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BEYOND SUSTAINABILITY
Reflections Across Spaces

VEGETATION COVER EFFECTS ON OUTDOOR THERMAL COMFORT AROUND HIGH-RISE DEVELOPMENTS

A Case Study of Havelock City, Colombo, Sri Lanka

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Abstract: Colombo, with its rapid development, is experiencing an influx of high-rise developments. These developments create a significant influence on the microclimate of the area around them, and therefore impact outdoor thermal comfort. With the intension of mitigating outdoor thermal comfort concerns, the enhancement of the vegetation cover is an often-proposed strategy. This is a research initiative to ascertain the optimum vegetation cover percentage to achieve outdoor thermal comfort around high-rise developments, utilising Havelock City, Colombo, Sri Lanka as a case study. A computer simulation process is adopted, using the software ENVI-met, to explore the optimum form and coverage of vegetation for outdoor thermal comfort. Results show, overall thermal comfort levels diminish, with the increased infusion of vegetation. Vegetation cover had a little or no impact in the daytime, while the strategy had distinct negative impacts in the night-time. The nature of the built morphology of the development together with the vegetation cover increase is shown to have significant impact on wind movement and nocturnal heat loss, therefore outdoor thermal comfort levels. Conclusions highlight the need for the extensive exploration of morphological studies, while encompassing key amelioration strategies, particularly for the high-rise development typology.

Keywords: *Vegetation cover; Outdoor Thermal Comfort; High-rise developments; Colombo, Sri Lanka; ENVI-met.*

1. Introduction

High-rise developments play an important role in modern cities and its urban form. Growth of the population and its ever-increasing concentration to cities has become a necessity in the pursuit of economic upliftment and a better quality of living. At the same time, high-rise buildings and developments significantly influence the urban climate of cites at all scales, including the microclimate of the immediate context. High-rise buildings are the least ecological out of all building types, as it consumes three times as much energy and material resources than an average low rise building during its life cycle (Yeang & Powell, 2007). However, due to high demands caused by urban growth on a global scale, building high-rises will remain in the foreseeable future.

The impacts of high-rise developments are well documented. Its negative effects on the microclimate of its surrounding area will be a key consideration going forward. The challenge of the developers and the design community is to approach these developments in a sustainable manner, thus ensuring that an urban context conducive for human habitation is realised.

To reduce urban heat stress and improve outdoor thermal comfort of city dwellers, increasing urban vegetation cover is an often-proposed mitigation strategy (Meili et al., 2021).

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As defined by (Norton et al., 2013), Vegetation Cover can be typologically –

- Green Open Spaces (Grass Cover) - Spaces of land without any buildings with grassed areas which provide cooler pockets.

- Tree Cover – Provide shade, absorb, and reflect solar radiation reduce urban heat while diversity of trees can moderate day and night temperatures. The arrangement of trees also affects the moderation of urban heat because some tall trees can store the heat under their canopies and may cause the nocturnal temperature to be high. Tree planting strategies, diversity of tree types can reduce the heat tapping under trees.

- Green Roofs – Green roofs are a more effective form of reducing surface temperatures which helps to reduce indoor temperature of the building as well as outdoor temperature in the micro scale, by covering the roofs which are considered as hottest surfaces during daytime in urban areas. Intensive green roofs that can facilitate a large range of plants are also called rooftop parks, and Extensive green roofs which are limited to a thin growing layer and limited to few plants are the two main green roof types. Studies have proved that these irrigated green roofs have a positive impact on Urban Heat Island effect.

- Green Façades - Green façades can be climbing plants growing on walls, plants that cover a façade attached structure or sometimes may be vegetation patches originating from plants growing on balconies. Transpiration is the main mode of providing cooling through green facades as well as a good substitute to areas which do not have enough ground space to grow trees. This helps to prevent the surface heat and provides air purification.

In this context, the primary aim of this paper is to quantify the effect of Vegetation Cover (VC) on outdoor thermal comfort (OTC).

The scope of the study is limited to the immediate microclimatic context around high-rise developments, with a special emphasis on Havelock City, Colombo, as a case study.

The computer simulation software ENVI-met is utilised to evaluate impacts on mean radiant temperature (MRT) and predicted mean vote (PMV) in the urban environment of the Havelock City high-rise development. The simulation scope is limited to a single day in the year, given the limitations of the simulation software. The recorded hottest day of the year was established as April 1st and therefore the simulation date. Properties pertaining to the total development was assumed as the same for all high-rise building blocks, thereby focuses emphasis on the impact of VC on the OTC. Five simulation cases are established with systematically varying percentages of VC types, to analyse the overall influence on OTC, with the objective to provide insight for settlement planning in high-rise precincts.

2. Background

2.1. HIGH-RISE DEVELOPMENT IMPACTS ON OUTDOOR THERMAL COMFORT

While high-rise developments can have a significant positive impact on social and economic elements of a city, "the high-rise building typology is not usually considered environmentally sustainable, due to its intensive use of energy, material and other resources during its whole life cycle, although it has merits such as saving land resources and transportation costs" (Goncalves, 2010). The creation of compact urban forms with a view to - minimise space and energy – more often than not, translates into high-rise developments. With a focus on energy management at their outer envelopes, means that buildings are treated as stand-alone entities with minimal consideration of their impact on the surrounding urban landscape and vice versa. If/when each building pursues its own sustainability agenda without regard to its urban context, the result will diminish the natural energy resources available to nearby buildings and worsen the outdoor environment generally. (Futcher et al., 2017).

High-rise developments alter its surrounding thermal environment in terms of; Urban geometry – variations in building heights and distances in-between them; Local climate – relative humidity, external air temperatures and prevailing wind speeds and directions; Orientation and overshadowing – position of tall buildings with respect to south (northern hemisphere) and its exposure to solar radiation and overshadowing over low rise buildings within the cluster; Solar access, solar radiation and albedo; and Urban canyons. (Pandya, 2014). In addition to reflecting direct solar radiation high-rise buildings also absorb and reflect solar radiation from other buildings. (Arslan and Sev, 2014).

Wind flow is significantly altered by the presence of high-rise buildings. The strong winds generated near a high-rise building result in loops of dust and air pollution forming near user areas while the cleaner air flows over the urban canopy layer. (Aldeberky, 2004)

Outdoor spaces are important to sustainable cities because they encourage pedestrian traffic and outdoor activities, and contribute greatly to urban liveability. The influence of thermal comfort on outdoor activities is a complex issue comprising both climatic and behavioural aspects. (Gatto et al., 2020)

2.2. VEGETATION IN THE URBAN ENVIRONMENT

As stated in (Gatto et al., 2020) - the role of vegetation is related to the following environmental improvements (Salmond et al., 2016; Livesley et al., 2016):

- Microclimate: increasing urban vegetation induces decreasing air and surface temperatures. In particular, trees influence the thermal environment by providing shade, intercepting radiation with their canopy and reducing surface temperature, followed by heat transference through convection from warmer areas. Additional cooling is provided by the conversion of radiation into latent heat and evapotranspiration (Taleghani et al., 2018; Santamouris et al., 2017)

- Pollutant Dispersion: vegetation modifies wind-flow patterns in the streets.

- Deposition and Absorption of Pollutants: urban vegetation increases the pollutants removed from air by means of deposition or uptake via leaf stomata.

- Noise Attenuation: trees can attenuate traffic noise, in particular close to roads or open busy streets.

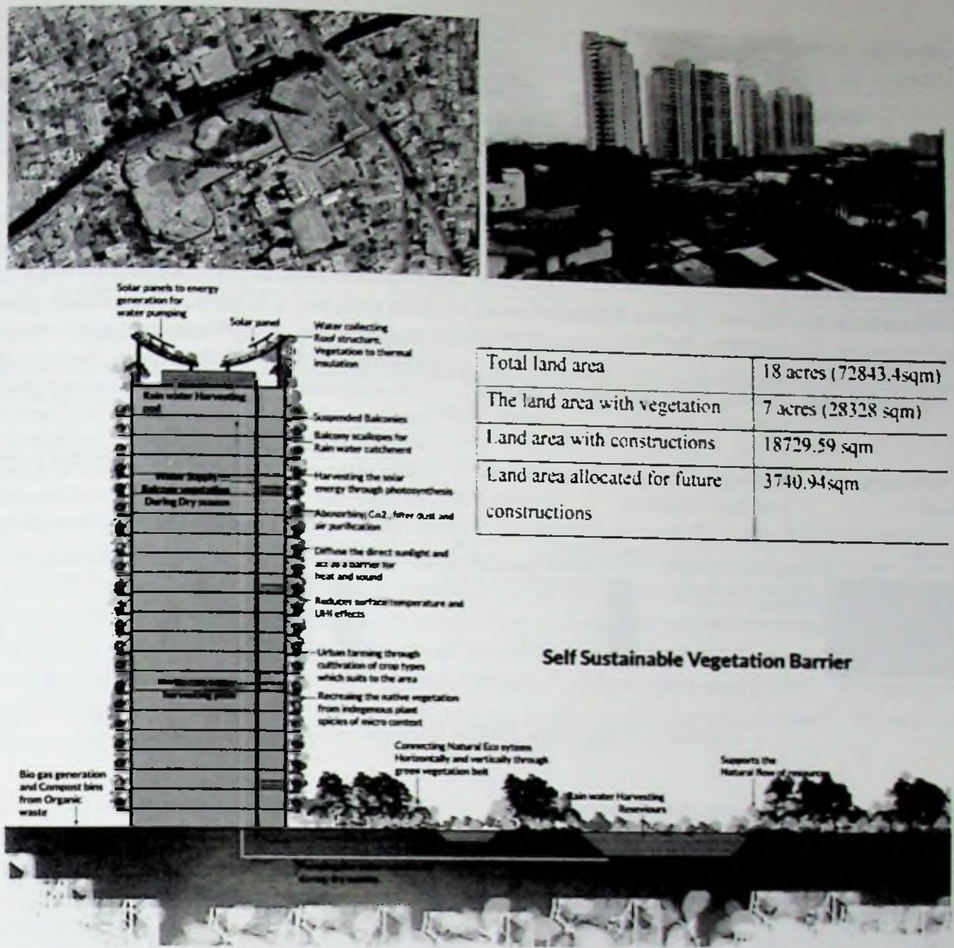
In contrast, the presence of vegetation may induce adverse effects such as the direct emission of biogenic volatile compounds (a precursor of the formation of secondary pollutants like ozone) and pollen. (Gatto et al., 2020)

Meili et al., 2021, (citing Chow, 2016) state – "While vegetation can decrease air temperature and reduce mean radiant temperature through shade provision during certain hours of the day, benefiting OTC in hot cities, plants transpire and increase humidity which might deter OTC in humid climates. Furthermore, vegetation can shelter and block wind flow, which could further reduce OTC in warm and calm-windless locations". (Meili et al., 2021)

3. Materials and Method

3.1. SITE SELECTION: HAVELOCK CITY, COLOMBO, SRI LANKA

Havelock City is a privately owned mixed-use development, that includes - eight residential towers and a commercial component with a shopping mall, a forty-six-storey office tower, and includes a seven-acre garden - as a high-rise zone that occupies a self-contained urban precinct spanning eighteen acres in Colombo. The land parcel can be termed a grey field site that prior to its development housed a large weaving and spinning mill. The land is bordered by a canal and the urban context is mostly residential, catering to a wide range of income groups. Thus, an urban fabric that encompasses single family houses on large land parcels, to former worker housing that have now transformed into compact highly dense settlements.



Total land area	18 acres (72843.4sqm)
The land area with vegetation	7 acres (28328 sqm)
Land area with constructions	18729.59 sqm
Land area allocated for future constructions	3740.94sqm

Figure 1, (clockwise) Arial image of the development (source google earth); The development and environs (source Dissanayake, 2016); conceptual section of VC application for Havelock city (Source: Author)

3.2. CASE STUDIES AND SIMULATION MATRIX

The simulation study explores both horizontal and vertical surfaces of the development as possible areas to integrate vegetation cover, in the form of grass cover, tree cover, green roofs and green façades. (See Figure 1). Further, as shown in Table 1, the research method, utilises the ENVI-met simulation software to model impacts of VC change as five simulation cases.

3.3. ENVI-MET SIMULATION SOFTWARE

ENVI-met is a holistic modelling software and it is designed to simulate three-dimensional microclimate models with surface-plant-air interactions in the urban environment. The typical simulations are done with a minimum resolution of 0.5m in space and 1-5 seconds in time (www.ENVI-met.info). This software can calculate fluid dynamics characteristics such as air temperature, relative humidity, wind speed, wind direction, mean radiant temperature, global radiation, turbulence and thermodynamic process in ground surfaces, walls, and plants. Yet, the model is not capable in calculating complex urban building forms and elements such as balconies, open breezeways, overhead galleries etc. (Simon et al., 2018).

Emmanuel and Fernando (2007) validated ENVI-met measurements with actual measurements in Colombo, Sri Lanka. It was shown that the model tends to over-predict the air temperature at night between 1900h to 0500h and under predict during the day between 0700h to 1700h. The reasons for deviation from actual values was cited as; the non-consideration of the regional exchange process of Colombo by ENVI-met, the non-inclusion of thermal mass of buildings, the thermal transmission, U-values, and surface temperatures that were taken as constant during the simulations. (Emmanuel and Fernando, 2007)

Simulation Matrix						
Case	Name	Havelock city premises				
		Building heights	Wall and roof materials	Window materials and WWR%	Façade vegetation cover percentage (Balcony vegetation)	Terrace garden cover percentage
Case 1	0% vegetation case	Existing condition	Existing (Material Profile A)	Glass and louvers, 19.5%	No green cover	No vegetation
Case 2	25% vegetation case	Existing condition	Existing (Material Profile A)	Glass and louvers, 19.5%	25% of the outer envelope with (Vegetation Profile B)	25% of the terrace with grass (Vegetation Profile C) and trees (15m height- 8, 5m height-22)
Case 3	50% vegetation case	Existing condition	Existing (Material Profile A)	Glass and louvers, 19.5%	50% of the outer envelope with (Vegetation Profile B)	50% of the terrace with grass (Vegetation Profile C) and trees (15m height- 8, 5m height-22)
Case 4	75% vegetation case	Existing condition	Existing (Material Profile A)	Glass and louvers, 19.5%	75% of the outer envelope with (Vegetation Profile B)	75% of the terrace with grass (Vegetation Profile C) and trees (15m height- 8, 5m height-22)
Case 5	100% vegetation case	Existing condition	Existing (Material Profile A)	Glass and louvers, 19.5%	100% of the outer envelope with (Vegetation Profile B)	100% of the terrace with grass (Vegetation Profile C) and trees (15m height- 8, 5m height-22)

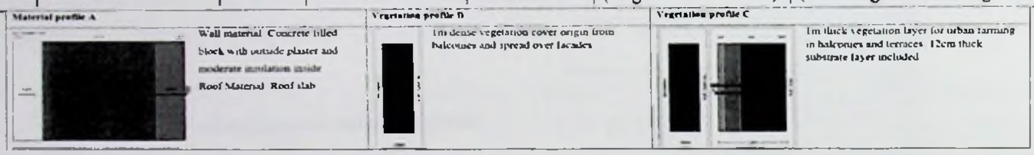


Table 1, Simulation Matrix (Source: Author)

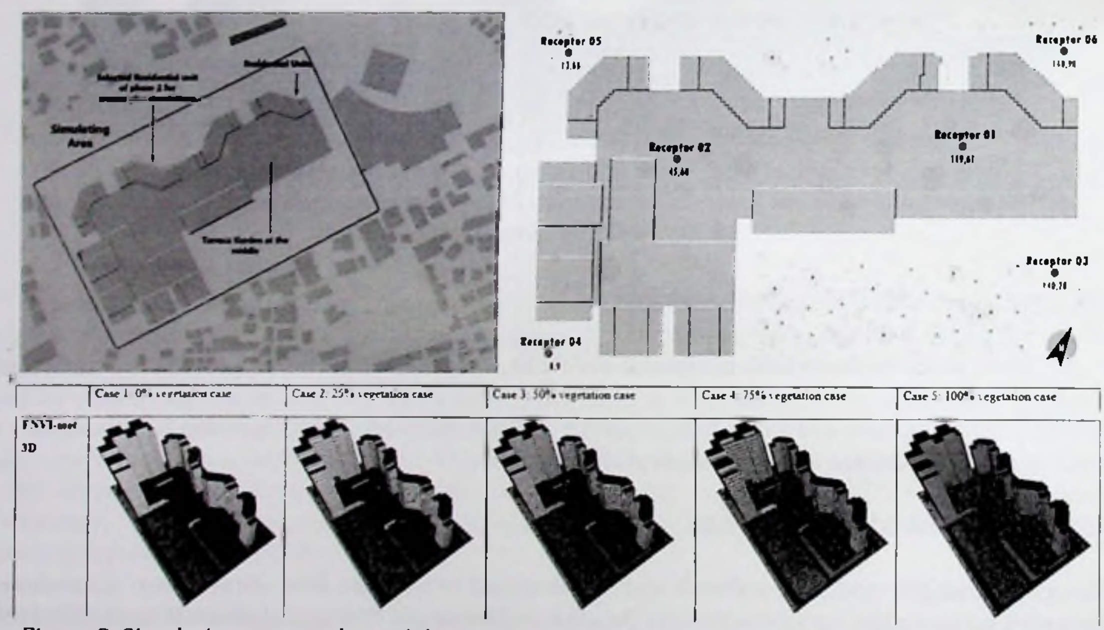


Figure 2, Simulation case study models in ENVI-met with VC changes, model domain and receptor point positions (Source: Author)

3.4. SCOPE LIMITATIONS, SIMULATION CONSIDERATIONS AND ASSUMPTIONS

Figure 2 shows the simplified model domain in ENVI-met, together with the key areas of the development identified for in-depth analysis. A significant consideration is the extensive green roof at the podium level of the development. The Havelock City development is unique in its approach to the upper-level garden and are the owners of the largest green roof in South Asia. Further, as shown in the model, the simulation area is limited to the residential blocks of the development, thereby limiting the typology of uses and therefore differences in its compositions and input parameters.

The simulation models the total duration of 24 hours of 1st April 2020, taken as the hottest day in the year and therefore the worst-case scenario. Minimum temperature of the day is 26°C and Maximum is 32° C, Humidity was ranging from 99% to 100%. Wind speed is 2.80 m/s, based on historical average data for the area ascertained from the Meteorological Department, Colombo, Sri Lanka.

As limiting factors of the model in ENVI-met and in consideration of parameters that effect OTC - Wall materials, roof materials are assumed as same for all the buildings. Light absorption, reflection and diffusion from building surfaces, embodied energy, specific building materials and energy consumption rates of the buildings are assumed as equal. Heat transfer rates from building materials and rate of heat generation from a unit area of a building was assumed as equal for all towers. Schedules of people and energy consumption were considered as equal for every floor level. Further, it is assumed that whole façade vegetation consists of a single plant type. Similarly, ground vegetation is of a single plant type with three different heights of growth.

3.5. ANALYSIS PROTOCOL

The results and discussion of the simulation study is presented according to the thermal comfort indices - Mean Radiant Temperature (MRT) and Predicted Mean Vote (PMV), and in terms of key parameters in the urban environment - Wind and Surface Temperature. The generated data is communicated as overall iso-contour maps of the variables - using the Leonardo plug-in included in ENVI-met, and comparative graphs at each receptor point (as seen in Figure 6) placed within the model domain. These maps are generated and compared for selected times of the day - 0400h, 0800h, 1200h, 1400h, and 2000h. The analysis further details and compares impact on parameters in relation to the receptor point position - for each case study - to draw insight on the impact of the building morphology on OTC.

4. Results and Discussion

4.1. VC CHANGE IMPACTS ON MEAN RADIANT TEMPERATURE (MRT)

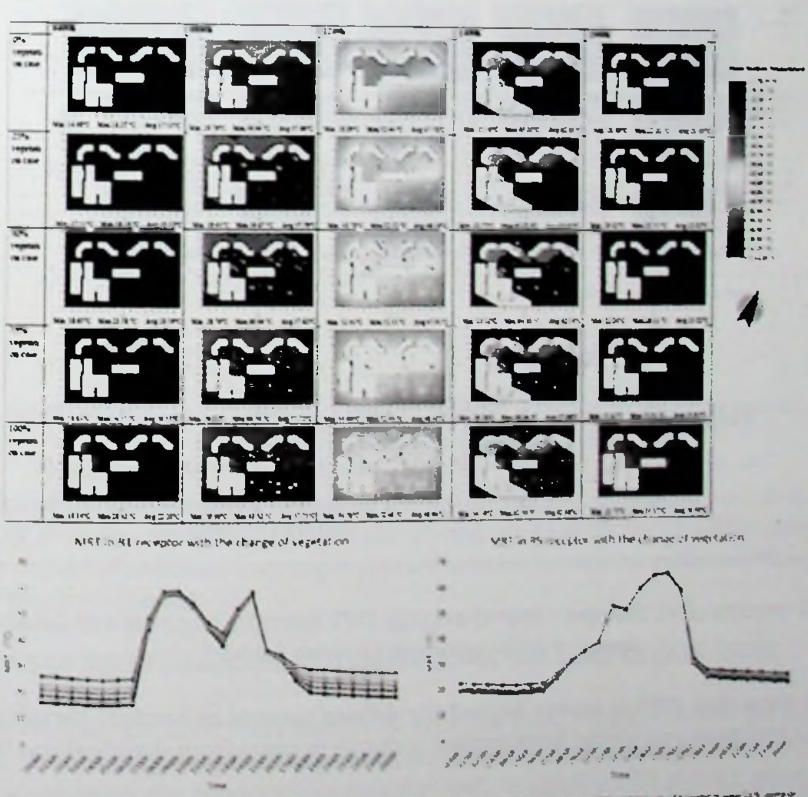


Figure 3, MRT impacts of VC changes – overall average MRT intensity mapping and detailed graphs at receptor point positions (Source: Author)

Results show, overall, an increase in the quantum of VC show minimum in MRT in the daytime hours. (See Figure 3). Yet, it is clear that the MRT change in different parts of the development significantly vary. The area where R1 and R2 are placed, an increase in vegetation shows significant warming in the night-time hours, while there are minimal changes in the daytime hours. The area is shown to be comparatively warmer. (See Figure 3). For all cases, the increase in VC creates a negative impact with a warming effect, rather than a cooling effect expected in utilising VC for mitigation.

Although the building morphology of the development can have an impact on the results, the form remains the same for all cases, therefore, the impact shown is deemed due to VC patterns.

The form of the development creates a distinct drop in MRT for R1 and R2. This is deemed to be caused by the shading effect of the high-rise towers. Similarly, R5 sees a slower warming rate, due to the shading of the morning sun.

4.2. VC CHANGE IMPACTS ON PREDICTED MEAN VOTE (PMV)

PMV and MRT are indices which are directly proportional. Typical PMV index indicator falls between -4 to +4 as defined by Fanger (1970). But ENVI-met (ENVI-met.info) cites that application of PMV for summer conditions in the outdoors in may easily produce values higher than +4, indicating higher heat stress. This study considered the hottest day of the year; therefore, it is seen that PMV values have exceeded defined limits.

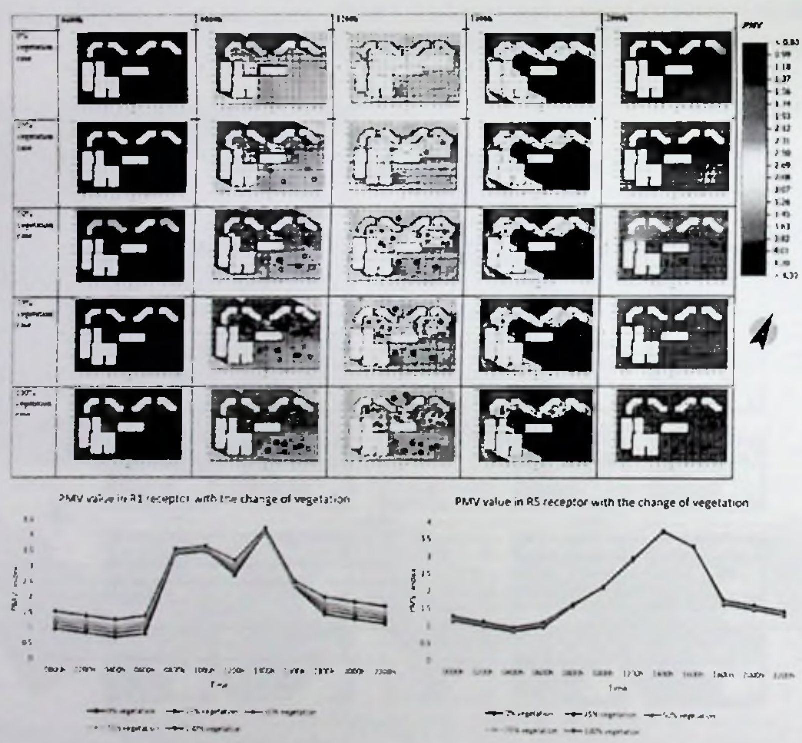


Figure 4, PMV impacts of VC changes – overall average PMV intensity mapping and detailed graphs at receptor point positions (Source: Author)

Results show that, PMV is always beyond the defined 'neutral or comfort' threshold value of '0', therefore the microclimate around the development is shown to range from slightly warm to hot.

As evident in the patterns highlighted under the impacts on MRT, PMV values increase with the increase of VC. The podium level of the development, denoted by R1 and R2 showed the highest level of heat discomfort in comparison. This phenomenon was intensified in the night-time hours. The North-West zone (R5) of the development was shown to be cooler at all times considered. (See Figure 4) Yet, even at the R5 receptor point, impact of increased VC seems to be negative on the surrounding conditions.

4.3. VC CHANGE IMPACTS ON WIND SPEED

In an attempt to ascertain the reasons for results that do not adhere to the excepted norm - where it is shown that an increase in VC can increase the level of OTC - the wind speed is mapped for comparative analysis.

Results show that the built morphology of the development creates a significant wind shadow in the area of the terrace garden (R1 and R2), while the Western (R4) and North-West zone (R5) experiences increased wind speed. The graphs show, with an increased quantum VC, the wind speed diminishes. This is more prominent at R1, where even when there is no VC (Case1) the wind speed is significantly lower.

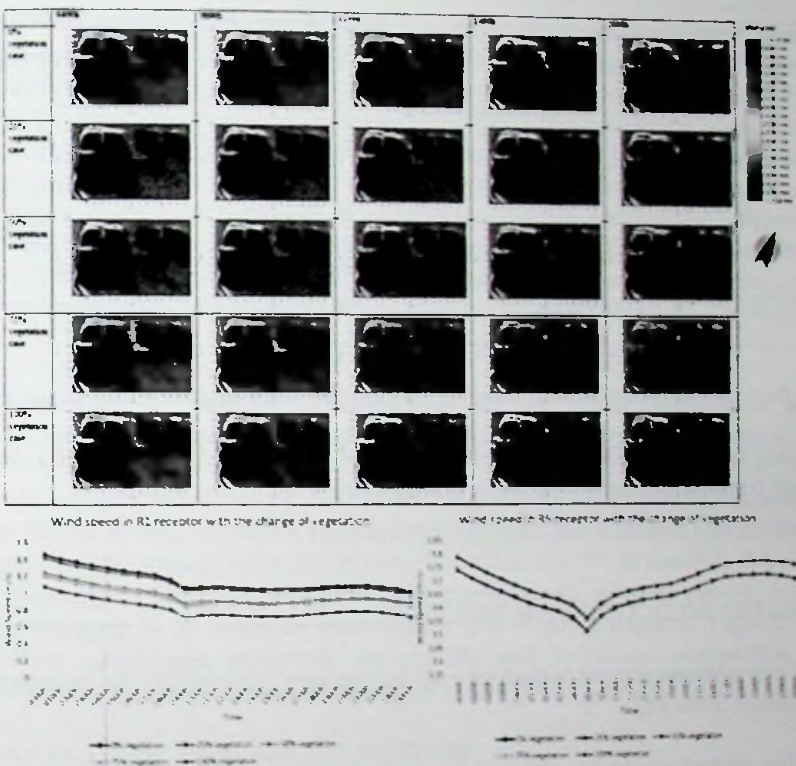


Figure 5, Wind speed impacts of VC changes – overall average wind speed mapping and detailed graphs at receptor point positions (Source: Author)

Wind speed comparison in the night-time shows that the area R1 experiences a drop, while R5 sees an increase. Thus, it can be concluded that with diminished wind speeds the radiation dissipation at night is curtailed. The impact of radiation trapping is deemed to increase with the enhanced VC, especially on the leeward side of the development.

4.4. DIFFERENCES OF RECEPTOR POINT READINGS WITHIN THE SAME VC CASE STUDY

The comparison analyses the differences seen in the receptor point readings around the development, for each case study. The receptors vary in their position according to the orientation within the model domain. They also vary according to the height of placement as seen in receptors R1 and R2, which are placed on the level of the roof terrace garden / podium level of Havelock City.

Analysis shows the variations in comparative receptor points have little or no influence from the changing VC. However, it is clearly seen that the built morphology, and the zones the high-rise blocks create around the development have distinct and significant impact.

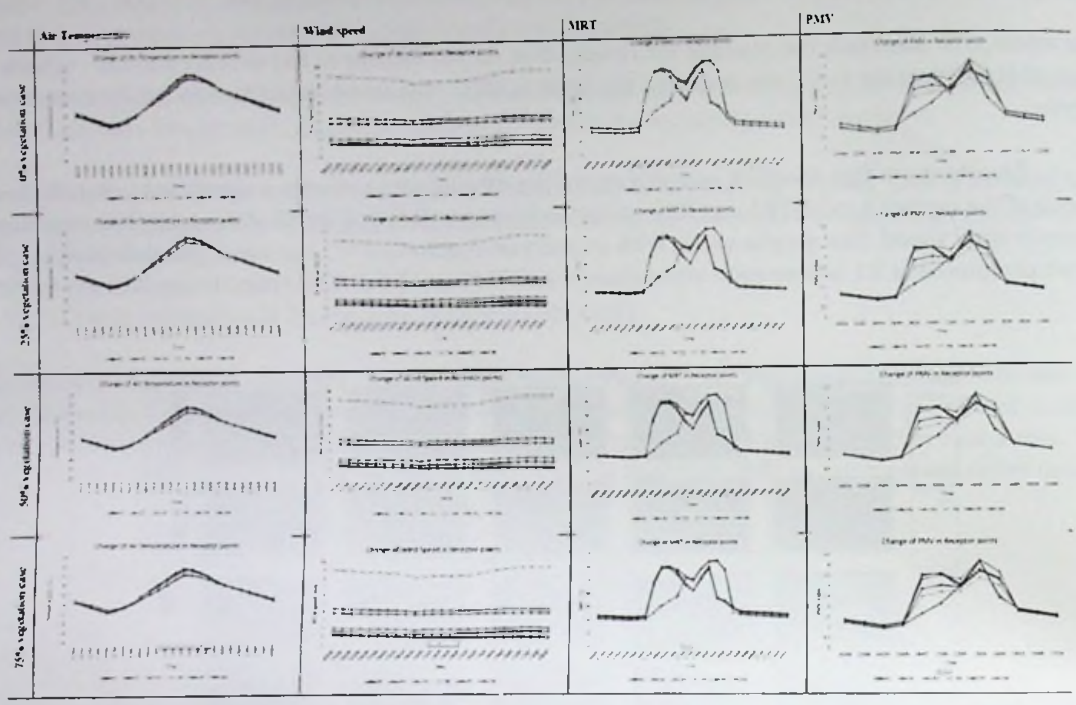


Figure 6, Differences of receptor point readings within the same VC case study (Source: Author)

The shading from the blocks at different times of the day, wind speed and wind shadow changes, and nocturnal heat trapping due to its overall form is evident.

5. Conclusions

5.1. KEY FINDINGS AND IMPLICATIONS FOR DESIGN

5.1.1 Vegetation Cover changes utilised in the high-rise development of Havelock City, have little no impact in the daytime hours of the day.

Vegetation cover on vertical and horizontal surfaces on the building envelop and around its development precinct is an accepted strategy for ameliorating local warming impacts and increasing thermal comfort in the outdoors. Yet, as seen in the study, the morphology and overall composition of the development have greater impact than increased VC. VC especially in the daytime hours are a means to increase the shading potential of the overall development. Given the scale of the high-rise development the overall VC and the quantum of shade provided for the outdoors is deemed insufficient, although the research explored maximum coverage of available areas. The strategy should be to shape and orient key morphological elements for shade. Shade for the building envelop as well as the urban precinct.

VC on the building envelop can have distinct advantages for indoor thermal comfort and reduced energy use. Therefore, the VC strategy can be deemed useful in other terms, even though it was not feasible for this particular case study.

5.1.2 The greatest impact of VC changes on OTC is seen in the night-time hours, albeit negative.

Radiation loss in the night-time is a key concern in urban climate studies and closely related to the sky-view-factor (SVF) of an urban area. This creates a dichotomy for designers, where low SVF values are encouraged during the day for shade and high SVF values are explored for night-time radiation loss. The challenge is to create a morphology that orient themselves for shade, increased wind movement and varied SVF values for heat loss. The role of VC is to create enhanced possibilities to avoid heat absorption by the building fabric, acting as second shading skins.

5.1.3 Factors such as built morphology, and therefore shading potential have significant impact. Yet, the shading impact of increased horizontal and vertical VC is seen to be negligible.

The morphology of the development demonstrates shaded zones that are comparatively cooler. Yet, the research shows the impact of VC is negligible. This research limits its scope to the outdoors: therefore, suggestions future development of this study needs to encompass the enhanced VC impacts on the indoor thermal comfort.

5.1.4 The correlation of wind speed around the development together with the increased VC have a negative impact on nocturnal OTC. Where, it is shown that, where wind speed is low the potential for those zones to lose heat is diminished, thereby creating warmer areas, than those that experience higher wind speeds.

The havelock city development with compact high-rise block composition is distinct. Further, the central sheltered podium space of the extensively planted roof terrace is unique. Research showed that although this is deemed a positive feature of the development, the space experiences an area of diminished wind speed, due to the wind shadow created by the high-rise blocks that surround the space. This in turn effects the heat loss potential of the zone. Wind movement potential and therefore enhanced wind speed, opportunities for pollution dispersal and anthropogenic heat dissipation become key concerns within large high-rise settlements. These aspects need to be addressed within the precinct itself, thus avoid impacts of these developments to affect the immediate microclimate and the areas they abut. VC cover can be deemed an advantage in this regard where they will work to reduce energy use and waste, and further, with selection of proper vegetation typologies, purify the air and provide potential for pollution trapping and dispersal.

5.1.5 Outdoor thermal comfort levels for all cases were found to be above the threshold values for human comfort. This was shown to be true for both the daytime hours and night-time hours of the specific day.

Urban precincts of warm humid, Colombo, Sri Lanka - a city effected by Urban Heat Island (UHI) impacts - are shown to be thermally uncomfortable. Perera, 2015; classifies the Havelock City development as Local Climate Zone One – LCZ1- compact high-rise. Perera shows that the UHI intensity in this classification, can be as much as 4k warmer. Since UHI is a night-time phenomenon, it needs serious consideration. The challenge of the designer is to minimise and mitigate the negative impacts. Vegetation in the urban environment offers advantages, especially for shading and increased evaporation potential. The quantification of these advantages is beyond the scope of this study.

5.2. LIMITATIONS AND DIRECTIONS FOR FUTURE STUDY

The aim of this paper is to quantify the effect of Vegetation Cover (VC) on outdoor thermal comfort (OTC). The scope of the study is limited to the immediate microclimatic context around high-rise developments, with a special emphasis on Havelock City, Colombo as a case study. The simulation-based study encompassed OTC impacts for a single day of the year. Key findings in the research showed little or no impact of VC on OTC; yet, impacts on the indoor thermal comfort and energy use can be expected. An expansion of the study to encompass indoor impacts are suggested. VC changes explored all typologies of VC defined in section 1 of this paper, a study that separates, each strategy can be taken on, to ascertain the degree of influence of each strategy, albeit as horizontal and vertical VC.

5.3. CONCLUSION

The study presented a research flow that encompasses mapping of the impacts of vegetation cover - both horizontal and vertical - on outdoor thermal comfort. This was carried out to better understand the possibilities to minimise the impacts of high-rise developments in the warm humid climatic context of Colombo, Sri Lanka. The research highlighted the fact that contrary to established knowledge on the influence of vegetation integration to ameliorate urban warming and enhance outdoor thermal comfort, vegetation cover had a little or no impact in the daytime, while the strategy had distinct negative impacts in the night-time. The findings underline the causative impact of high-rise typology as a contributor to urban heat island intensity.

Findings and implications for design highlight the need for the extensive exploration of morphological studies, while encompassing key amelioration strategies, for the high-rise building development typology, in particular. As, shown by Perera et. al (2013), by policy and planning, the development of Colombo is headed towards extensive high-rise developments, and thus does not bode well for the overall sustainability of the city. Thus, clear policy and planning decisions with climate sensitive strategies for overall and long-term sustainability needs to be incorporated in any development initiatives.

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