Surface Fraction as a variable for Urban Heat Island Amelioration in Colombo

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Abstract

Rapid urbanization has resulted in the change of land use and thus land cover from rural natural, pervious green surfaces to impervious urban land. It is identified as a key reason for microclimatic changes that create the Urban Heat Island (UHI) phenomenon that effect many cities.

Although, the planning parameters for Colombo, Sri Lanka do specify the building to non-built surface fraction, it does not define the nature of the non-built areas. It is also deemed that such planning and building regulations are not based on any overall climatic goals for the city. In this context, the need is to quantify urban parameters that can be controlled by urban design.

This study explores the effect of the building surface fraction, impervious surface fraction, and pervious surface fraction of an urban block, as a strategy for UHI amelioration in Colombo.

The range of the combinations of the above are limited to the range defined by the Local Climate Zone (LCZ) classification system. It is further focussed on the predominant LCZs of Colombo, LCZ3 - Compact Lowrise and LCZ2 – Compact Midrise.

The study uses the computer simulation software ENVI-met to model the existing as well as the modelled surface fraction of a particular urban block, in Colombo.

Results and Analysis will discuss the comparative implications of the changing surface cover on the UHI mitigation possibility in warm humid Colombo.

Keywords –Surface fraction, Urban Heat Island, Warm Humid Tropics, Local Climate Zone, Sri Lanka

Introduction

The rapid urbanization has brought in its wake to many challenges to Sri Lanka's largest commercial city. One such significant challenge is the warming of the city and therefore the increased energy use. This is evident by the well documented Urban Heat Island (UHI) phenomenon that affects the city.

Urbanization has resulted in change of land use / land cover from natural green surfaces to impervious urban land. It is identified as a key reason for microclimatic changes that create the Urban Heat Island (UHI) phenomenon. The study explores the relationship between urban microclimate and land use / land cover patterns in terms of building surface fraction, impervious surface fraction and pervious surface. The study is limited to predominant LCZs of Colombo, LCZ3 - Compact Lowrise and LCZ2 – Compact Midrise. The study is a research initiative to explore the possibility of building in climatic goals for the city and urban planning regulations.

Background

Built environment and its effects on urban heat island phenomenon

The variations in the localized climate of an urban block or a city, termed as its “Micro Climate”, and the microclimate of a given urban block can result from independent design features, that affect urban microclimate in different ways such as fraction of urban land covered by buildings, distances between buildings, and average height of buildings (Givoni, 1998). These parameters affect the urban microclimate in terms of solar radiation, solar reflection, wind speed and wind direction, etc.

Urban heat island amelioration through the manipulation of microclimate is one of the main focuses among researchers in the present world. Urban geometry and the properties of surface materials have been found to be the two main parameters influencing urban climate. Under these two themes, UHI mitigation strategies can be listed as follows;

1. Increase vegetation cover.
2. Increase thermal reflectivity [albedo] of urban surfaces, particularly roofs.
3. Manipulating urban geometry.

Manipulate urban geometry

Urban geometry manipulation has the greatest potential for microclimate modification. The urban geometry of a particular city is characterized by a repetitive element called the urban canyon. Urban canyon defined as the Three - dimensional space bounded by a street and the two adjacent buildings.

Height to Width ratio and the Sky view factor of an urban canyon are the crucial factors when discussing the impact of that particular urban canyon to the adjacent microclimate.

Land cover changes and heat island effect

Extensive efforts have been devoted to find relationships between the UHI intensity and specific urban surface parameters, such as surface albedo, thermal properties of surface materials and vegetation fraction, but quantifying the relative contributions of each causative factor to the UHI intensity has received less attention. (Ryu and Baik, 2011)

According to US Environmental Protection Agency (USEPA), albedo is 'the fraction of the total solar radiation incident on a body that is reflected by it'. By definition the albedo of an object ranges from 0 (no light reflected) to 1 (all reflected). Surfaces that have high albedo values absorb less incident radiation. Additionally, increasing the albedo of surface material of a city will lower air temperature by reducing the absorption of shortwave radiation.

When considering the land cover changes and heat island effect, Oke (1981) found no significant correlation between types of man-made surfaces and heat island intensity. The only significant difference observed was between man-made and natural surfaces. Thus, concrete surfaces and asphalt paving, brick walls and cinder blocks, all contribute more or less equally to the problem of urban heat built-up, while vegetative cover show remarkable reduction in heat built-up. (Emmanuel, 2005).

Wong and Chen (2009) stated 'increasing vegetative cover in cities is the most effective strategy for mitigating the UHI effect'. No matter how it is arranged throughout a city in the form of landscape on the ground or placed around buildings, place a very important role in regulating the urban climate. And also vegetative cover can modify the energy balance of the whole city by adding more evaporating surfaces. It is important to emphasize that solar heat extremes can be greatly reduced by vegetation; leaves can seize most of the incoming radiation. Inside processes of plants, such as evapo-transpiration and photosynthesis process are acting in a beneficial manner to the micro climate.

Local climate zones for urban heat island studies

With the intention of providing a research framework for UHI studies, Stewart and Oke (2009) introduced 'local climate zone' classification covering all the lacking parts of the conventional approaches. It provides the ability to differentiate climate zones in a city by observational data.

LCZs are defined as ‘regions of uniform surface-air temperature distribution at horizontal scales of 10^2 to 10^4 metres’ (Stewart & Oke, 2009).Their definition is based on characteristic geometry and land cover that generates a unique near-surface climate under calm, clear skies. Urban land use and land cover have comprehensively described in this classification. The factors considered include vegetative fraction, building/tree height and spacing, soil moisture, and anthropogenic heat flux. This comprehensiveness allows comparing any given LCZ across many different cities. (Stewart, 2012)

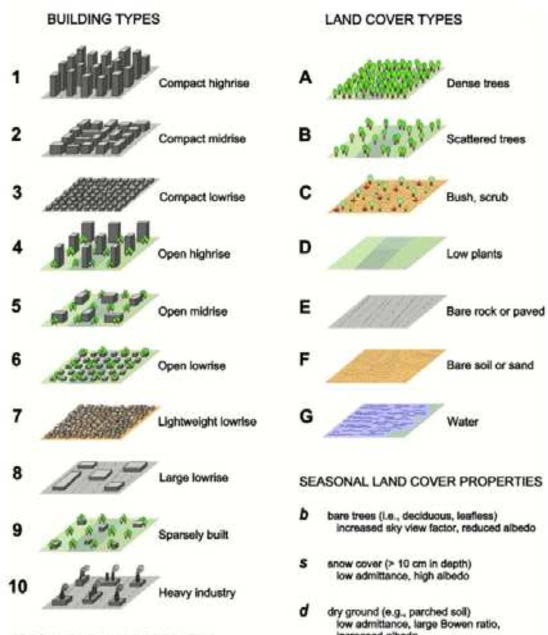

Fig.1: Local Climate Zones
Source: Stewart et al (2012)

LCZ classification has 17 climatic zones as shown in fig.1. (10 built types and 7 Land cover types). These building and land cover types are combined to create sub categories. These have been validated in Sweden, Japan and Canada (Stewart, 2011)

Method

This study is an attempt to employ a quantitative approach in exploring the relationship between Mean Radiant Temperature and several indices, including the Building surface fraction, Impervious surface fraction, and Pervious surface fraction. The process first adopts the LCZ system to simplify and categorise the existing urban fabric of Colombo in order to determine the most common LCZ typology and their evolution pattern. By referring the Colombo LCZ map, case study site will be identified and then Simulated in ENVI-met software according to pre-determined cases. Results would point out the best cases of manipulating the building surface fraction which effectively decreases the urban heat island effect to achieve new comfort goals for the rapidly urbanizing Colombo metropolitan area.

Mapping Local climate zones for Colombo

Perera et al. (2012) classified Colombo into local climate zones in 2012. They revealed that Colombo is dominated by LCZ3 (Compact low-rise), LCZ2 (Compact Midrise) and LCZ8 (Large low-rise).

Selection of the study area

Colombo metropolitan region (CMR) which has recently witnessed a significant physical development is selected as the study area.

As Colombo is dominated by LCZ-3 (Compact low-rise), LCZ-2 (Compact Midrise) and LCZ-8 (Large low-rise), It can be said that LCZ typology of most of the CMR area would gradually change to LCZ-3 and then to LCZ-2.

As this study is predominantly aims to find the relationship between surface fraction and the UHI phenomenon, the selection of the case study should encompass several factors.

- LCZ 3 typology (considering their changing pattern - Primary consideration)
- A rapidly developing area (This will give an insight into potential mitigation and adaptation strategies against UHI effects at a microscale.)

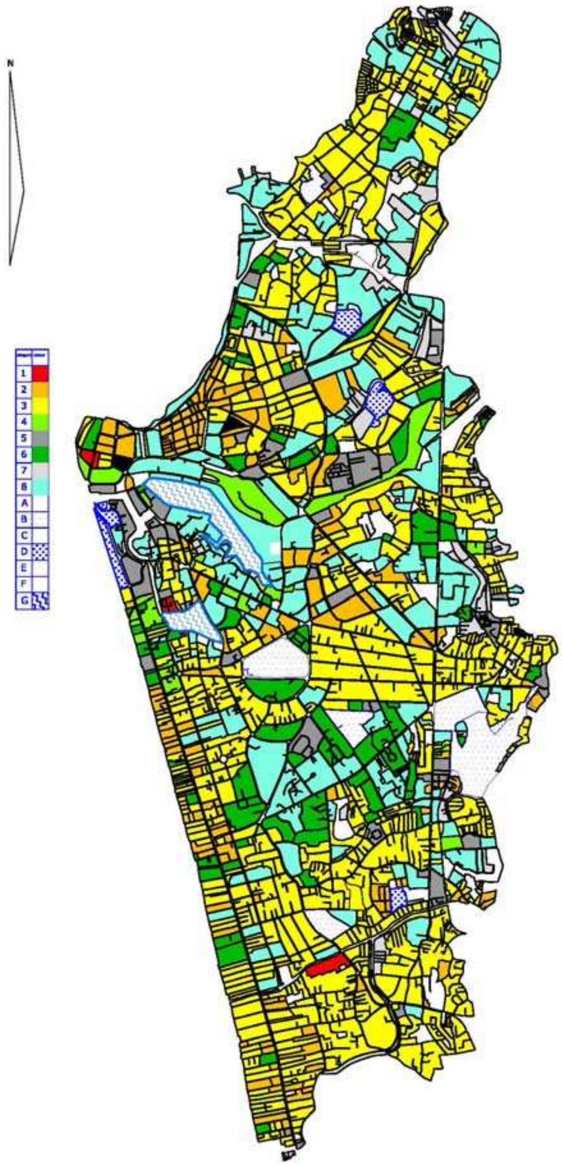

Fig 2: Local climate zone map, Colombo
Source: Perera *et al.* (2012)

The urban context along Galle road is identified as a rapidly developing area. This factor is further highlighted in the 'Zoning Plan 2020 for City of Colombo' published by the Urban Development Authority of Sri Lanka.

A land plot next to Galle road [6°53'25"N & 79°51'19"E (Land mark- Asoka garden)] has been selected as the case study. Fig.3.

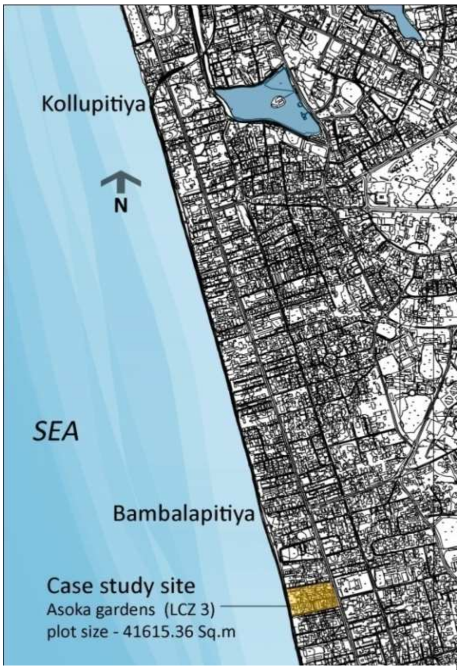

Fig 3: Case study site map
Source : Author

Case matrix

The case is based on the Surface Fraction Parameters defined by Stewart (2012) for particular LCZs. The range of each factor is broken up for greater understanding and analysis. In this regard the 65% surface cover that the UDA regulations mandate is not taken into consideration. The height of roughness elements (building height) is taken as maximum.

Table 1. Case Study Matrix

		Building surface fraction[c]	**Impervious surface fraction[d]**	**Pervious surface fraction[e]**	**Height of roughness elements[f]**
	Case B	40%	30%	30%	9m
	Case C	40%	40%	20%	9m
	Case D	40%	50%	10%	9m
	Case E	50%	20%	30%	9m
	Case F	50%	30%	20%	9m
	Case G	50%	40%	10%	9m
LCZ - 3	Case H	50%	50%	0%	9m
	Case I	60%	20%	20%	9m
	Case J	60%	30%	10%	9m
	Case K	60%	40%	0%	9m
	Case L	70%	20%	10%	9m
	Case M	70%	30%	0%	9m
	Case N	40%	40%	20%	27m
	Case O	40%	50%	10%	27m
	Case P	50%	30%	20%	27m
	Case Q	50%	40%	10%	27m
LCZ - 2	Case R	50%	50%	0%	27m
	Case S	60%	30%	10%	27m
	Case T	60%	40%	0%	27m
	Case U	70%	30%	0%	27m

[c] Ratio of building plan area to total plan area (%)
[d] Ratio of impervious plan area (paved, rock) to total plan area (%)
[e] Ratio of pervious plan area (bare soil, vegetation, water) to total plan area (%)
[f] Geometric average of building heights (LCZs 1–10) and tree/plant heights (LCZs A–F) (m)

Simulation software - ENVI-met

Computer simulation tool ENVI-met is used to simulate the projected variations of the mean radiant temperature (MRT). ENVI-met is a three-dimensional non-hydrostatic model developed by Michael Bruse (University of Bochum, Bochum, Germany) for the simulation of surface-plant-air interactions and reproduces the major processes in the atmosphere that affect the microclimate, including the simulation of wind flows, turbulence, radiation fluxes, temperature and humidity, on a well-founded physical basis (www.envi-met.com).

ENVI-met inputs;

- Meteorological:
    - Wind speed and direction at 10 m above ground
    - Roughness length (Zo)
    - Initial temperature of the atmosphere
    - Specific humidity at 2500 m
    - Relative humidity at 2 m level
- Morphology:
    - Site plan (incl. buildings, trees, man-made surfaces
    - Height of buildings and trees
- Surface property:
    - Ground, building and all surfaces plus water

The main limitations of the software are as follows;

- Buildings are modelled as blocks where width and length are multiples of grid cells
- Buildings have no thermal mass and constant indoor temperature
- Albedo and thermal transmission (U-value) for walls and roofs are the same for all buildings

ENVI-met was validated for Sri Lanka by Emmanuel, R., & Johansson, E. (2006).

Results and Analysis

Relationship between surface fraction variables and the Mean Radiant Temperature in LCZ-3 typology

Fig.4 shows the comparison of cases where the built surface fraction is 40%. The pervious surface fraction varies from 30%, 20%, and 10% for the B, C, and D cases respectively. The results show that there is little or no variation in the in the MRT.

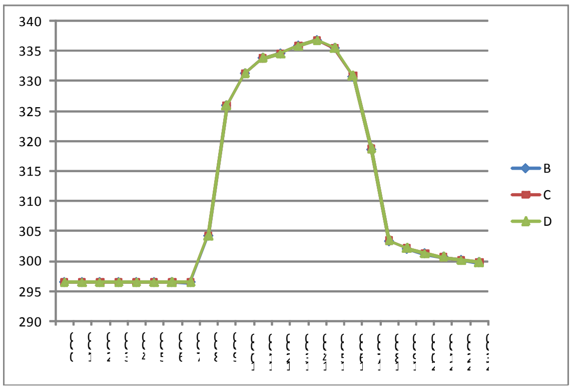

Fig 4. - LCZ3 cases B, C, D - MRT values

Fig.5 shows the comparison of cases where the built surface fraction is 50%. The pervious surface fraction varies from 30%, 20%, 10% and 0% for the E, F, G and H cases respectively. The results show a significant reduction in MRT throughout the day for case E. The greatest difference of 7.48^{0}C is seen at 14.00 hrs. There is little or no variation in the in the MRT for cases F, G and H.

Fig.6 shows the comparison of cases where the built surface fraction is 60%. The pervious surface fraction varies from 20%, 10%, and 0% for the I, J, and K cases respectively. The case devoid of a pervious surface in the non-built area is significantly warmer than the cases with even a minimal area of pervious surface. There is little or no variation in the in the MRT for cases I and J.

Fig.7 shows the comparison of cases where the built surface fraction is 70%. The pervious surface fraction varies between 10%, and 0% for the L and M cases respectively. Case M with no pervious fraction is warmer throughout the day with a greatest MRT difference of 7.40^{0}C at 14.00 hrs.

Comparison of all cases with a similar pervious surface fraction show a reduction of MRT with an increase of built surface fraction. In this regard it is seen that a plot with impervious non-built areas are warmer than those of a similar area replaced by buildings. Overall the best cases for LCZ3 are for the cases with higher built surface fraction. (Fig8) These cases namely case I, J and L have a higher pervious surface fraction than the other cases with a similar built surface fraction. The worst case scenario is seen in case H which has a built fraction of 50% with the total non-built area impervious.

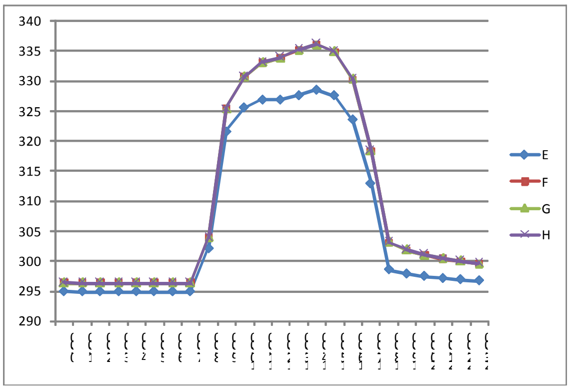

Fig 5. - LCZ3 cases E, F, G, H - MRT values

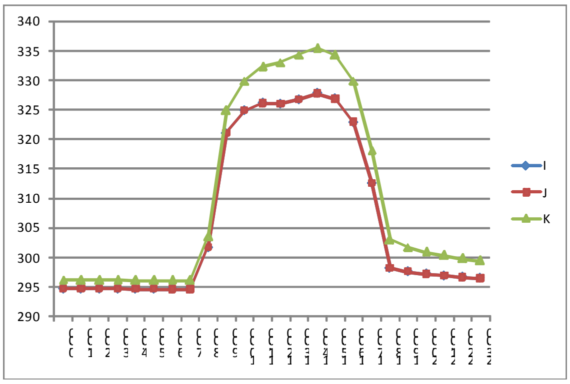

Fig 6. - LCZ3 cases I, J, K - MRT values

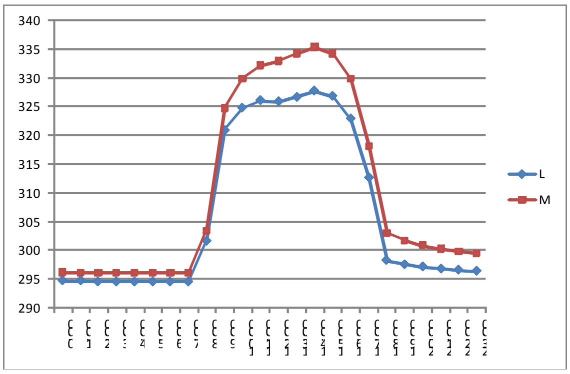

Fig 7. - LCZ3 cases L, M - MRT values

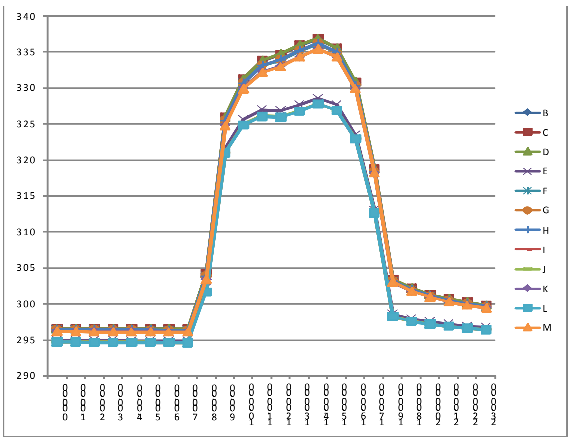

Fig 8. – All LCZ3 cases

Relationship between surface fraction variables and the Mean Radiant Temperature in LCZ-2 typology

Fig.9 shows the comparison of cases where the built surface fraction is 40%. The pervious surface fraction varies from 20% to 10% for the N and O cases respectively. The results show that there is little or no variation in the in the MRT.

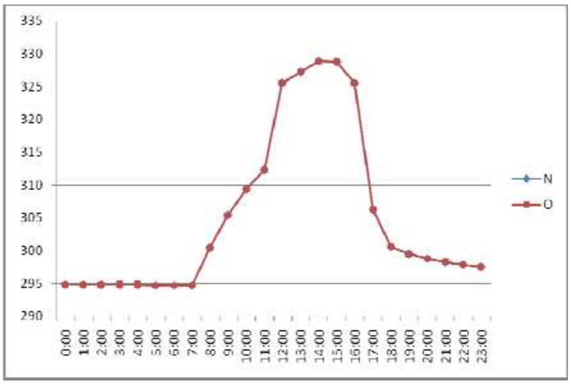

Fig 9. – LCZ2 cases N, O - MRT values

Fig.10 shows the comparison of cases where the built surface fraction is 50%. The pervious surface fraction varies from 20% to 10% to 0% for the P, Q and R cases respectively. The results show that there is little or no variation in the in the MRT.

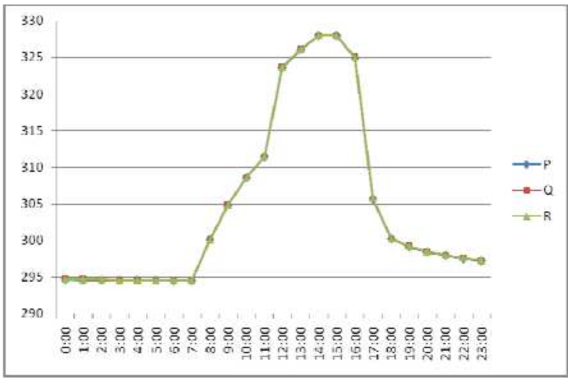

Fig 10. – LCZ2 cases P, Q, R - MRT values

Fig.11 shows the comparison of cases where the built surface fraction is 60% for cases S and T. The pervious surface fraction varies from 10% to 0% respectively. A significant reduction in MRT can be seen in case S where the non-built area incorporates pervious surfaces as opposed to that of case T, where it is totally impervious. A similar trend is seen in case U. All cases show a dip in MRT at 14.00 hrs. This is deemed to be caused by the shading created by the deep urban canyons of LCZ2.

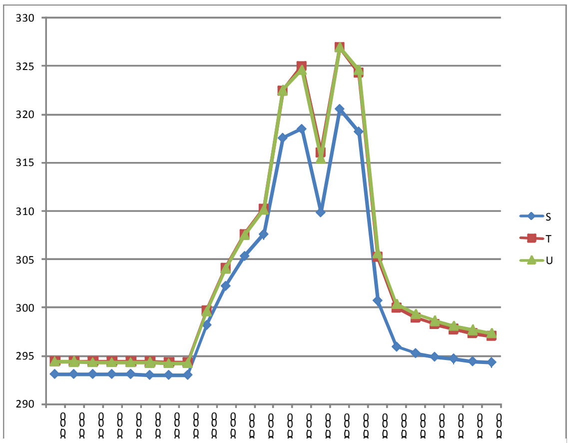

Fig 11. – LCZ2 cases S, T, U - MRT values

As it was with LCZ3, here too the comparison of cases with a similar pervious fractions show a reduction in MRT as the built fraction is increased. This is seen more distinctly in LCZ2 due to the increased shading potential of the fabric.

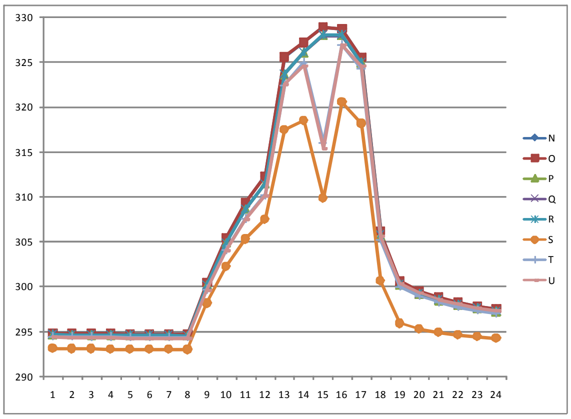

Fig 12. – All LCZ2 cases

Overall the best case scenario (Fig.12) is seen in case S, which has a built fraction of 60% with a 10% pervious fraction.

Relationship between cases of a similar built surface fraction of both LC3 and LCZ2 typologies

The comparisons analyse the built to the non-built surface of the urban block.

Fig.13 shows the comparison of cases where the built surface fraction is 40%. The results show that there is little or no variation in the in the MRT for one typology of LCZ. A distinct difference is between the 2 typologies, where LCZ2 is cooler than LCZ3 right throughout the day. The rises slower in the morning hours for LCZ2, yet the evening hours show a similar rate of cooling as LCZ3.

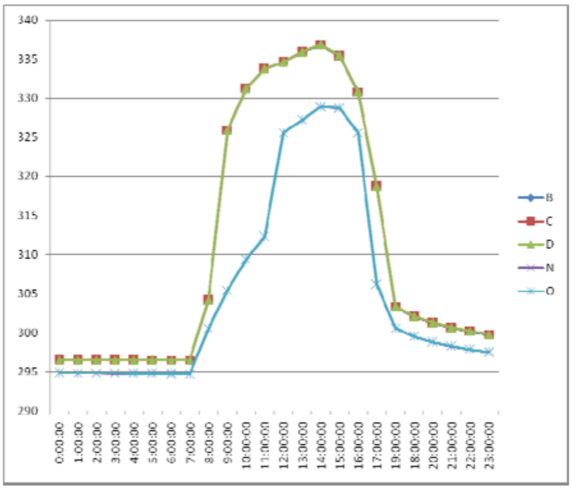

Fig 13. – 40% Built Surface Fraction - MRT values

Fig.14 shows the comparison of cases where the built surface fraction is 50%. The results show that there is little or no variation in the in the MRT for most cases of LCZ in both typologies. Although in case E, where the pervious fraction of 30% is highest among the cases, show a distinct drop in the MRT. As with the previous comparison (fig 10) LCZ2 is cooler than LCZ3.

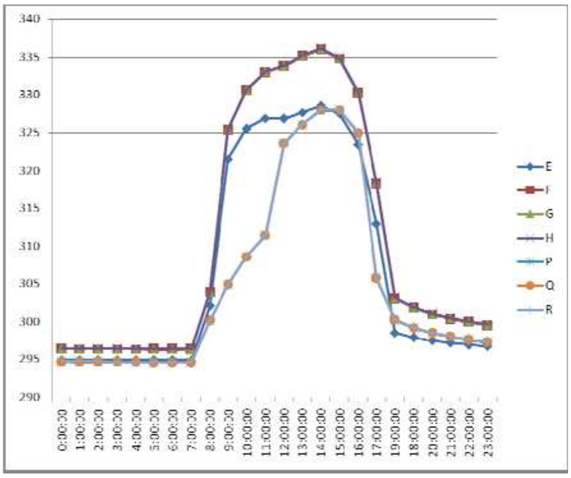

Fig 14. - 50% Built Surface Fraction - MRT values

Fig.15 compares cases where the built surface fraction is 60%. The results show that there is a distinct difference in the MRT between LCZs. The cases devoid of pervious surface cover (cases T and K) are warmer. This is seen in both typologies of LCZ.

As mentioned above, the differences between the LCZ typologies are attributed to the better shading potential of deeper urban canyons and therefore MRT reduction in LCZ2.

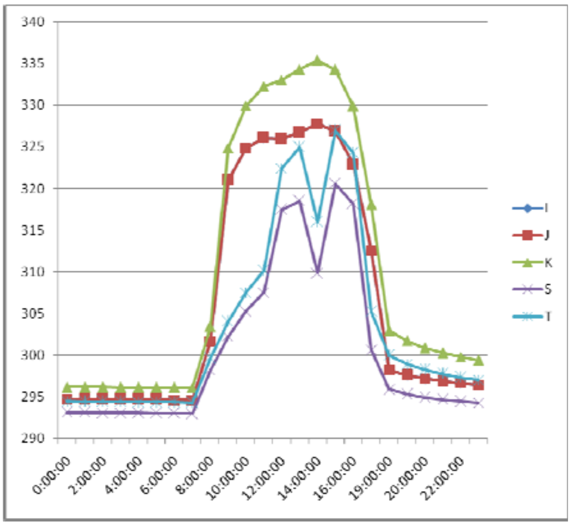

Fig. 15 - 60% and 70% Built Surface Fraction - MRT values

Conclusion

The main objective of the study was to ascertain the impact of the nature of the surface cover in an urban context and its influence on local level warming. The study focuses on the warm, humid Colombo, Sri Lanka.

The use of the LCZ classification system allows for the effective simplification of the urban fabric, therefore the comparison of intensities ascertained by the simulations are deemed more relevant and can be applicable to similar climatic contexts. The main limitation to the method is that the simulation assumes an urban fabric of relatively uniform materiality and is conducted for a single day in March.

Results and analysis reveal that;

- A LCZ zone change from LCZ3 to LCZ2 has a positive effect on the MRT reduction of a urban block.

- The MRT reduces by over 7.5^{o}C between LCZ3 and LCZ2, in blocks of similar built surface fraction.

- Blocks that incorporate pervious surfaces have a distinct advantage in relation to those that do not, especially in the higher built surface fraction cases. (Case K, T and U)

- The ratio of pervious to impervious surfaces have minimal or no effect on the overall MRT within a given built surface fraction case set. Exceptions to this is seen when the pervious cover is 30% in case E.

In this context it can be concluded that though a percentage of pervious surfaces are important for a cooler urban block, it is the building morphology change that creates the greatest effect. An urban context that is devoid of a pervious surface fraction is distinctly warmer.

The implications of the above is, a city devoid of pervious surface cover will result in warmer urban contexts with increased energy use. The overall impact is that a city already effected by UHI, will see a continued increase in its intensity.

This is particularly critical for Colombo, where many parts of the city is getting covered by impervious surfaces, where they were pervious before.

The challenge for future research is to see how to develop the City of Colombo to meet the demands of the future while adapting to, maintaining, mitigating the negative effects of such changes.

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