Mexico City adaptation: water- and energy-creating microclimates

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Abstract

The history of Mexico City is bound to water. The city was founded within a lacustrine environment. But the alterations made by humans transformed a basin rich in water into a water scarce one, causing an imbalance in its radiant energy system and its water cycle. For this research, the analysis is based on the lakes desiccation as a crucial factor prompting the warming in the basin of Mexico, along with the urban growth. Based on that precondition this research investigates: If the original water and energy elements of the Valley of Mexico could be partially restored by the creation of microclimates, then the water cycle and the energy balance in the urban environment would stabilize. The possibilities will be explored through the analysis of the reintroduction of water elements in the urban environment of Mexico City, which seek to demonstrate three key factors. First the essential function of water as a thermostat and driver of human thermal comfort. Second the water as the basis of the natural radiant energy cycle restoring the growth of vegetation and biodiversity in the basin. Third its function as a stabilizer and generator of urban energy balance processes and vice versa, of radiant energy as the engine to achieve fundamental phases of the water cycle. Its complementary character will be strengthened by the proposal of design strategies that lead into a water and energy balance in Mexico City through the creation of microclimates for an effective adaptation to the environment and the climate changes caused by global warming.

Keywords: water and energy, sustainable city, microclimate, city adaptation.

WIT Transactions on Ecology and The Environment, Vol 191, © 2014 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SC141022

1 Introduction

The Aztec capital was founded within a lake system. However, through history the basin of Mexico was transformed from a basin rich in water into an area with scarce water resources. This change began through the artificial desiccation of the lake system as a flood control measure, which caused an imbalance in its water cycle and its radiant energy system. As Mexico City is located in a basin, rainwater flows from the mountains into its base. Nowadays, to prevent flooding, the rainwater is mixed with blackwater that runs through the sewers and the former rivers, to be discarded without adequate treatment from the basin. This system represents a latent flood risk, as in strong rain events the system may overflow. Freshwater is extracted from the underlying aquifers. But with the large sealed surface, only a very small proportion of water returns to this main supply. As a consequence, the city subsides at varying rates and its infrastructure gets damaged, causing leakages in the water supply. Additional water is imported with a high-energy consumption, mainly by the Cutzamala system, which overcomes 1,000 meters of altitude (CONAGUA [1]).

In addition to the water imbalance, the city suffers from an energy imbalance. Its temperature rises over the thermal comfort, forcing the use of air-conditioning systems. The warming of the large urban surfaces modifies the wind patterns, reducing the ventilation and contributing to the pollutant concentration near the surface, which promote warming at the same time. With global warming, the risks presented today might be intensified in future years. Of particular concern for Mexico City is the increase in frequency and intensity of rainshowers, which worsens its innate flood risk due to its endorheic basin condition. In contrast, there is as well an increase in temperature and heat waves (León Diez [2]). This research proposes that: If the original water and energy elements of the Valley of Mexico could be partially restored by the creation of microclimates, then the water cycle and the energy balance in the urban environment would stabilize and lead the path into a water and energy sustainable city.

2 Methodology

This research seeks to analyse the effect that the reintroduction of water elements might have on the radiation and urban energy balance of Mexico City's microclimate. The feasibility is explored through the quantitative analysis of rainwater management strategies, based on the German standards of the DWA [3]. The proposed strategies will respond to the conditions, threats and opportunities of three sites that represent different zones of Mexico City. Each of the sites will be analysed in regard to its water balance and energy conditions, comparing its current status to the changes achieved with the applied strategies. The overall water balance is calculated with STORM.WB software [4].

Data from Mexico's National Meteorological Service (SMN) [5, 6], Climate Consultant [7], and Meteonorm [8] was inserted in ENVI-met [9] and Rayman [10] to develop simulations of the three sites. The energy conditions are compared through the results of these simulations, including: mean radiant temperature

(T_{mrt}), human thermal comfort and potential temperature. T_{mrt} figures synthesize the site's radiation fluxes, which, in addition with potential temperature figures, serve to depict the variation in the microclimate with the presence of water. Additionally, two thermophysiological significant indexes of human thermal comfort are observed: the Physiological Equivalent Temperature (PET) and the Predicted Mean Vote (PMV). These indicate the level of physiological stress and thermal perception by humans (Matzarakis *et al.* [11]). Both consider the human energy balance, determined by the climate conditions, the clothing thermal resistance and the internal heat production. Among the climate conditions considered: the T_{mrt}, the air temperature, the relative humidity, and the wind speed. The clothing thermal resistance considered is of 0.8 Cloths, for a person wearing a suit but adapted to the summer temperatures without a jacket. The internal heat production for the simulations is of 167W for a person walking and performing light-work activities or shopping (Matzarakis *et al.* [11]). The height was set to 0.8m to approach a biometeorological significant height (centre of gravity) of a person in Mexico.

3 Water and energy framework

The past, present, and a future scenario of Mexico City's precipitation and temperature is depicted (fig. 1). As the local effects of global warming are uncertain, the IPCC [12] A1B scenario is used here only as an example to illustrate a possible future scenario for 2050. These figures result from the interpolation of data gathered by Meteonorm [8] software from the monitoring stations of Tacubaya Central, the National University (CU) and the Meteorological System Coordination. The energy consumption of the water systems in Mexico City is based on the data of the Mario Molina Center [13], the air conditioning and lighting consumption data is based on Kerdan [14].

Comparing the period 2000–2009 with the 1961–1990, it could be observed that the months with the highest precipitation are: June with 66% more precipitation, and September with an increase of a 100%. Still, September's precipitation is distributed in more days. It was concluded that June is the month that represents a constant risk for Mexico City during the three periods analysed, as it presents a higher precipitation in a shorter time period. That is why June has been selected for this analysis. Yet, tendencies indicate that the number of rainshowers will continue to increase (León Diez [2]). These strong rain events represent a high risk, as large volumes of water should be managed quickly. Therefore, the second factor is the quantity received in a single rain event. The information from the National Meteorological Service [5], as well as the Meteonorm data, registered June's highest average precipitation in the period 2000–2009. From the hourly data of Tacubaya weather station SMN [15], June 27th 2002 reported the highest rain event with 32.6mm in one hour. Due to the unavailability of 5-minute measurements, an assumption of a 5-minute-intensity scenario for one hour was developed (fig. 1). The highest risk resulted from the 15-minute rain event, as it allots a larger volume (17mm) in a short period of time. For this reason, it is the basis for the quantitative analysis.

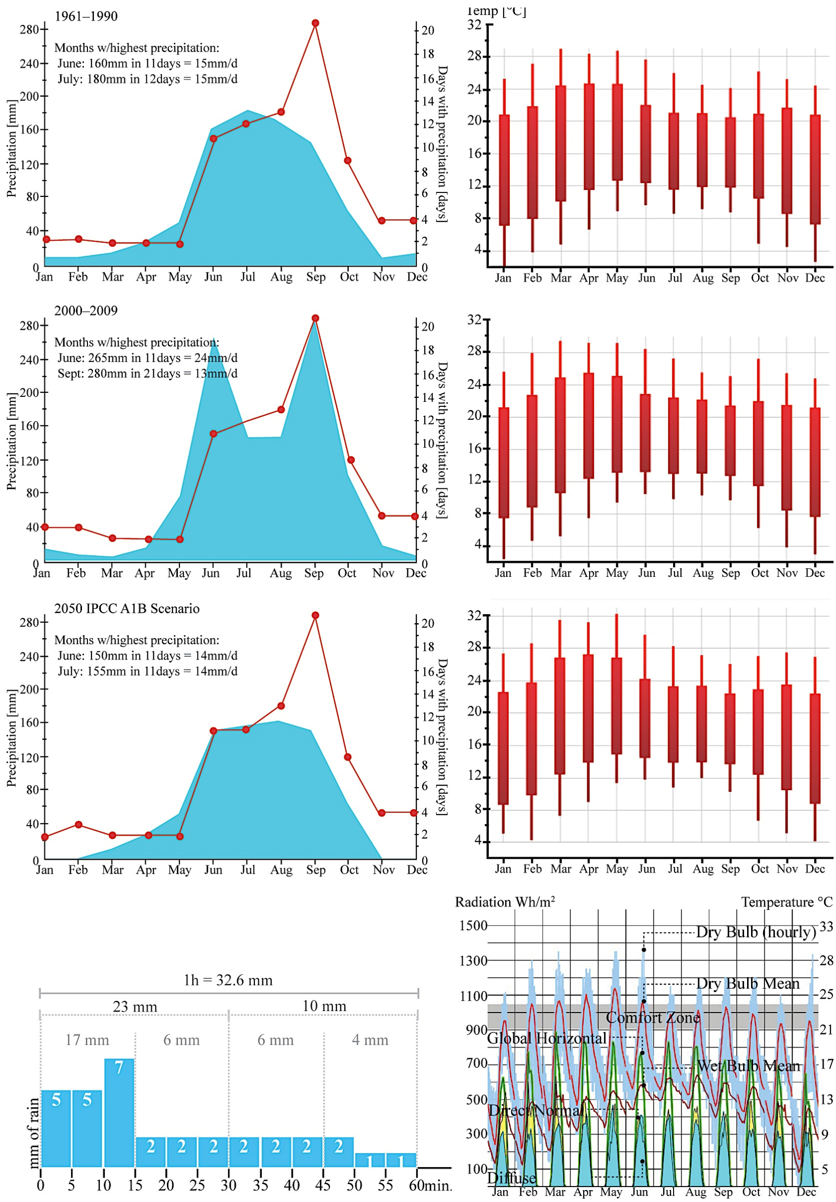

Figure 1: Precipitation (left) and temperature (right): 1961–1990, 2000–2009, and 2050 IPCC A1B scenario (Meteonorm [8]). Precipitation 5-minute intensity distribution in one hour (below left). Temperature hourly average (below right) (Climate Consultant [7]).

When comparing the temperature of the period 1961–1990 with the 2000–2009, an increase of 0.5K is noted. Even though the temperatures could rise under a global warming scenario, the magnitude is uncertain. Nevertheless, the highest risk for Mexico City is not the average temperature, but rather the daily peak temperatures. Currently, peak temperatures occur between 14:00 and 16:00 hours during winter, and from 12:00 to 18:00 hours during the rest of the year, surpassing the comfort zone for Mexico City. In comparison, the wet bulb temperature is considerably lower and its behaviour shows smaller amplitude than the dry bulb temperature, fig. 1. Based on this framework it is suggested that the presence of water could stabilize the urban thermal conditions of Mexico City. To prove this, the simulations were made first with the current conditions only with the urban structures, then with the presence of trees and finally with the introduction of water features in three different urban settings.

4 Results

4.1 Site 1. Historical City Centre

Directly in the City Centre the meteorological station of Tacuba 7 SMN [5] reported a yearly average precipitation of 930mm, which is used to estimate a yearly average water balance (fig. 2). The evaporation mode for this site is 2.9mm/day SMN [6], which represents ca. 18% of a 15-minute rain event of 17mm. The City Centre is located in the lacustrine geologic zone, which is non-permeable. As it is a historical ground, deep excavations are inadvisable. These conditions give the possibility of using an open-air collection system.

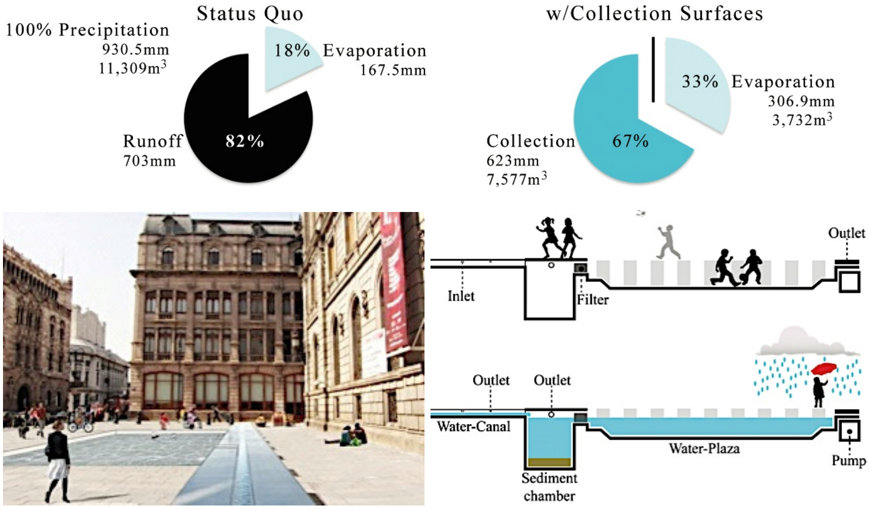

Figure 2: City centre year water balance and Water-Plaza view (based on [16]).

Based on the DWA guidelines [3], a volume (V) of:

$$V=\left[(A_u)\cdot 10^{-7}\cdot r_{D(n)}\right]\cdot D\cdot 60\cdot f_z \tag{1}$$

220m^3, eqn (1), could be collected from a block-unit of 12,000m^2, after a 15-minute rain event (D) for June of ($r_{D(n)}$) 188 l/(s*ha). Where A_u is the result of this area considering its surface runoff coefficient Ψ. As urban canyons, impervious surfaces and scarce vegetation characterize this first site; a runoff coefficient Ψ of 0.9 is considered. f_z is an additional factor of 1.2.

In a status quo, 763mm of rainwater is lost on average every year in the sewers. Instead, the rainwater could be collected through Water-Canals in the streets that discharge into open-air storages in strong rain events. Its storage would allow recirculating it through the Water-Canals for several days, until the complete volume is evaporated, used or evacuated to larger waterbodies. These storages could be installed in open spaces, to revitalize them into Pocket-Rain-Parks and Pocket-Water-Plazas (based on De Urbanisten [16] design). These spaces could hold activities when they are dry, such as sports facilities, children games, art, etc. As the collected rainwater will be kept in an open-air system, a higher evaporation may occur especially during peak temperatures. Considering 33% evaporation (STORM.WB [4]) from the collected volume (V), would reduce the final volume obtained from 1 block-unit to 147m^3 after a 15-minute rain event. A higher runoff may occur in sporadic storms that surpass the storage capacity of this system. In such events, the water surplus would be safely redirected to the sewers trough emergency outlets. Nevertheless, this system would enhance the regulation of the volumes evacuated through the sewers, reducing its pressure and the probability/severity of floods. If this system is applied in the entire lacustrine area, which accounts for 23.94% of Mexico City's surface, 199million-m^3 rainwater could be collected yearly.

To evaluate the microclimate changes with such a system, the average of the maximum and minimum results from the ENVI-met simulation is depicted in fig. 3 for Madero St., an east–west urban canyon. The simulation model has a spatial resolution of 13 ha, clear sky conditions, and a temporal resolution of 24 hours. First, the effect of trees following the current arrangement was evaluated, already grown by 2050. A slight reduction in the mean radiant temperature, as well as in the PMV and PET, could be noticed. Yet, the reductions with trees are limited to the canopy area of influence. The rest of the urban canyon behaves in the same form as in the current conditions without trees. To achieve a significant reduction the trees should be densely distributed at both sides along this iconic pedestrian street, obstructing the view to the historical buildings.

With the insertion of water in the City Centre streets, the heat energy transferal between the urban structures and the atmosphere is reduced and sped up. The presence of a higher latent heat flux indicate that the paved areas that were substituted with water features would use the solar radiation as energy to evaporate water, instead of storing it as heat. This would humidify the dry environment of the City Centre, and prompt an evaporative cooling effect. This allows a reduction of the grade of physiological stress from a strong heat stress to a moderate one during a clear-sky summer day in June (fig. 3). A direct comparison was made between the potential temperature in the current conditions and with the introduction of water canals in the streets of the City Centre. In table 1 a comparison of the prevailing temperatures in Madero Street canyon is shown. It can be observed that from 12:00 to 16:00 hours there is a reduction of 2K and at 18:00 hours this becomes 1.5K. Overall, the peak temperatures are reduced, making the temperature and radiation more stable. Additionally, the water presence in the simulated model shows a faster cooling of the urban canyon during the first evening hours. In contrast, typical impervious urban surfaces store so much heat that they keep on radiating it after sunset. With an open air Water-Canal + Pocket-Rain-Park/Water-Plaza systems, the rainwater could be reintegrated into the water cycle, the flood risk would be controlled and the microclimate enhanced. At the same time this would allow a reduction of the Urban Heat Island effect. The reduction in temperatures and enhancement of the human thermal comfort could be translated into savings in the energy consumption by air-conditioning systems. In Mexico City these systems are only used during the daily peak temperatures. Dietrich [17] estimates, for an optimized-energy-building, 10% savings per degree reduced. For the City Centre this would mean that if 2K are reduced from the peak temperatures an approximate reduction of 20% in the energy demand by air-conditioning could be achieved. For the City Centre this is translated in a yearly reduction of 4kWh/m^2 in offices, 14.64kWh/m^2 in commercial uses, 9.5kWh/m^2 in restaurants, and 24.4kWh/m^2 in hotels.

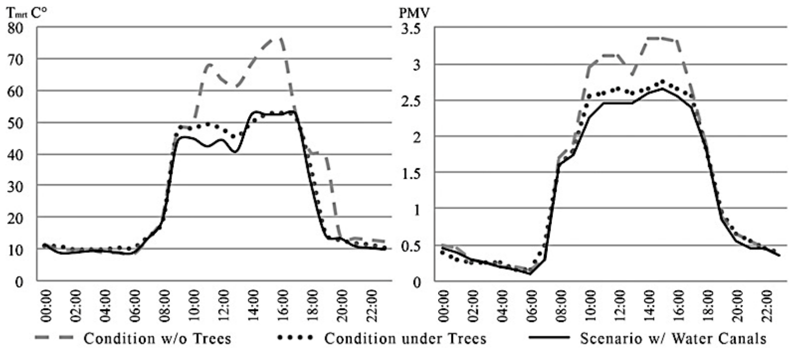

Figure 3: T_{mrt} (left) and PMV (right) for Madero St., ENVI-met 3 [9].

Table 1: Comparison of prevailing temperature in Madero St. ENVI-met 3 [9].

June 23	Current Conditions (°C)	w/ Water-Canals (°C)
07:00	20.61	20.61
08:00	20.29	20.66
10:00	24.64	23.16
12:00	27.23	25.28
14:00	28.20	26.11
16:00	27.32	25.45

4.2 Site 2. Coyoacán-North

The data is taken from the meteorological station Campo Exp. Coyoacán, located 650m from the site. For the period 1951–2010, it reports an average precipitation of 876.7mm SMN [5], and an evaporation mode of 3mm/day SMN [6]. This is equivalent to 18% for a 17mm rain event. For the following analysis an evaporation of 19% is considered, as this site has a slightly higher evaporation and heating risks, as well as the presence of more greenery that retains water longer than in the City Centre. Coyoacán-North is located over the alluvial zone, near to the transition to the volcanic rock zone. Its geology allows a good permeability, making this site a suitable sample of urban infiltration with a rate of 1.39 x 10^{-5}m/s. This results in a permeability coefficient K_f higher than 10^{-6}m/s (DWA [3]), which ratifies a good infiltration. For this reason a combination of swales and bioretention areas is proposed for this site. The swales would serve to convey the rainwater, remove particles and store the water for some hours while it gets infiltrated at the vegetated canal. This combination will be called BioSwale, which could become a prototype for unsealing urban surfaces that would permit the recovery of the soils' environmental functions. The BioSwales will take part of the street and of the sidewalk, unsealing them to achieve rainwater infiltration for the recovery of the aquifers. The Storage Volume (V) and its emptying time (t_E) was calculated based on the DWA [3]:

$$V=\left[(A_u+A_s)\cdot 10^{-7}\cdot r_{D(n)}-A_S\cdot \frac{k_f}{2}\right]\cdot D\cdot 60\cdot f_z \tag{2}$$

$$t_E=2\cdot\frac{z_M}{k_f} \tag{3}$$

The selected sample block-unit has a 1.5ha surface. The runoff coefficient Ψ that is considered for the sealed surfaces (A_u) is 0.9 for roofs, sidewalks, private surfaces and streets, while the one for permeable areas (A_s) is 0.0.

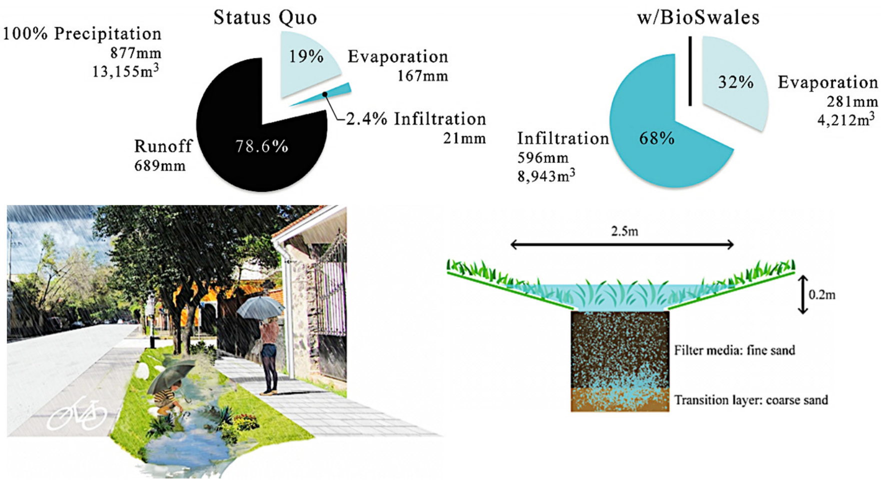

Figure 4: Coyoacán-North year water balance and BioSwale view.

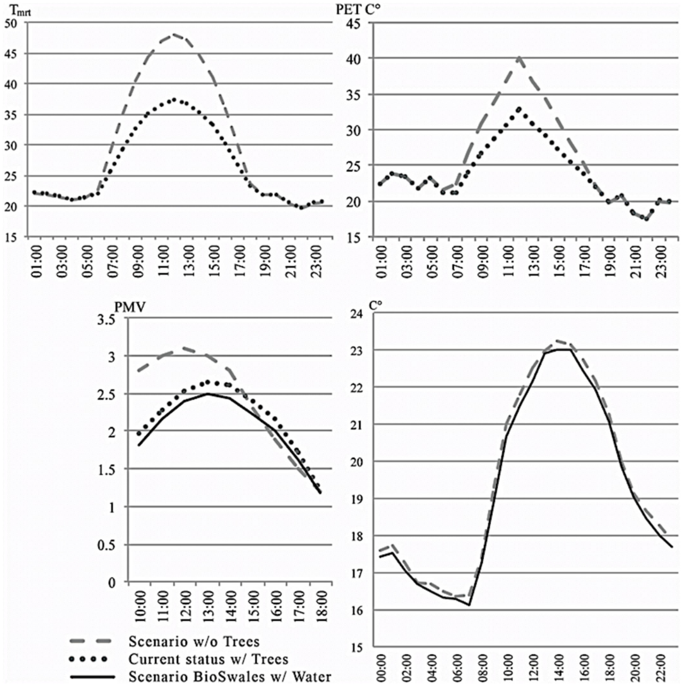

Figure 5: Paris St. Tmrt and PET (above); PMV and Pot. Temperature (below), Rayman 1.2 [10] ENVI-met 3 [9].

With $r_{D(n)}$ as the crucial rainfall of 188 l/(s*ha), D is the rated rain duration of 15-minute, Kf is the saturated zone permeability coefficient of 1.39 x 10^{-5}m/s, fz is an additional factor of 1.2, A_s is the infiltration area due to soil type of 0.20(A_u), A_u is the impervious areas sum of 11,794m^2, and Z_M is the storage depth of 0.31m. This gives a storage volume (V) of 317.5m^3, eqn (2), and an emptying time (t_E) of 12.4 hours, eqn (3). Considering a high loss through evaporation, during very hot days, there would be a reduction of the total volume collected by this BioSwale to 195 m^3 per block-unit after a 15-minute rain event. Then the BioSwale storage depth could be reduced to 0.20m, with an emptying time of 8h. With the application of this system in the alluvial zone (8.18% of Mexico City's surface), 64.37 million-m^3 of rainwater could be infiltrated every year.

The energy analysis is concentrated in Paris Street. Coyoacán presents a high heating risk due to the presence of wide asphalt streets (13m width w/4.8m width sidewalks) and short buildings (2–3 stories), with a dominant single-housing use. These conditions generate a Tmrt above 40°C in the simulation model with cloud coverage, from 9:00 to 16:00 hours. At Coyoacán-North this risk is reduced through the presence of large old trees. With trees, the Tmrt remains under 38°C in the middle of the street at all times. The tree crowns provide a wide shadow that protects the area from direct solar radiation, ergo reducing the heat storage in the urban surfaces. The absence of trees results in PET temperatures above the 30°C between 9:00 to 16:00 hours. At noon PET temperature reaches 40°C. During these hours the PMV shows a strong heat stress for humans. With the presence of trees in this area, PET remains under 33°C at all times and PMV is reduced to moderate. This makes a difference in the thermal stress for humans of ca. 8K, in a June summer day with sky cover, between the non-treed and treed conditions. The presence of trees in this simulation, allowed the potential temperature to remain within the comfort zone for Mexico City, during the solar radiation hours from 9:00 to 18:00 hours.

Temperature reduction between the treed area and the insertion of water features is lower than in the City Centre, but existent. Yet, the difference to a non-treed situation is high. The reason is that the trees give already large shading, so the addition of water is actually raising slightly the reflected short-wave radiation, hence the T_{mrt}. Additionally, the water was located by the side of the trees between the sidewalk and the street, so it does not receive direct solar radiation. The effect of locating it in the middle of the street could be higher, but the water collected in this site has a more valuable purpose, as this soil is suitable for infiltration. Nevertheless the presence of water allows the level of thermal stress to stay under a moderate level, even during peak temperature hours.

4.3 Site 3. Tarango Ravine

At the city's western edge, there is a ravine system that has been severely invaded by the urban expansion. Its location at the mountains slope and the large urban surfaces with scarce greenery cause the rainwater to run downslope too fast to efficiently use the ravines infiltration potential. Additionally, these conditions cause a high landslide and flood risk. It is suggested to increase the retention times to support the infiltration capacity of this ravine. This could be achieved through a Terraced-Retention design to obtain a surface infiltration for large rainwater volumes, including the rainwater that falls in the surrounding urban area. This will slow down the runoff giving opportunity for longer retention times and for vegetation to grow, especially larger native trees. The trees will enhance the rainwater infiltration, improve the quality of the soil and reduce the erosion. All of these factors together further support the environmental benefits this ravine represents as a link between the 'Desierto de los Leones' national park and the city core. This will give the opportunity for the biodiversity to grow and move safely along a wide city area.

A permeability of Kf = 1 x 10^{-4}m/s is considered for the Tarango ravine. For each block-unit of 1.5ha, an area of 8,302m^2 will be required in the ravine for a surface infiltration. As the Tarango ravine has a surface of 2,671,893.18m^2, it would be able to infiltrate the runoff coming from 321 block-units (483ha) and the precipitation falling directly over its surface. With this design the Tarango Ravine would be able to infiltrate 4,711,959m^3 every year. Since the Tarango ravine is a natural area at a higher altitude, its climatic impact in a small urban scale like in the other two sites is not significant. A simulation of its impact in a large scale was not possible with the available software and hardware. Nevertheless the impact of this design relies on its infiltration potential to support the recovery of the aquifers.

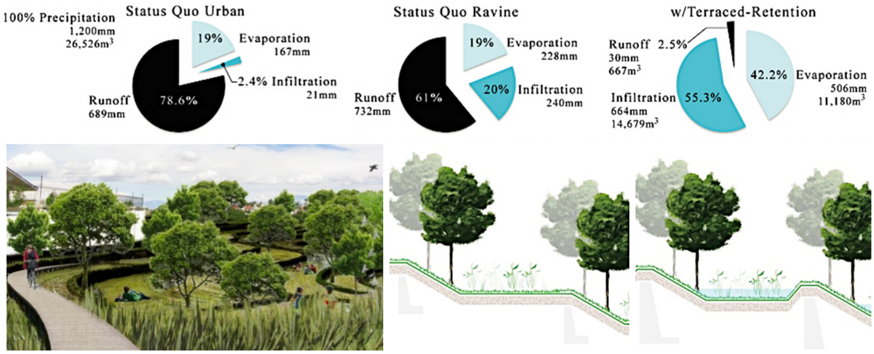

Figure 6: Tarango Ravine year water balance and Terraced-Retention view.

5 Conclusion

With this research it was attainable to evaluate possible microclimate enhancements by taking advantage of water-energy nexus, through the reintroduction of water elements in the urban environment of Mexico City. These elements were created by means of rainwater recovery with a combination of Water-Canal collection and storage (Pocket-Rain-Park/Pocket-Water-Plaza) in the lacustrine zone, with BioSwales in the alluvial zone, and with Terraced-Retention in the western ravine system. These microclimates achieve more stable temperatures, an enhancement of the human thermal comfort, a direct evaporative cooling effect at daily peak temperature hours and an enrichment of the water cycle in this urban area. It could be observed that the stabilization of the microclimate was not equally distributed throughout the different areas of the city. But it depends on the urban conditions, position in the basin, and the proper design. This resulted in a stronger effect in either the water balance or in the radiant energy balance. The most significant outcome for the water balance was achieved by the BioSwales in the alluvial zone, which contribute with 32% of the received rainwater to evaporation and infiltrate 68% to recover the aquifers. In comparison, a significant effect in the radiation energy balance was achieved at peak temperature hours under direct solar radiation conditions especially in the City Centre. This effect was intensified by the urban canyon conditions, where a reduction of approximately 26K in the T_{mrt} and of 2K in the peak temperature hours could be achieved. Additionally, the human thermal comfort conditions were improved, performing under a moderate heat stress even at peak temperature hours in the presence of water.

Taking into account historical averages, it is concluded that a total of 293.65million-m^3 rainwater could be recovered every year with the application of the proposed strategies throughout Mexico City, a volume equivalent to the importation of the Cutzamala system. This total is distributed in 94million-m^3 through infiltration and 165 million-m^3 collected every year. With the recovery of this rainwater volume, yearly energy savings of 1.54TWh could be achieved. This saving comprises the volume that will not need to be imported from the Cutzamala system, that will not be pumped through the sewers out of the basin, and that will not need to be treated in a wastewater treatment plant. The application of similar strategies in the Metropolitan Area could give considerably larger benefits. This should become part of a Water and Energy Plan for 2050 to stabilize these vital factors in the Valley of Mexico and to serve as an example for other cities.

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