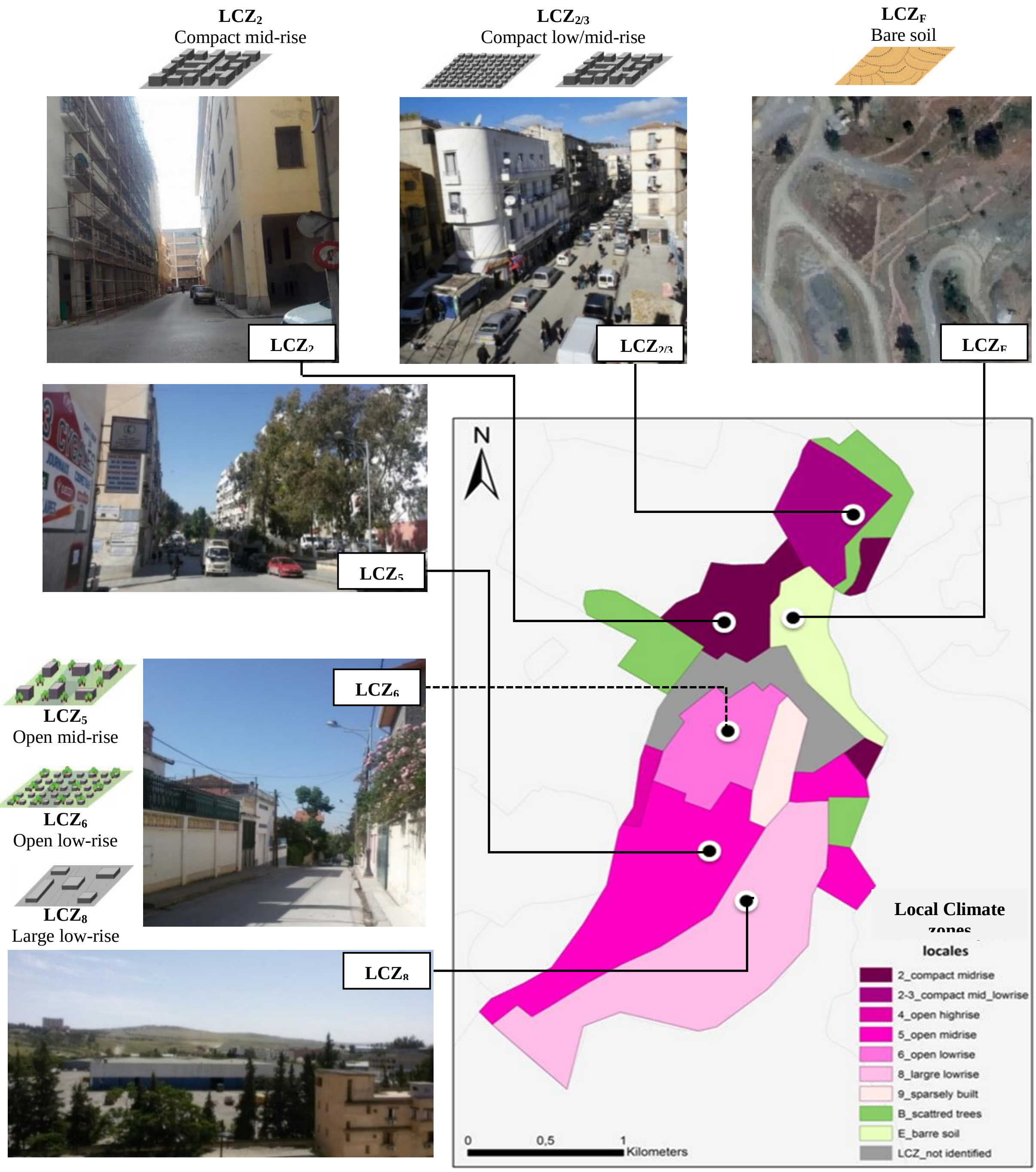
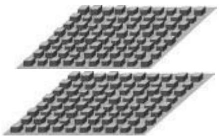
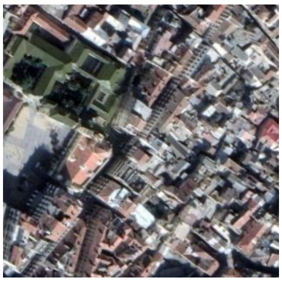


Figure 5- LCZs map of the study area (circles correspond to the LCZs where we have deepened our study).

The urban fragments that do not meet the classification scheme requirements are not retained in our study, either because they represent a mixture of landscapes and local specificities (important heterogeneity), defined as “Not identified”, or because they have a small area. According to Stewart and Oke each LCZ must have a minimum diameter of 400 to 1000 m [7].

Seeking to validate whether the LCZ classes addressed to each urban fragment - the previous phase - are adequately selected, a calculation of the seven urban indicators related to urban morphology and land cover, at the source area of each class, is operated. Table 2 summarizes metadata for urban LCZ retained in our study.

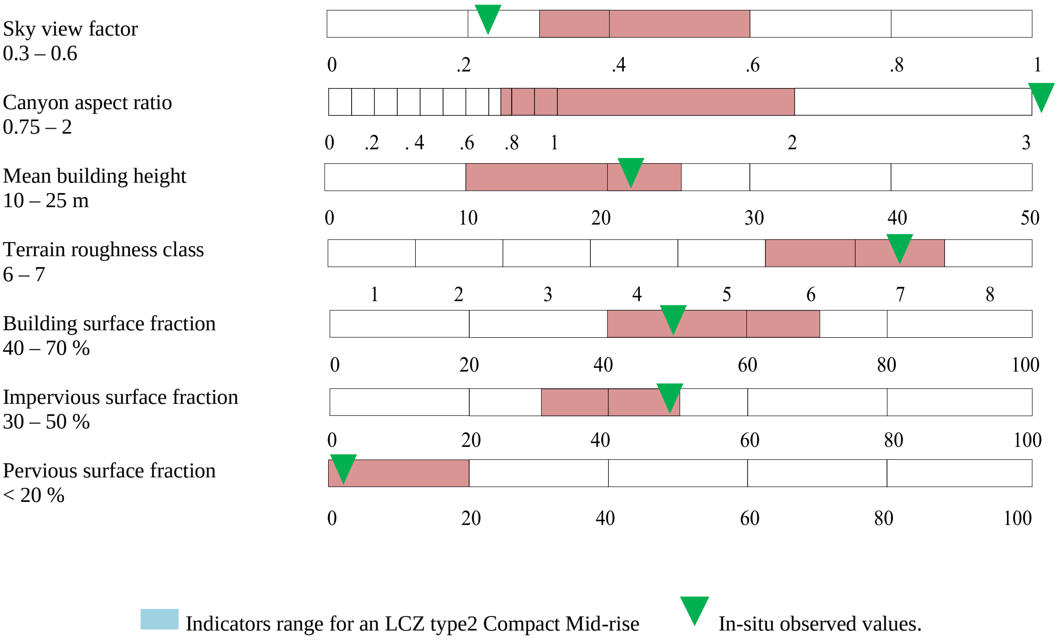
Table 2
Metadata descriptions of the five LCZs retained in this study.

LCZ	Description	Aerial View (Google Earth)	Physical indicators
LCZ_2 Compact mid-rise			SVF: 0.22 AR: > 3 H: 22.8m R class: 7 BSF: 48.87% ISF: 48.52% PSF: 2.61%
$LCZ_{2/3}$ Compact mid/low-rise			SVF: 0.18 AR: > 2 H: 12.58m R class: 7 BSF: 67.31% ISF: 29.94% PSF: 02.75%
LCZ_5 Open Mid-rise			SVF: 0.59 AR: 0.54 H: 15.35m R class: 7 BSF: 19.45% ISF: 49.28% PSF: 31.26%
LCZ_6 Open low-rise			SVF: 0.74 AR: 0.68 H: 7.5m R class: 5 BSF: 31.36% ISF: 20.65% PSF: 47.99%
LCZ_8 Large low-rise			SVF: 0.63 AR: 0.34 H: 7.58m R class: 6 BSF: 31.73% ISF: 52.15% PSF: 16.11%

These values are compared with intervals suggested in the framework. Urban indicators values of three LCZ are presented in figure 6 to 8.

(a)

(b)

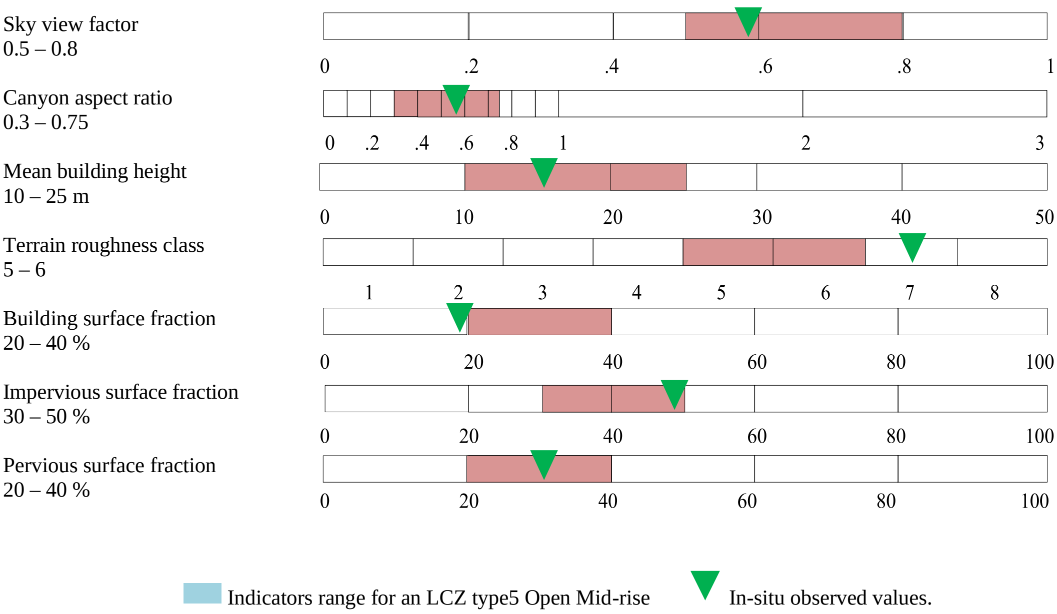


(c)

Figure 6. (a). Airborne view of LCZ_2 ; (b) Street view in LCZ_2 ; (c) Indicators values for the LCZ_2

(a)

(b)

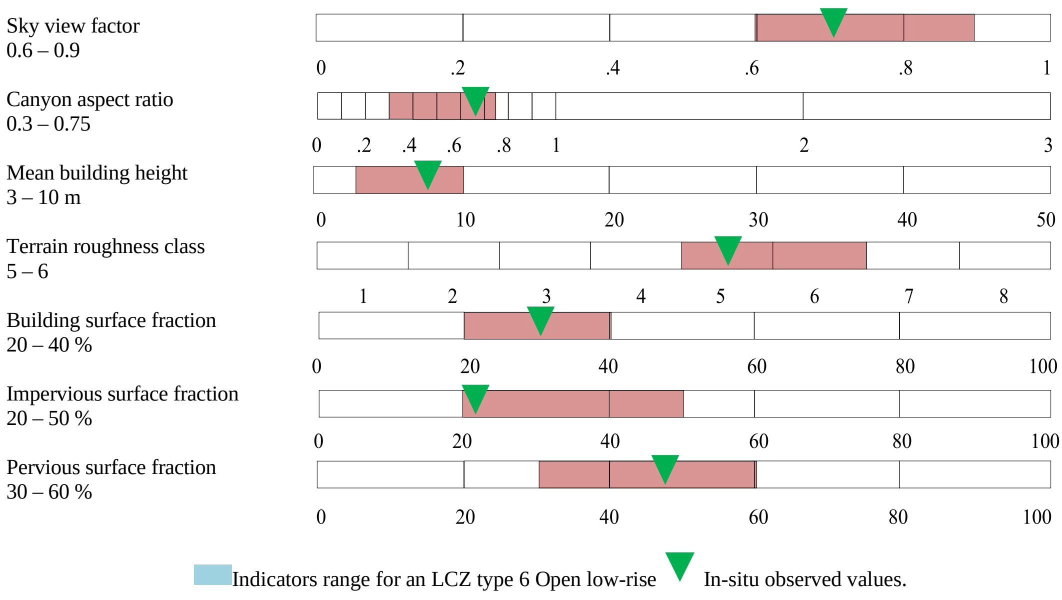


(c)

Figure 7. (a). Airborne view of LCZ_5 (b) Street view in LCZ_5 (c) Indicators values for the LCZ_5

(a)

(b)



(c)

Fig-8. (a). Airborne view of LCZ_6 (b) Street view in LCZ_6 (c) Indicators values for the LCZ_6

The class LCZ2 "Compact Mid-rise" represents the dense urban environment found in the old town center (Coudiat, Saint-Jean). Quantitative values of urban land cover are within the original recommended boundaries. In terms of urban morphology, two (height, roughness class) of the four parameters agree with the proposed values, while intervals suggested in the guideline for the aspect ratio were too reductive for this LCZ. Moreover, the spatial entity of dense urban fabric that covers "Medina of Constantine" is on the edge between two types (hybrid buildings of low to medium height). The calculation of physical indicators does not allow to determinate an LCZ type. In terms of land cover, the observed properties correspond to a compact low-rise LCZ3, while the morphology values are of the "Mid-rise

LCZ2" type. For this purpose, this sample is considered as LCZ2/3.

In the previous cases, Sky View Factor (SVF) and aspect ratio (AR) values are outside the suggested intervals. Both indicators (SVF, AR) are strongly depending on urban configuration and urban composition.

It should be noted that the rang of different parameters values proposed by Stewart and Oke [7], were based on results of their work in three representative cities of Europe, North America and Asia. It may not be adequate to describe the land features of cities in Algeria (a developing country) which represent a heterogeneous profile with different urban structures and forms. This statement is found in Nigeria [19], China [34] and Barranquilla[4] [35]. Thus, the calculation of indicators corresponds to the average over the whole area, including the hearts of islands, square and more [18]. In this study, given the lack of data, the work was done at the level of canyons only (patios are not taken into consideration).

The LCZ5 class "Open mid-rise" is characterized by open arrangement of mid-rise residential buildings (3-9 stories). The LCZ6 category "Open low-rise" is dominated by residential neighborhoods of single-story houses with 1 to 3 levels. The Large Low-rise class (LCZ8) has been selected at the industrial zone. In line with its activities (tertiary, light industry), it has large low buildings with a considerable footprint (warehouse, factories). The only sample of land cover type selected in this study represents natural landscape "bare land" (LCZF).

In these last four classes, the observed data (definitions, illustrations and physical properties) match perfectly with the metadata of the corresponding types suggested in the classification scheme. In general, the results found in the study area show an acceptable correspondence between the theoretical reference values proposed in the framework and those found in reality.

3.1. Field observations

Stewart *et al.* [36] have argued that one of the advantages of the LCZ scheme is that each class has a unique thermal behaviour that would establish in advance the possibility of an UHI, between urban and rural areas, as well as thermal variations between urban areas. Thermal differentiation of LCZs varies with the degree of structural and material separation between zones [31]. Hypothetically, classes must demonstrate thermal gradient from the most compact to the most open.

The greatest intensity of temperature would develop at the level of the city center dominated by compact types (LCZ2, LCZ2/3), explained by the high rate of soil waterproofing (> 97%) and the height of buildings. In second place are open urban fragments: (LCZ5) open mid-rise followed by (LCZ6) open low-rise and (LCZ8) large low-rise class. The natural zone LCZF would have a behaviour favourable to the formation of a coolness island. This possible nocturnal UHI has been checked by making field observations.

Data acquisition took place over a 3-day period. In this paper, we presented one typical measurement day. The Hourly profiles of screen height air temperature through two LCZs in summer are shown in the figure 9, in which, the x-axis shows the hours of measurement and the Y-axis shows the average air temperature of each LCZ type.

[4] The capital district of Atlántico Department in Colombia

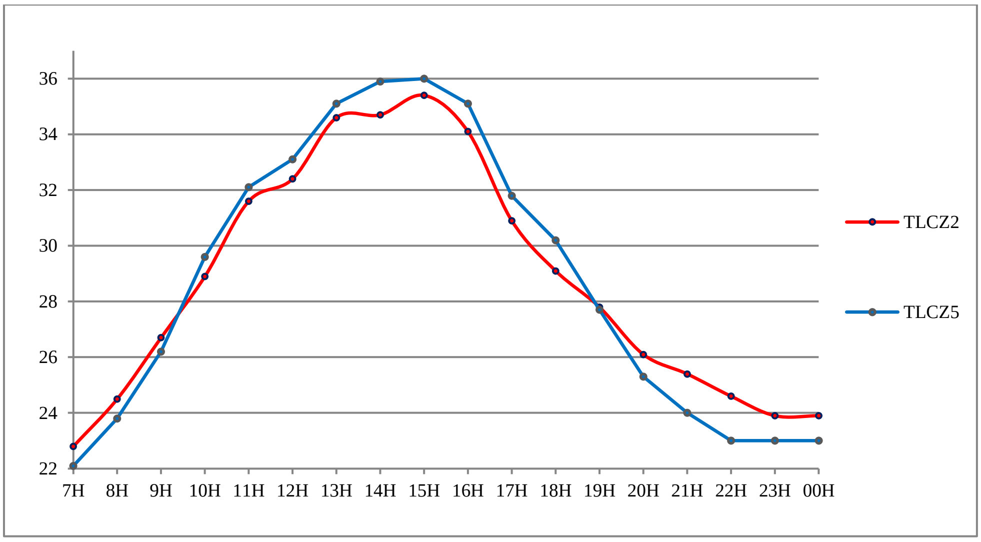


Figure 9. Screen-air temperature measured within LCZ_2 and LCZ_5

Profiles show that:

- During the day, air temperature T_{air} values recorded within the two fragments have a very similar tendency. The results indicate a range of difference with a small gap (0.5 to 0.9°C). The LCZ2 "compact Mid-rise" shows temperature values slightly lower than those observed within LCZ5 "Open Mid-rise". This magnitude is attributing to the fact that solar radiation penetration in the LCZ5 is higher. In open mid-rise area, the buildings are not smaller than the compact mid-rise area, but the dominant range of the SVF decreased significantly.

The relationship between LCZ air temperatures derived here corresponds well with recent work done in cities elsewhere. Observational results in Uppsala [31], confirmed that ΔT LCZ5 - LCZ2 is less than 0.8°C. Leconte *et al.* [18] found temperature difference of approximately 0.4°C in Nancy. These results are in line with T. Oke [37] observation that suggests that diurnal air temperature magnitudes within an agglomeration are small.

- During the night, when there was no direct solar radiation in urban areas, the air temperature results tend to reverse. The Tair values observed in LCZ2 are higher than those of the open zone with maximum deviation of 1.6°C after three to four hours of sunset (22h).

This is attributed to the surface characteristics of the two zones that are highly different (materials and morphology), which causes a difference in the cooling rate. Radiative losses are developed in the open area due to the high SVF values, thus reducing the air temperature. In opposition, radiative trapping at the canyons of the compact zone considerably reduces the rate of cooling. In view of the conceptual typology of UHI proposed in [38], the temperature difference obtained in this study (1.6°C) is below the limit proposed by the researcher (2 to 5°C), moreover, it shows similarities with that obtained in Nancy by [18] (1.3 to 1.8°C). Leconte *et al.* [18] argued that the size of the agglomeration and the number of population different of Vancouver, Uppsala and Nagano, could be a justification for this difference. Alexander *et al.* [1] highlighted that comparison with other studies should be interpreted with caution in light of the differences in instrumentation, study period, sitting and background climate. In each study, the micro and local scale differ in term of surface cover, surface relief, built structure, thermometer exposure and thermometer accuracy at the measurement sites.

4. Conclusions

This paper discusses the quantification of UHI magnitude of Constantine during the summer season. To that purpose, LCZ workflow has been applied in a small sample of the city. An LCZ cartography has been built allows for the construction of 12 class. Urban physical parameters have been calculated within a selection of 6 LCZ. Results show a good correlation with the LCZ scheme categories.

LCZ can be used to make a reasonable suggestion about thermal behaviour in fragments where there are no observations. A hypothetical scenario of a possible nocturnal UHI has been advanced. Analysis of spatial air temperature distribution inside the two LCZ reveals that maximum intensity was seen in compact mid-rise zones which cover the central part of the city.

Some limitations have been assigned to the application of LCZ methodology in Constantine:

1. Methods used to define the LCZs contours, which was based on the author's visual estimation, poses problems especially in the case of our cities with their heterogeneous profile.
2. The determination of most urban indicators is a difficult and time-consuming task, especially in the absence of information and an urban database. Calculation methods used such as manual estimation could be associated with uncertainties.

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