EVAPOTRANSPITATION MODEL TO EVALUATE THE COOLING POTENTIAL IN URBAN AREAS - A CASE STUDY IN SWITZERLAND

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ABSTRACT

An evapotranspiration model, based on the FAO Penman-Monteith method, taking into account the surface temperature, has been developed and implemented in the ground temperature model of the CitySim software. A case study was conducted in a district of Geneva, Switzerland, which consists of 704 buildings and 714 ground surfaces, to understand the influence of evapotranspiration on the ground surface temperature and water requirement for the irrigation of these areas at urban scale. The simulations were conducted to investigate the cooling potential of green areas in present and future climate scenarios. To handle the large quantity of inputs needed by CitySim and the large amount of results produced, a PostgreSQL database and QuantumGIS software have been used for this case study.

INTRODUCTION

The current observed rise in global air temperature will not only entail changes in weather patterns, it will also have a significant impact on human health (Epstein, 2005). One of the primary concerns is an increase in heat wave intensity, which has been associated with heat stroke, hyperthermia and an increased mortality rate (Stott et al., 2004). Increased air temperature is expected to be particularly problematic in urban areas, where temperature already tends to be higher than in surrounding rural areas due to a phenomenon called Urban Heat Island (UHI). This is due to the absorption of solar radiation by the built environment (buildings structures, roads, *etc.*) and the trapping of heat in urban canyons. Many studies have shown that the UHI effect also has a significant impact on building cooling systems (air-conditioning) and can put stress on the electrical power grid (Memon et al., 2009). Thus, there is an urgent need to evaluate strategies that can mitigate temperature increases due to UHI effect in urban areas and the associated negative impact on human health and energy consumption (Givoni, 1991).

Green areas have been proposed in many studies as a strategy to mitigate UHI effect. Urban green areas have a lower air temperature than surrounding city areas (Oke et al., 1991). A key process to explain this phenomenon is evapotranspiration, which is basically the loss of water from the plant or soil into the atmosphere. This is the combination of two separate processes: 1) evaporation 2) and transpiration. Evapotranspiration utilises primarily the energy from solar radiation. This leads to the evaporation of the water molecules from the surface of the plants. Further, the vapour pressure difference between the surrounding air and the plant surface, drives the movement of water vapours (Taha, 1999). This cooling effect can hence improve the climatic conditions in urban areas and reduces the environmental stress produced by urban heat islands (Hamada and Ohta, 2010).

The cooling effect of green areas on the surface temperature has been studied by many researchers in the past (Honjo and Takakura, 1990; Gómez et al., 2004). However, the actual extent of this cooling depends on many factors (type of vegetation, adjacent urban fabric, building geometry, irrigation pattern, *etc.*) (Chang et al., 2007). These factors need to be taken into account while planning the integration of green areas. Moreover, most of the studies have not considered the impact of surface temperature on evapotranspiration and use air temperature as the approximation of the surface temperature. This might not give a realistic picture as the energy fluxes, such as the longwave radiative heat flux, the convective heat flux, *etc.* used in the energy budget to determine the evapotranspiration depend on the surface temperature (Oke et al., 1991).

To address this issue, an evapotranspiration model has being developed based on the FAO Penman-Monteith method (FAO, 1990). This method has been considered as a universal standard to estimate evapotranspiration in crops (Labdzki and Kanecka-Geszke, 2011). It has been implemented in the ground model (Upadhyay et al., 2015) of the CitySim software, a simulation tool evaluating urban energy flows by integrating the thermal, radiation and behavioural aspects of urban energy use with an hourly timestep (Robinson, 2011). It should be noted that the amount of data required for a CitySim simulation at the urban scale is proportional to the number of buildings and ground surfaces involved, similarly for the results produced (Perez, 2014). To deal with this, we have used a PostgreSQL database which is an open-source database management systems for the data storage (Postgresql, 2015). In addition, GIS software QuantumGIS has been utilised to access, visualise and modify data in a PostgreSQL database, and to produce 2D map representations of any parameter linked with the scene geometry (QGIS, 2013). Their usage for urban energy simulation programs are very effective and have been demonstrated in few studies (Perez, 2014).

This paper first discusses the approach used in the evapotranspiration model. Then, a methodology has been presented to access and handle data for the simulation using PostgreSQL database and QauntumGIS software. A case study in a district in Geneva is further considered where the change in the ground surface temperature is analysed with and without green areas for two climatic scenarios (present Year 2015 and future Year 2030). The hourly weather files obtained from the Meteonorm software have been used for this analysis (Meteonorm, 2013). Finally, the results and the limitation of the models are outlined.

METHODOLOGY

In this section, we present the methodology that has been used to model the evapotranspiration using the FAO Penman-Monteith method and database used to perform the CitySim simulation for the case study.

Evapotranspiration heat flux (Q$_{et}$)

A reference plant surface has been used to determine the reference evapotranspiration. This reference surface is a hypothetical grass surface with an assumed height of 0.12 m. It is assumed to be well watered, of uniform height, actively grown, consisting of green grass and completely shading the ground. The evapotranspiration heat flux (Q_{et}) can be given as

$$Q_{et} = \gamma[e_s(T_s) - e(T_{air})] \tag{1}$$

where e_s is the saturated vapour pressure (Pa), T_s denotes the surface temperature (°C), e is the current vapour pressure (Pa), T_{air} is the ambient air temperature (°C), and γ (W Pa^{-1}) is given by EQUATION 2 (FAO, 1990):

$$\gamma = \frac{C \cdot \lambda \cdot S}{(T_{air} + 273.15)(1 + \frac{r_s}{r_a}) \cdot r_a} \tag{2}$$

where C is a constant which is equal to 7570 (K s mm^{-}1 m^{-1} Pa^{-1}), λ is the latent heat of vaporisation (W m^{-2} mm^{-1}), S is the surface area (m^2), r_s represents the plant surface resistance (s m^{-1}) and r_a denotes the aerodynamic resistance (s m^{-1}).

The transfer of heat and water vapour from the evaporating surface into the air above the canopy is determined by the aerodynamic resistance r_a as shown in EQUATION 3:

$$r_a = \frac{208}{u_2} \tag{3}$$

where u_2 represents the absolute value of the hourly wind speed at 2 m height (m s^{-1}).

Further, the plant surface resistance r_s is assumed to be 70 s m^{-1} which has has been shown to give a good estimation of the reference evapotranspiration (Jensen et al., 1990). Therefore, γ reduces to

$$\gamma = \frac{37 \cdot u_2 \cdot S}{(T_{air} + 273.15)(1 + 0.34u_2)}\lambda \tag{4}$$

where the hourly value of λ is equal to 694.5 (W m^{-2} mm^{-1}) which is the timestep for the CitySim simulation. λ has been assumed to be constant which is a good approximation for temperatures in the range of -20°C to 100°C (Fritschen and Gay, 1979).

In the FAO Penman-Monteith model, saturated vapour pressure $e_s(Ts)$ is calculated assuming that the surface temperature is approximately equal to the air temperature. This might introduce discrepancies when there is a significant difference between the surface temperature and the air temperature. Hence, we can use the surface temperature obtained from the former timestep T_s^{n-1} instead of the air temperature. The hypothesis made is that the surface temperature does not vary rapidly within the considered one hour timestep. Further, by using first-oder Taylor expansion around T_s^{n-1}, we can obtain

$$e_s(T_s^n) = e_s(T_s^{n-1}) + \Delta \cdot (T_s^n - T_s^{n-1}) \tag{5}$$

where n is the timestep, Δ represents the slope of the saturation vapour pressure curve evaluated at T_s^{n-1}, which can be obtained using the following approximation (Murray, 1967):

$$\Delta \approx \frac{4097.73 \cdot \left(0.61078 \exp\left(\frac{17.27.T_s^{n-1}}{T_s^{n-1}+237.3}\right)\right)}{(T_s^{n-1} + 237.3)^2}. \tag{6}$$

Furthermore, the vapour pressure difference can be expressed in terms of relative humidity as shown in EQUATION 7:

$$e(T_{air}) = e_s(T_{air}) \cdot \frac{RH}{100} \tag{7}$$

where, RH is relative humidity (%).
Finally, the evapotranspiration heat flux Q_{et} is reduced to

$$Q_{et} = \gamma\left(e_s(T_s^{n-1}) + \Delta \cdot T_s - \Delta \cdot T_s^{n-1} - e_s(T_{air})\frac{RH}{100}\right). \quad (8)$$

A crop coefficient factor (K_c) can be introduced, based on the database provided by the Food and Agriculture Organisation (FAO, 1990), to account for different types of plants and soil water conditions by multiplying Q_{et} with it. Furthermore, FAO Penman-Monteith method assumes weather parameters measured (wind speed, air temperature and relative humidity) at 2 m above the surface under consideration. However, the weather data used in the CitySim software, is obtained from the Meteonorm software which are measured at 10 m above the ground surface.

Database management systems (DBMS)

The PostgreSQL database consists of various tables each containing objects such as buildings, grounds, wall types, materials *etc.* These tables contain essential information for creating an input file for the simulation. Building and ground footprints were added in the database using cadastral maps, which is a 2D representation. This information was completed with the ground type (asphalt, concrete and grass) for the ground table and construction date, average height *etc.* for the building table in the database. For each building, a 2D geometrical footprint is used to develop a 2.5D representation based on the altitude and average height of each building. Furthermore, the common surfaces among the buildings are considered adiabatic as the thermal losses or gains are usually negligible between attached buildings. Each building surface (wall, roof or floor) is then described by a construction type, a glazing ratio and physical properties, as well as albedo.

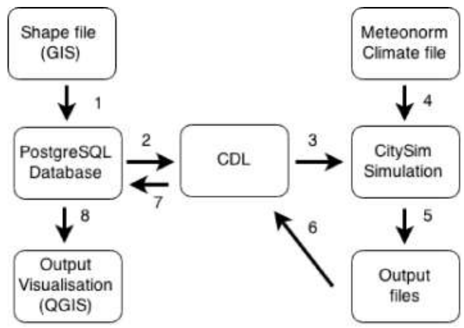

Figure 1: Methodology used for simulation with CitySim using Shape file from geographical information systems (GIS).

There are many advantages to DBMS: 1) disparate original source files, shape files (shape files for maps) can be loaded as temporary databases in form of simple tables, 2) a data model can be used as a link between the specific input file of CitySim and the main data source and 3) SQL and spatial functions can be used to combine the different data sources, based on the common identifiers such as the building ID or the spatial location.

A script based on JAVA programming language, which called CDL (CitySim Database Linker), has been written to retrieve data stored in the database and to create the input file for CitySim and runs the simulation. This program is again used to insert the output results obtained from the simulation into the database. Further, QuantumGIS software can be used to visualise or modify data in the database. Figure 1 summarises the execution sequence to get a CitySim simulation based on the information retrieved from the database and visualise the output (Upadhyay et al., 2014).

CitySim uses 2.5D information of the buildings for the simulation and outputs, such as surface temperature, are created for all the vertical (walls) and horizontal (roof and ground) surfaces. Whereas, QuantumGIS can display only 2D horizontal surfaces. To handle this issue, the surface temperature of the building is calculated by taking an average over its walls and roof surface temperature which can have a 2D representation. This procedure was followed for all the buildings in the scene to visualise the results from CitySim using QuantumGIS.

CASE STUDY

A case study was performed on the Pâquis district in Geneva (see Figure 2), to determine the effect of evapotranspiration cooling to mitigate UHIs. The studied area consists of 704 buildings and 714 ground surfaces. The geometrical footprint of the surfaces and the buildings were obtained from a SITG database (SITG, 2015). Further, SITG database has been used to complete the information required for the CitySim simulation such as the surface type of the ground and the average height, altitude, construction period *etc.* of the buildings.

The buildings were assumed to be constructed using the following materials: render, rubble masonry, air gap, hollow clay brick and plaster. Their thermo-physical properties are given in Table 1. The U-value of the building façade is 1.35 (W m^{-2} K^{-1}). The ground surface types were broadly categorised into three: asphalted, grass and concrete as shown in Figure 2(b).

Asphalted roads were modelled as asphalt, sand and gravel; concrete surface as concrete, sand and gravel; green surfaces as clay, loam and sand. Molasse has been used as the foundation soil for Geneva (Graf and Frei, 2013). The thermo-physical properties of the different ground layers are presented in Table 2.

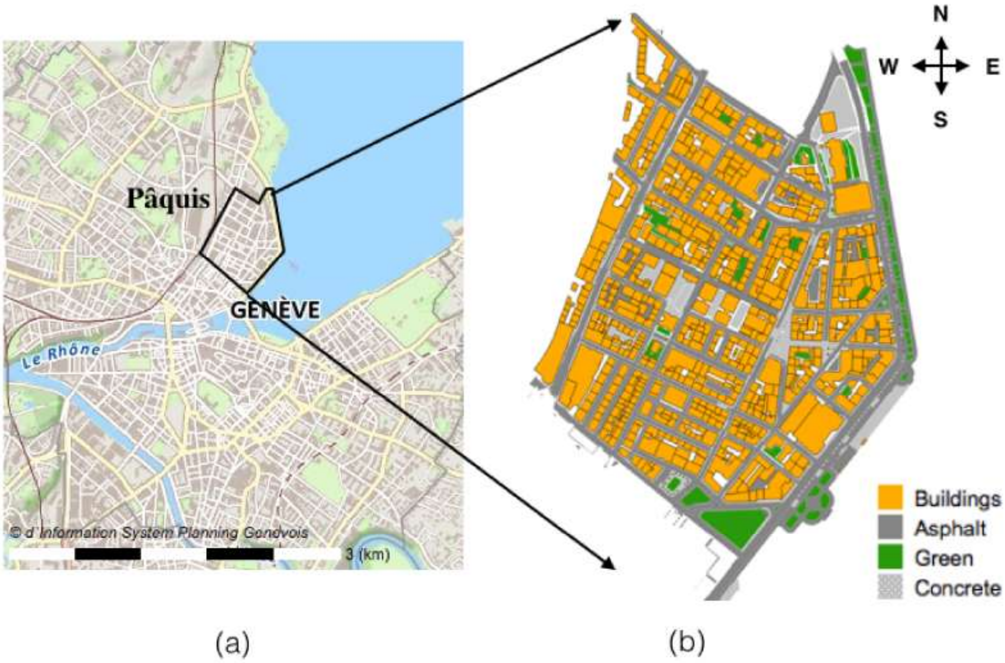

Figure 2: Geneva case study (a) Satellite image from SITG website (SITG, 2015) (b) 2D representation of the model used for the simulation (QGIS, 2013).

Table 1: Building construction material properties (Perez, 2014).

Material	**Conductivity ($W\ m^{-1}\ K^{-1}$)**	**Specific heat ($J\ kg^{-1}\ K^{-1}$)**	**Density ($kg\ m^{-3}$)**	**Thickness (m)**	**# layer**
Render	0.87	1100	1800	0.02	1
Rubble masonry	0.81	1045	1600	0.22	2
Air gap	0.33	1005	1.2	0.06	3
Hollow clay brick	0.80	900	1600	0.06	4
Plaster	0.43	1000	1200	0.01	5

Table 2: Asphalted, concrete and green surface material properties (Concepto, 2010).

Ground	**Material**	**Conductivity ($W\ m^{-1}\ K^{-1}$)**	**Specific heat ($J\ kg^{-1}\ K^{-1}$)**	**Density ($kg\ m^{-3}$)**	**Thickness (m)**	**Layer #**
Asphalted surface	Asphalt	0.75	920	2360	0.025	1
	Sand	0.5	828	1300	0.05	2
	Gravel	0.7	792	1800	0.05	3
	Molasse	2.4	1200	1600	0.875	4
Concrete surface	Concrete	0.8	1200	2400	0.025	1
	Sand	0.5	828	1300	0.05	2
	Gravel	0.7	792	1800	0.05	3
	Molasse	2.4	1200	1600	0.875	4
Grass surface	Clay	0.97	920	1760	0.025	1
	Loam	1.4	864	1800	0.05	2
	Sand	0.5	828	1300	0.05	3
	Molasse	2.4	1200	1600	0.875	4

Furthermore, an albedo of 0.4, 0.14, 0.23 and 0.21 respectively for buildings, asphalted, concrete and green surfaces (Levinson and Akbari, 2002) were assumed to calculate the shortwave irradiation absorbed by the surface. Due to the large number of ground surfaces, the simulations were performed using the lumped ground model of the CitySim software which is computationally faster (Upadhyay et al., 2015).

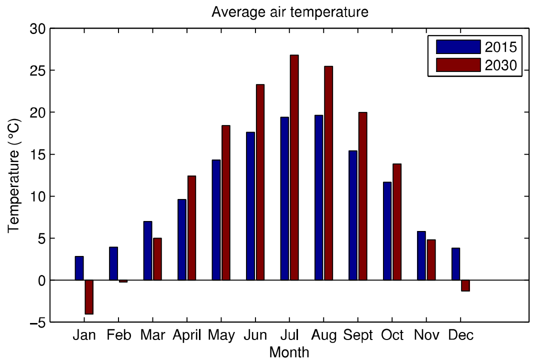

Figure 3: Monthly average air temperature in the year 2015 and 2030.

In order to analyse the potential effect of evapotranspiration cooling on the surface temperature, two scenarios have been considered, the present climate (Year 2015) and a projected climate (Year 2030) for Geneva. The hourly weather data for these two scenarios were produced using the Meteonorm software (Meteonorm, 2013) and used as the input for the CitySim software. The monthly average air temperature of the two scenarios is shown in Figure 3. It can be seen that in Year 2030 there is an average increase of 1.11°C and during the summer period (June, July and August) the average increase is much higher (6.2°C) compared to Year 2015.

Two cases were considered for each scenarios where one simulation run conducted using the original ground surfaces obtained from SITG database and the second was performed by assuming that the asphalted and concrete ground surfaces were covered with grass. This was performed to analyse the maximum cooling potential due to evapotranspiration. This might not be true in reality as all the ground surfaces (asphalted and concrete ground) will not be transformed into green area. The building roofs could be a potential solution to increase the green surface area at an urban scale, however the evapotranspiration model is not yet implemented for the building roofs in the CitySim software.

Further, a hot day in the year 2030, with an average air temperature of 32.2°C, was chosen to illustrate the decrease in ground surface temperature using grass and the water requirement associated with it. As an UHI indicator, average surface temperature (AST) has been used for the cases presented above:

$$AST = \frac{\sum_{i=1}^{n} S_i \cdot T_{si}}{\sum_{i=1}^{n} S_i} \qquad (9)$$

where i represents the surface, S_i is the area of that surface (m^2) and T_{si} denotes surface temperature (K).

RESULTS

In this section, the results are presented for the simulations mentioned above.

The annual average surface temperature distribution for the two scenarios with the original ground surfaces and with all grass surfaces are shown in Figure 4.

It can be seen that there is a significant decrease in the surface temperature when using evapotranspirative cooling, especially for the scenario 2030 where the ambient air temperature is projected to be higher than in 2015. There is an annual decrease of 1.8°C and 2.4°C respectively for 2015 and 2030 as shown in Figure 5. Moreover, the cooling effect due to evapotranspiration is more prominent during the summer months as there is a decrease of 2.6°C and 3.7°C respectively in 2015 and 2030 scenarios (see Figure 6).

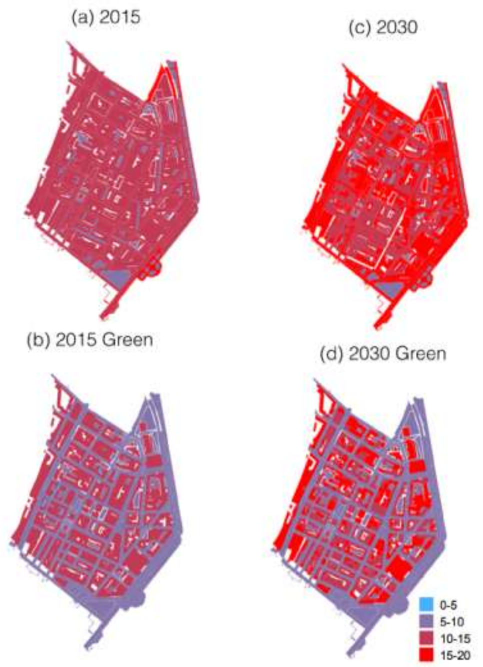

Figure 4: Annual AST distribution a) 2015 with original surfaces b) 2015 with all green surfaces c) 2030 with original surfaces d) 2030 with all green surfaces.

Additionally, the surface temperature profile of the scene on a hot day in the year 2030 scenario is shown in Figure 7. The decrease in the surface temperature is higher during daytime compared to the night. It can be observed that the average ground surface temperature is halved in the case of surface with grass compared to the original surfaces. For example, during day time when the air temperature is 38°C (around 1 pm), the average surface temperature of the scene is around 59°C. When using grass, the average temperature is decreased to 29°C: this is a significant cooling effect due to evapotranspiration. Further, the water requirement distribution on this day is presented in Figure 8 (a). It can be seen that the net water requirement is 146 m^3 for the irrigation (Figure 8 (b)). Moreover, there is a rapid increase in water demand during the day time, for example, 40 m^3 h^{-1} from 9 am to 10 am.

DISCUSSION AND CONCLUSION

An evapotranspiration model based on the FAO Penman-Monteith method has been developed. This model has been integrated in the ground model of the CitySim software which uses a surface energy balance to calculate the ground surface temperature on an hourly timestep at urban scale. This new model considers the impact of surface temperature on the evapotranspiration phenomenon which is an improvement compared to other existing models. CitySim can now predict the surface temperature over a green area and also the water requirement for irrigation, thus improving its functionality.

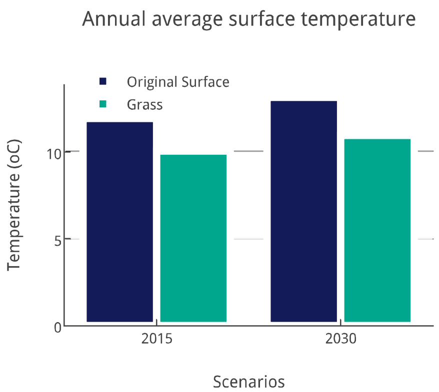

Figure 5: Annual average temperature for the Years 2015 and 2030.

The evapotranspiration model assumes a well watered reference grass surface of height 0.12 m with fixed surface resistance of 70 s m^{-1}. A crop factor given by FAO can be used to take into account the various factors such as water conditions, soil condition, plant type, *etc.* in the reference evapotranspiration. It should be noted that this model assumes all the plants (trees, bushes, *etc.*) to act as grass surface hence ignoring the cooling due to the shadowing effect. The weather parameters (air temperature, wind speed and relative humidity) have been assumed to be measured at 2 m above the surface for FAO Penman-Monteith method. However, most of the building energy simulation softwares including CitySim uses climatic data from the weather softwares as the boundary condition, which might not be measured at 2 m. It is considered that an average weather behaviour is being experienced by all the surfaces in the scene (Clarke, 2001). Further, an average surface temperature was introduced as an indicator of UHI.

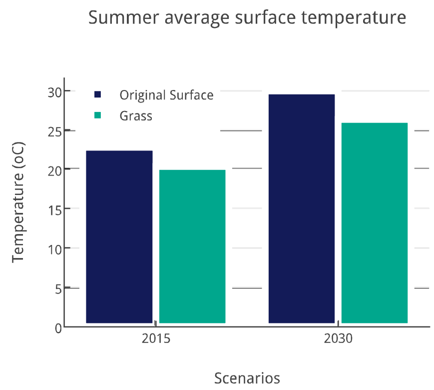

Figure 6: Summer period (June, July and August) average surface temperature for the Years 2015 and 2030.

A PostgreSQL database has been used to store the buildings and ground surfaces data. This is used to create an input file for the CitySim software and also to stores output data from the simulation. The output has been visualised using the QuantumGIS software.

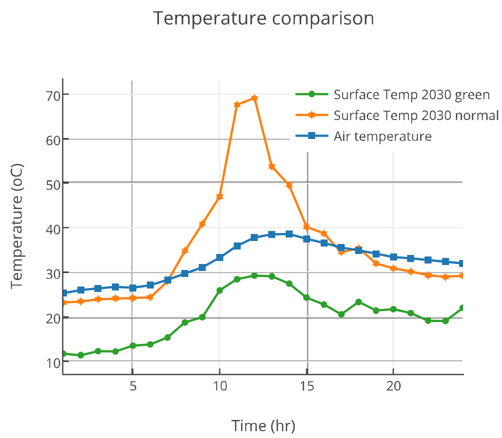

Figure 7: Ground surface temperature on a hot day in the Year 2030

A case study was performed on the Pâquis district in Geneva, which is considered to be the city centre where the buildings density is comparatively higher. Two climatic scenarios, present (2015) and future (2030), were considered to analyse the cooling potential due to evapotranspiration. In the first case, the surface temperature was determined considering original ground surfaces. The second case was simulated assuming the entire ground surface to be green to increase the green area coverage. The latter thus represents the maximum cooling potential due to green areas. However, it should be noted that the green roofs will be implemented in future to increase the available green surface area at an urban scale.

One hot day was chosen in the Year 2030 to illustrate the water requirement for the green area. It was observed that by evapotranspiration, the average surface temperature could be halved. During day time, evapotranspiration effect on the surface temperature is higher compared to night which shows its strong dependence on shortwave radiation incident on the surface. It should be highlighted that the shortwave radiation on the surface is influenced by the surface geometry and shadowing effect from the neighbouring buildings (Hopkins and Goodwin, 2011). This confirms that the geometry of the neighbouring buildings have an impact on evapotranspiration effect. Furthermore, the evapotranspiration phenomenon modifies the microclimate around the buildings by changing the air temperature and relative humidity above the green surface area. The microclimate is required for the calculation of thermal comfort for the pedestrians (Fanger, 1970) and also the building energy consumption (Oke et al., 1991). Presently, the microclimate has not been considered in this model.

Further, the hourly water requirement for the irrigation on this day was analysed. It was observed that the outskirt areas requires more water that the interior. The net water requirement on this day was 2000 m^3 for the entire ground surface which has a total area of 0.8 km^2. This is equivalent to the daily household water consumption for 20,000 person (0.1 m^3 per capita per day) (Howard, 2003). For a city such as Geneva, which is located on a lake shore (Lac Léman), this water requirement might be feasible but for cities with water issues (Fuso Nerinia et al., 2015), this could be challenging as the rapid increase in the water demand during the hot periods can be extremely difficult to handle (2-3 L human drinking water requirement). This should indicate to city planners that the water requirement, can play an important role in the design and logistics (such as water scheduling and costs) when considering ground surface cooling strategy. One solution could be the rain water harvesting in the region. The tank sizing for this purpose could be determined based on the water requirement for the irrigation of the green areas calculated by the model and the precipitation expected using the weather file.

This study confirmed that evapotranspiration has a strong cooling potential to act as a moderator for UHI. Further, it demonstrate the application of DBMS for handling a large amount of data required for urban simulation using buildings and ground surfaces. The methodology employed in the work, can be used by city planners, stakeholders and architects to analyse the impact of green areas and the water requirement for the irrigation of these areas in the city in order to mitigate UHI.

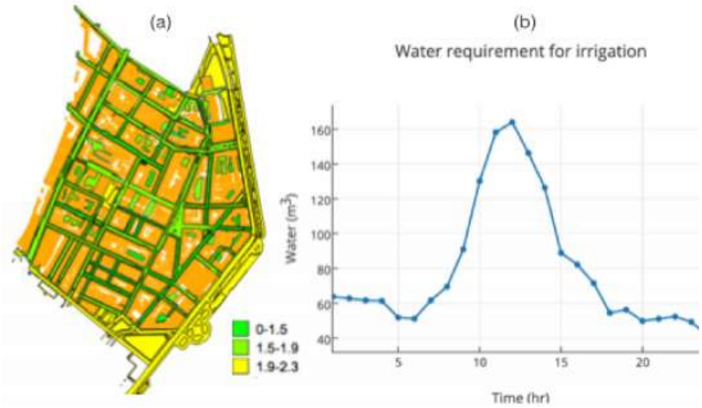

Figure 8: (a) Water requirement distribution (m^3) (b) net water requirement for the irrigation on a hot day in the year 2030.

NOMENCLATURE

Q_{et}	= evapotransipration (W)
T_s	= surface temperature (°C)
T_{air}	= ambient air temperature (°C)
RH	= relative humidity (%)
u_2	= wind speed measured at 2 m (m s^{-1})
e_s	= saturated vapour pressure (Pa)
e	= actual vapour pressure (Pa)
r_s	= plant surface resistance for the water (s m^{-1})
r_a	= bulk surface aerodynamic resistance for water vapour (s m^{-1})
λ	= conductivity (W m^{-1} K^{-1})
S	= area (m^2)

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