Desert garden techniques to ameliorate urban microclimates

– an example of application in Granada, Spain

Ökenträdgårdstekniker för att förmildra urbana mikroklimat – ett exempel på implementering i Granada, Spanien.

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Desert garden techniques to ameliorate urban microcliamtes –with an example of application in Granada, Spain

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Summary

In this day and age we are faced with urban cores getting hotter, with the main drivers being climate change and the urban heat island effect. This gets even more complicated as the parts of Europe that have the largest need too cool down, i.e. the south, has the least amount of space available for interventions in the form of green space. The aim for this study is to connect the potential between ideas from ancient desert cultures and the current climactic challenges in the urban framework.

This thesis consists of two parts, the first is to identify gardening techniques from the following desert cultures: Ancient Egypt, Ancient Persia and Ancient Andalusia. The second part is to examine what microclimactic effect these techniques would have on an open urban area in Granada, Spain. The effects are examined using a software that examines the climactic effects of changing the radiation and latent heat flux.

Fifteen main techniques were found to be relevant to combat the challenges of hot microclimates in the city. Some of these techniques are chosen to be part of a scenario of intervention. On a normal summers day with an air temperature of 34.8 °C, the difference of intervention and no intervention is 5.01 °C in *mean radiant temperature* (max). The areas with the maximal thermal change had their *mean radiant temperature* lowered by 7.31 °C. It can therefore be concluded that the garden techniques from these desert cultures can be used in city spaces to have a real impact on the microclimate. This is a possible solution for the climate adaptation of the cities in the south of Europe that have little space for very large interventions.

Resumen

En esta época nos enfrentamos a núcleos urbanos cada vez más calientes, como principales impulsores; el cambio climático y el efecto isla de calor urbano. Esto se vuelve aún más complicado ya que en el sur de Europa dónde hay la mayor necesidad de combatir el calor, no disponemos de espacios de intervención. El objetivo de este estudio es conectar el potencial entre las ideas de las antiguas culturas del desierto y los desafíos climáticos actuales en el marco urbano.

Esta tesis consta de dos partes, la primera consiste en identificar técnicas de jardinería de las siguientes culturas del desierto: Antiguo Egipto, Antigua Persia y Antigua Andalucía. La segunda parte es examinar qué efecto microclimático tendrían estas técnicas en un área urbana y expuesta en Granada, España. Los efectos se examinan utilizando un programa que calcula los efectos climáticos de cambios en la radiación y flujo de calor latente.

Quince técnicas principales son relevantes para combatir los desafíos de los microclimas cálidos en la ciudad. Algunas de estas técnicas se eligen para formar parte de un escenario de intervención. En un día normal de verano con una temperatura ambiental de 34,8 °C, la diferencia entre la intervención y no intervención es de 5.01 °C en *mean radiant temperature* (máx.). Las partes con el cambio térmico más grande tuvieron su

mean radiant temperature bajada en 7,31 °C. Por lo tanto, se puede concluir que las técnicas de jardinería de estas culturas del desierto se pueden utilizar en los espacios de la ciudad para tener un impacto real en el microclima. Esta es una posible solución para la adaptación climática de las ciudades del sur de Europa que disponen poco espacio para intervenciones muy grandes.

Sammanfattning

Vi ställs nu inför stadskärnor som blir allt varmare, pådrivet av klimatförändringar och den urbana värmeöeffekten. Detta blir ännu mer komplicerat då de delar av Europa som har störst behov av svalka, det vill säga Sydeuropa, har minst grönytor tillgängliga för interventioner. Syftet med denna studie är att koppla samman potentialen mellan idéer från antika ökenkulturer och de nuvarande klimatutmaningarna i en urban kontext.

Examensarbetet består av två delar, den första är att identifiera trädgårdstekniker från följande ökenkulturer: Det antika Egypten, det antika Persien och det antika Andalusien. Den andra delen är att undersöka graden av mikroklimatisk effekt teknikerna har på ett öppet stadsområde i Granada, Spanien. Effekterna undersöks med hjälp av en programvara som räknar ut klimatiska effekter av förändringar i strålning och latent värmeflöde (latent heat flux).

Femton huvudtekniker visade sig vara relevanta för att möta mikroklimats-utmaningarna i staden. Vissa av dessa tekniker är valda för att ingå i ett interventionsscenario. Under en normal sommardag med en lufttemperatur på 34,8 °C är skillnaden mellan ingrepp och inget ingrepp 5.01 °C i *mean radiant temperature* (max). Delarna med den maximala termiska förändringen fick sin *mean radiant temperature* sänkt med 7,31 °C. Vi kan därför dra slutsatsen att trädgårdsteknikerna från dessa ökenkulturer kan användas i stadsrum för att ha en verklig inverkan på mikroklimatet. Detta är en möjlig lösning för klimatanpassningen av städerna i södra Europa, som saknar utrymme för mycket stora ingrepp.

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1. Introduction

1.1. Background

The urban heat island effect is making our urban centres very uncomfortable, and in some cases even dangerously hot for vulnerable groups. This problem is in turn exacerbated by climate change (Guerreiro et al, 2018 ; Holden, 2017).

Humans have an environmental tolerance just like all other animals that shouldn't be surpassed (Holden, 2017). This is making us vulnerable to urban microclimates that have temperatures outside of this range. Clearly there is no natural environment that has the exact same climatic conditions as those of the city. For the sake of classification and comprehension of a city like Granada, close similarities can be be found with volcanic desert canyons. Anthropogenic heat radiates from within of the city out on the streets, just like magma radiates heat from underneath a volcano. The shape of the urban canyon can furthermore also be likened to that of a natural canyon. The lack of latent heat transfer; meaning the lack of water, make conditions similar to that of a desert. In many ways the modern city is actually *worse* than a desert, as I explain in my work and many have before me, since asphalt is better at absorbing heat than sand is (fig. 8). So then, where to search for a solution to this problem of an urban heat engine and heat absorbent? I propose a look into the desert cultures, whose knowledge on combatting desert heat spans from the dawn of human civilization until recent times. These cultures also have some of the oldest settlements known to to date and therefore a long history of climactic interventions within the spacial limitation of urban structure (Ruggles, 2008 ; Turner, 2005).

The European cities also have a problem with lack of space that needs to be taken into account. Southern Europe has the most pressing need of greenery for climatic regulation, but ironically it has a lower amount of green space as compared to northern Europe (Kabisch et al, 2016). As Berlin is putting forth their vision of the *sponge city* (Zimmerman, 2016), the south of Europe could benefit from a less polemic solution. Surely we *could* tear down thousand year old architecture to make space for grand green solutions, but this thesis is an attempt for a more diplomatic approach.

1.2. Research aim

The aim of this research is to find garden techniques from the ancient Egyptian culture, Persian culture and Andalusian culture that could fit in an urban context. When these techniques are identified, the effect of these techniques on temperature (Mean Radiant Temperature & Physiological Equivalent Temperature) is to be examined through application on a site in Granada, Spain.

The aim for the intervention proposal is for it to be in the form of a *prototype.* This means that the is a suggestion, and not a completely site specific proposal.

1.3. Research question

The main inquiry is: can these desert cultures help us mitigate modern microclimates in the city? This is divided into two main questions, these are stipulated here below.

What garden techniques from the ancient Egyptian, ancient Perisan and Andalusian garden traditions are best fitted to be implemented in city space?

What effect could such an intervention have on mean radiant temperature and physiological equivalent temperature?

1.4. Main focus area and delimitations of the study

This thesis is limited to the background of: the urban heat island effect, urban micro-climate and desert garden techniques.

The microclimate and urban heat island is focused on outdoor space, since an indoor environment also can be considered to be a microclimate as well. The microclimate study is focused on the causes of extreme conditions generated from warm temperatures and heat radiation. There is furthermore some focus into the local climate of the site in Granada, Spain, since this is a part of analyzing the conditions of the site.

The garden techniques that are examined are limited to ancient Egyptian traditions, Ancient Persian traditions and Andalusian traditions. These three garden traditions are sometimes referred to as "*paradise gardens*" or *"desert gardens"* in this thesis.

1.5. Definitions and concepts

There are some concepts and that are used in this thesis that need to be clarified. These are presented here below.

Paradise/desert garden

In this thesis this concept refers to the combination of the garden traditions of ancient Egypt, ancient Persia and ancient Andalusia.

Urban heat island

The urban heat island effect refers to the phenomena that urban cores exhibit higher temperatures than their surroundings (Holden, 2017).

Microclimate

Microclimate in this thesis refers to the climate that is local enough to vary within a city structure. One example variation is that the temperatures in a park can be cooler than those of a square on a hot summers day.

Latent heat flux

This is the energy flux that is absorbed by materials changing state instead of temperature change (Holden, 2017). An example would be the energy required to turn one liter of 0 °C ice into one liter of 0 °C water, the added energy only changes the state. It's the same dynamic between water and vapor. This type of energy flux is more predominant in humid regions since they have more water.

Sensible heat flux

The sensible heat flux is an energy flux that can be felt, i.e. a temperature increase. This is prominent in climates without any available water, such as a desert or an asphalt road.

Mean radiant temperature (MRT)

MRT represents the equivalent surface temperature, and as such it is the result of all the long wave and short wave fluxes. The mean radiant temperature is the description of a perfect black body that has the same energy balance as its surrounding area (Kantor & Unger, 2011).

PET

PET stands for *physiological equivalent temperature*. PET takes the human heat balance into account with a reference to indoor climate. This means that a certain temperature is experienced much hotter than it is on a sunny windless day, in comparison to a cloudy and windy day (Höppe, 1999).

ENVI-met

ENVI-met is a set of programs that is used to build 3D models to calculate and analyse microclimactic data.

Rayman

Rayman is a software that calculates the radiation for a 3D model. In this thesis it has only been used to transform the MRT values from ENVI-met into PET.

Lateral boundary conditions

Is an option in the meteorology settings in ENVI-met, and it refers to the climactic conditions of the site, i.e. air temperature and relative humidity.

Leonardo

Leonardo is the program in the ENVI-met suite that analyses the data.

Blender

Blender is a software that is used for renderization, model building and video editing.

2. Materials and Methods

This thesis consists of three main parts; background research, applying the findings to a site and presenting the findings. Here below a summary over the work flow is presented.

Background research

The background consists of three major desk studies:

A) the urban heat island effect; B) The microclimate in the city; C) Desert garden techniques from ancient Egypt, ancient Persia and ancient Andalusia.

The studies of microclimates and the urban heat island were made in order to create a scientific framework to help understand the factors that influence urban microclimates and thermal comfort. This framework then served as a framework to identify the best desert garden techniques.

There was also a minor desk study on the climate of the site in Granada, Spain.

Identification, application and thermal study

The second part of the study identified the techniques from the desert gardens that were useful to ameliorate the urban microclimate. These were then selected with the help of the desk studies and subsequently applied to the site in Granada to test the effects of the design on thermal change. This latter step was accomplished in ENVI-met (see section 2.3).

Presentation

Lastly the findings from the desk studies and the thermal calculations were presented as text, renders, tables and a video.

2.1. Literature studies

The literature study was made in order to gather material on the following three subjects; the urban heat island, microclimate and desert garden traditions from the near east. These garden traditions are; the ancient Egyptian gardens, the ancient Persian gardens and the gardens of ancient Andalusia.

The aim for the literature study was to gather information that connects the potential between ideas from ancient desert cultures and the current climactic challenges in the urban fabric. This was done by identifying desert gardening techniques from the traditions mentioned above, these were then chosen on how easily they could be implemented in city space, mostly based on how much space the interventions would occupy. The identification was also guided by the theoretical framework established from the theory on the urban heat island and microclimates.

Much of the material on the urban heat island stemmed from literature from a university course on the subject (Climate change theme course, faculty of landscape architecture and planning), the rest is included in the following search words on *Primo* or *Google Scholar*; Persian gardens + mircoclimates, Ancient gardens + microclimate, Alhambra + microclimate, Islamic garden + microclimate, climate building materials, Alcazar gardens + microclimates.

The desk study of the climate of Granda was a mixture between a previous literature on the urban heat island (Holden, 2017) and data from the Spanish governmental meteorological agency (AEMET, 2021). The results of the climactic desk study are shown in paragraph 2.4 (table 2).

2.2. Study of the site of Puerta Real, Granada, Spain

The site of Puerta Real (Royal Gate) in Granada, Spain, was chosen to elaborate how the garden techniques from the desk study will affect thermal comfort. The location of the site inside of the city is very central in order to experience the maximal amount of urban heat island effect. There were also other limiting factors that make the project more interesting and representative of southern Europe, such as large amounts of traffic, both in terms of vehicles and pedestrians.

When it comes to Granada in particular, it came as a natural choice for a number of reasons. First of all, the famous gardens of Alhambra are situated in this city making it an ancient center of the Islamic influence. This has served as a connection with the ancient desert world and its extreme temperatures. The Arabic influence has had a significant impact in Andalusia, since it was a part of the Islamic Empire for hundreds of years (Ruggles, 2008). Other cities like Cordoba and Seville share this history, but in my *personal opinion*, Alhambra is more impressive than the Réal Alcazar. This being said, examples of gardening techniques from both Seville and Cordoba were considered in the background research even if the intervention was not set there.

2.3. Analyzing the proposal in ENVI-met

ENVI-met is a software that lets the user calculate microclimate of an area. It is comprised by a number of smaller programs that work together.

The following workflow was undertaken in ENVI-met;

1) Create a 3D model of the site
2) Add climate conditions for the site (meteorology settings)
3) Calculate the effect of the climate conditions combined with the model
4) Analyze the resulting data and run simulations in “Leonardo”

This process had to be repeated two times as two models were built. The first one was of the site before intervention (Model 0) and the second one of the site after the intervention had reached most of its potential (Model 1). It should be noted that the raster size of the beta version of ENVI-met is 2x2 meters, this makes it impossible to have any accuracy that is smaller than two meters.

Three simulations were then run in Leonardo, the first being the MRT of *Model 0*. The second simulation was made to analyze the MRT of *Model 1*. Lastly the datasets of *Model 0* and *Model 1* were compared in a simulation that shows the change in MRT.

There is a database of vegetation available in ENVI-met to add into the 3D model. The vegetation represents the thermal effect these plants would have in terms of shade and added latent heat flux. Some of the vegetation types on the site had no equivalent in ENVI-met, equivalents have therefore been chosen in order to liken their counterpart. “Wild fruit tree” was chosen for pomegranate, and to simulate the crown cover by climbers, palm trees were set since they only have one layer vegetation. This study used the free beta version of ENVI-met, with a raster of 40 x 40 pixels. Furthermore all the house heights are approximated to 18 meters and the channels that are featured in the proposal have been left out. Instead an extra amount of water was added to area near the parapet and fountain. Here below (table 1) is a table showing the different material choices for the models.

Area	**Model 0**	**Model 1**
Car road	Asphalt road	Dark concrete
Sidewalk	Concrete pavement gray	Concrete pavement gray
Plant beds	Sandy loam	Sandy loam
Plants	Wild fruit tree	Palm, hedge

Table 1, materials used for the ENVI-met models.

ENVI-met used the geographical data of Granada to calculate the radiation, and the date was set to the 10th of July 2021 at 14:30. Moreover the thermal values of a normal summers day is used, being 34.8 degrees with a humidity of 38 percent.

Settings for meteorology and Leonardo in ENVI-met

For the individual calculations (fig. 35 & fig. 39) the meteorology was set to the mode “lateral boundary conditions”, with all values in default except for air temperature and humidity, that were set to the values mentioned previously. In Leonardo the data output was set to MRT, the contour was set to temperature flux, both the x vector and the y vector were set to MRT, and finally position of view plane was set to 1.8 meters. All other values in Leonardo were set to default.

In the comparison simulation (fig. 40) the different data sets were compared with the data output set to MRT, and all other values set to default.

Rayman

The program Rayman was used after the simulations to convert the MRT values into PET values. PET is preferred over MRT since this says more about the felt temperature experienced by the pedestrians at the site. In Rayman the geographical data of Granada was used, as well as the date used in the ENVI-met calculations (10.07.2021). The temperature and relative humidity were set to the same ones as in the ENVI-met calculations, i.e. 34.8 °C and 38 %. All other values were set to default.

2.4. The climate of Granada

For the application of the findings, a physical site was chosen, this is an urban location in Granada, Spain. Here below (table 2) is data presented, that was collected from the Spanish government agency “Agencia Estatal de Meterología”(AEMET, 2021).

MONTH	**T_{MAX} (^{O}C)**	**T_{MIN} (^{O}C)**	**REL HUMID. (%)**	**PERCIP.(MM)**
JANUARY	13	0	72	42
FEBRUARY	15.4	1.6	67	38
MARCH	19	3.8	59	32
APRIL	20.6	6	57	36
MAY	25	9.4	51	28
JUNE	31	13.6	44	11
JULY	34.8	15.7	38	2
AUGUST	34.2	15.5	42	4
SEPTEMBER	29.4	12.8	52	19
OCTOBER	23.2	8.7	64	40
NOVEMBER	17	4.2	72	54
DECEMBER	13.4	1.7	76	56
AVERAGE	**23**	**7.8**	**58**	**365(anually)**

Table 2: The table shows both the daily normal maximum temperature and minimum temperature. It also shows the monthly precipitation and relative humidity.

Overall winter is cool and somewhat humid, whereas summer is very hot and dry. In July the normal maximum temperature is 34.8 degrees, meaning that it rises well above that on a hot day. December, January and February on the other hand experience much cooler temperatures both during the day but especially at night. It is important to note that it gets warm in summer during the day, but the temperature falls drastically at night. The diurnal variation is sometimes almost 20 degrees centigrade.

The geography of Granada is mountainous, with the airport at an altitude of 567 meters (AEMET, 2021). Granada is a part of the Mediterranean climate zone, being characterized but hot and dry summers, and wet winters. Summer temperatures in this climate are over 30, and sometimes 40 degrees, whereas winter maximum temperatures go as low as 10-12 degrees. The normal precipitation range for Mediterranean climates is 300-500 mm, which fits well with the 365 mm received in Granada (Holden, 2018).

2.5. Blender and applying the findings

Blender is a multi-functional software, and in this thesis it has been used to build the models, render, composition(rendering) and to animate a video. The renders were made to showcase each of the different techniques that have been identified to fit in the urban fabric of the project.

The video is comprised of three different models that show the site at three different stages. Model 0 is shown for 10 seconds and Model 1 is also shown for ten seconds, with a quick flash of the phase in-between.

For rendering in Blender the render engines “Cycles” and “Eevee” were used. Cylces was used for single images, and “Eevee” for the video. “Eevee” has a lower image quality than Cycles, but without the access to a “render farm”, it was impossible to create a high resolution video of more than a few seconds with the hardware available within this time frame. The video has been uploaded to *youtube* for free access and a link is put in the appendix. Whereas the visualizations are photo-realistic, the video is instead meant to be stylized to decrease render time. The main goal of the visualizations was to show the detailed parts of the techniques, and how they can be put into context. The video on the other hand has the purpose of showing how the techniques change the public space, showing the difference between no intervention and intervention. The stylization of the video takes inspiration from studio Ghibli and one of its famous directors; 宮崎 駿 (Hayao Miyazaki). This style has great values in my personal opinion, as it simplifies the geometry at the same time as it makes it more aesthetically complex. It’s very beneficial to the rendering to simplify the geometry, as it takes less time to model and to render. It should be mentioned that the visualizations of model 0 (fig. 34) and model 1 (fig. 38) follow the same format as the video, being excerpt renders from the video. *481* frames in total have been rendered to create the video.

For all the visualizations a mixture of “auto-CAD”, Illustrator and “Blender” was used. For editing pictures “Photoshop” or “Illustartor” was used.

All the visual interpretations if not stated otherwise were made by the author, *Otto Lundberg*. All photographs have also been taken by the author using an Iphone 6.

2.6. Limitations

The background of this thesis has been limited to: ancient Persian gardens, ancient Egyptian gardens, ancient Andalusian gardens, the climate conditions and spatial conditions of the site in Granada, the urban heat island and microclimates.

The main tools of research have been desk studies of source material, analysis in ENVI-met and photography. Rayman has only been used to convert MRT values into PET values.

The main tools of representation have been photography, Illustrator, Photoshop and Blender.

3. Theory: The urban heat island, micro-climates and desert gardens

3.1. The Urban Heat Island effect (UHI)- a brief introduction

In the case of urban climates it is very common to talk of the *urban heat island effect*. This is a local modification in climate due to human influence. The term refers to the urban climate being warmer in contrast to the cooler air in the rural land surrounding it. The urban heat island effect (UHI) is mostly a nightly phenomenon since the urban environment loses heat energy slower than the surrounding countryside, as well as having more energy stored. In mid-latitude cities the highest UHI effect is recorded on summer nights. Urban heat loss from housing often exacerbates the difference, resulting in very large temperature variations between urban and rural climates (Holden, 2017). In short, the main drivers of the UHI could be concluded as e.g. the imbalance of hydrologic systems in urbanized landscapes (predominantly less water content compared to the country side) thus providing drier conditions; the spatial structures of buildings and spatial layout of street infrastructure affecting wind and radiation, the amount of visible sky (sky view factor) with influence on long and short wave radiation, etc. In the following sections I will provide a more in-depth analysis of the different qualities and parameters of the UHI effect.

3.1.1 The urban layers affecting the UHI effect

The climate of the UHI is commonly divided into four categories that are usually used to describe it; the urban substrate layer, the urban surface layer, the urban canopy layer and the urban boundary layer (Holden, 2017; Stewart, 2021). The difference in spatial extent between the urban canopy layer and the urban boundary layer can be seen in the graphic on below (fig. 1).

Fig.1, The conceptual illustration shows the urban boundary layer, the urban canopy layer and the transitional layer in-between (white layer).

The urban boundary layer is the layer that surrounds the urban micorcliamte and that has minimal influence from it (Holden, 2017). This layer is well above the roof tops and outside of the city (Stewart, 2021).

The urban canopy layer is in turn the part of the atmosphere that stretches from the ground to the tops of the built structures (Holden, 2017). It could be referred to as the “three dimensional city space”. The usual studies of the urban heat island are conducted in the canopy layer at a height of two meters, were the measuring sensors are exposed to all the different elements of the city. These may include; walls reflecting radiation, trees giving shade, cooling water etc (Stewart, 2021).

Another important layer is the climate of the urban surface layer, e.g. the surface of roofs, streets and walls. These surfaces generate different temperatures depending on air temperatures, heat transfer and radiation (Stewart, 2021).

Finally there is an extra layer which is the urban substrate layer. This layer is based on the temperature of the soil below the ground. This however has received little attention in cases where it’s not evidently very present, like in the case of melting permafrost or other extreme instances (Stewart, 2021). I personally think that this is an interesting aspect, since soil can be a great source of thermal isolation, as well as containing soil moisture. This has been shown in the Arabic “qanat”, which are underground water channels, where water is protected from the desert heat (Beaumont, 1971).

3.1.2 Spatial structure of the built environment and vegetation

To understand why these different layers form, it can be helpful to examine the different forms of city structure in relation to the UHI. Oke (2012) started to classify this into a system that is easy to understand. The built structures are classified from 1-10 and the vegetative structures are classified from A-G. However it should be noted that “E” could refer to a paved area as well as bare rock since they have similar climactic attributes. There are also subcategories based on ephemeral ground cover, these are titled; b, s, d, w (Oke, 2012). In the subcategories *b* means bare ground, *s* means snow covered ground, *d* means dry ground and *w* refers to wet ground. The other categories are described in fig. 2, 3, 4.

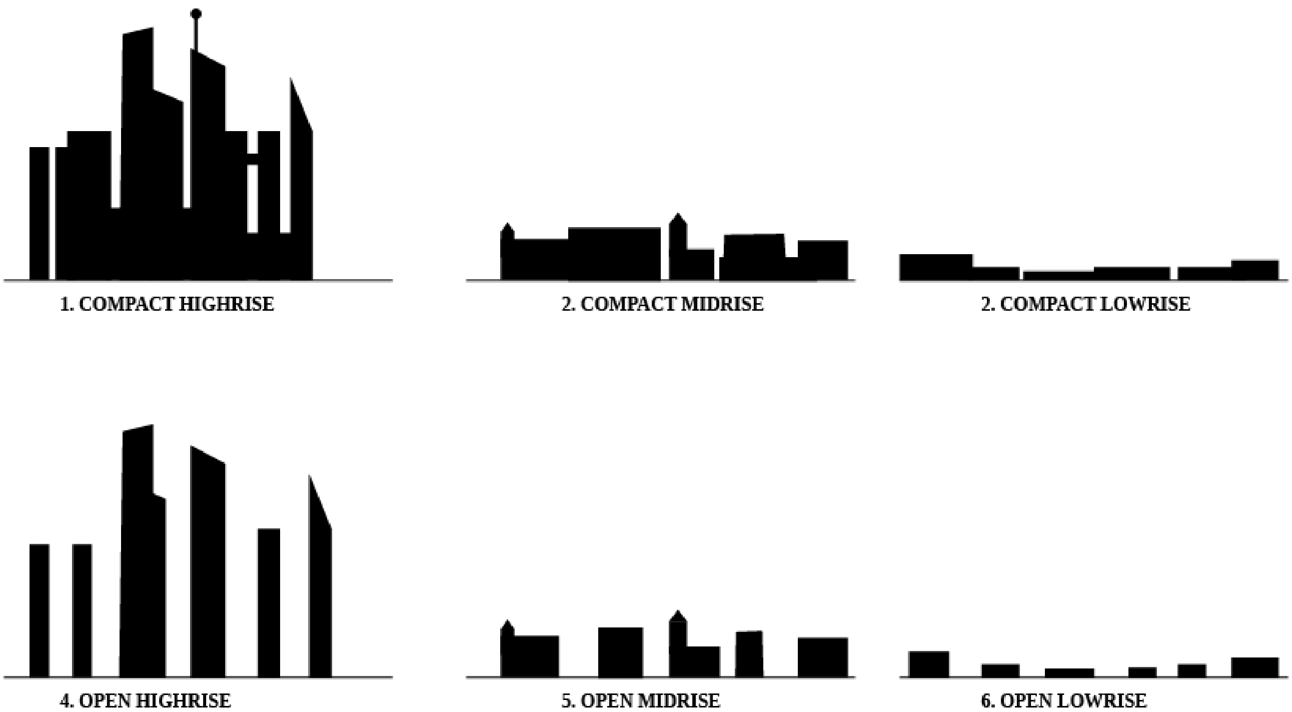


Fig. 2: The first six categories have some similarities as shown above. One big difference apart from the density is the amount of permeable land cover, as the 4-6 have and abundance of permeable land cover, which is the opposite of 1-3, meaning an abundance in impermeable land cover. High-rise corresponds to 10+ stories, mid-rise corresponds to 3-9 stories and the low-rise would refer to buildings in the range of 1-3 stories (Oke & Stewart, 2012).

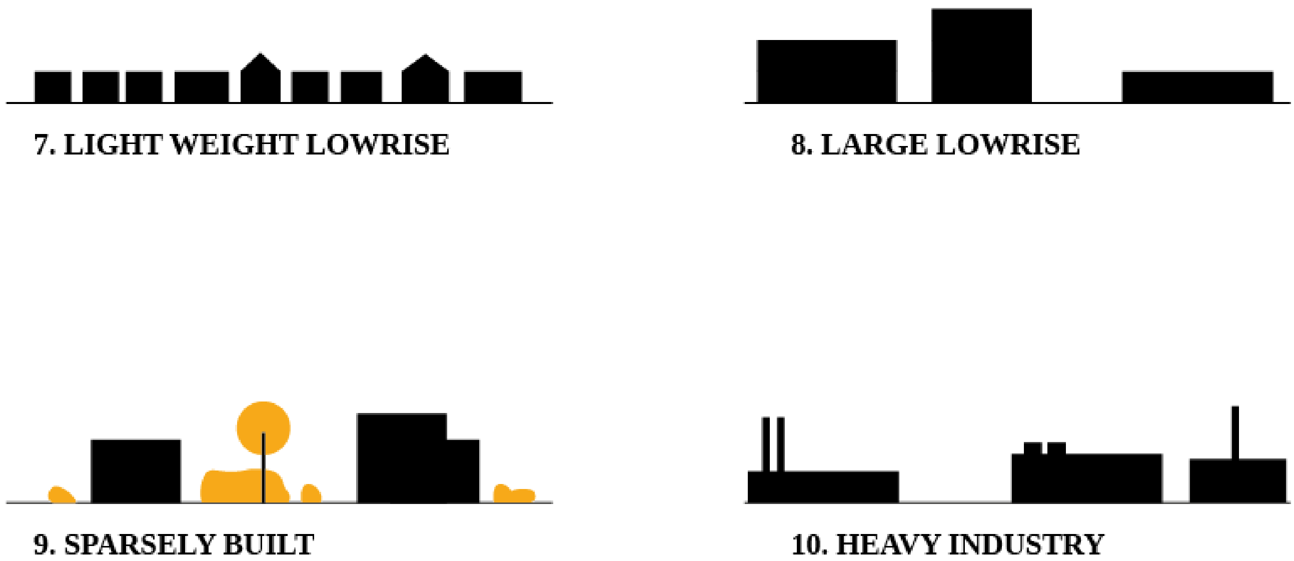


Fig. 3: Number seven refers to a densely built one story area that has been constructed in lightweight materials. The land is usually hard packed and there are few to no trees. Number eight is made up of large 1-3 story buildings with heavy construction materials, the ground is mostly paved and there are very few trees. Number nine is a built area set in a natural environment such as forest or the like. Number ten is made up of heavy construction materials, paved and can be both mid- and low-rise (Oke & Stewart, 2012).

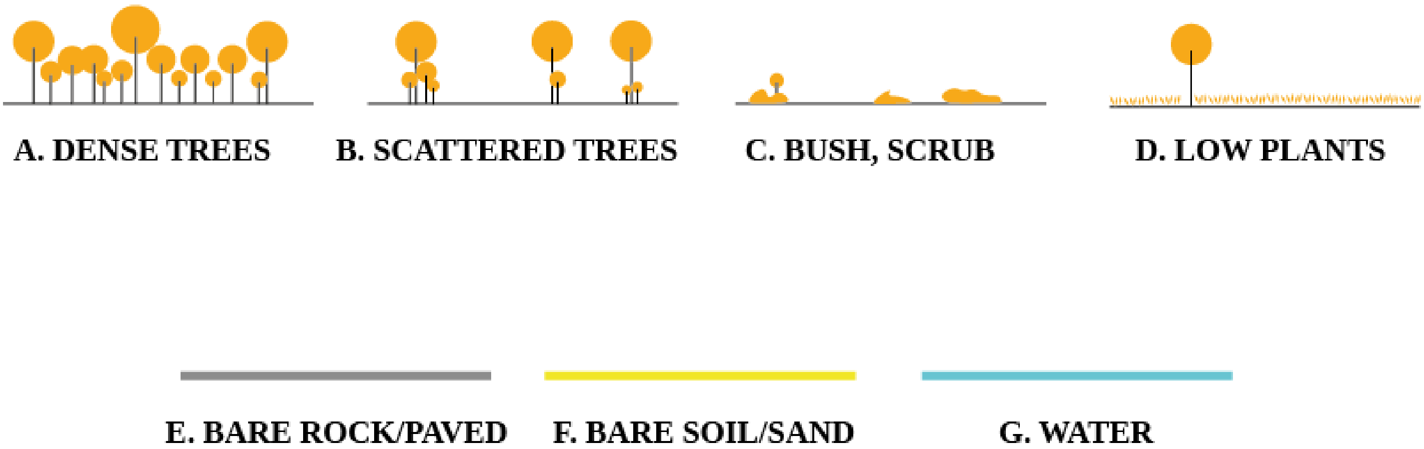


Fig 4: *A* refers to a dense forest with thick vegetation, it is mostly permeable and a natural example would be a forest or a very dense urban park. *B* is a lightly wooded area with mostly permeable ground cover, examples would be urban parks or open forests. *C* is a scrub-land with low scattered vegetation with mostly bare soil. *D* is an open landscape of mostly grass or crops, with few trees. *E* is a bare rock or paved area, a city equivalent would be an asphalt road. *F* is bare soil or sand, that could be seen in agricultural land or deserts. *G* is open water (Oke & Stewart, 2012).

When it comes to the urban structure and geometry, different strategies should be employed depending on if the climate is always warm or if it is seasonal. The wider the street, the more direct solar radiation it will receive but a wider street will also allow for a larger sky view factor. The larger sky view factor will make it easier for the energy to escape the urban fabric since there is less space for the energy to bounce around and be recycled within the system. There are however ways to decrease the direct solar radiation, one effective way is the use of trees. In very hot climates where the sun reaches high in the sky narrow streets are commonly used. Narrow streets will create more recycling of recieved solar energy but it will also decrease the amount of energy that reaches the system in the first place (Stewart, 2021).

Wind is also affected by the urban structure since convection makes the air masses mix and change places. The winds can be manipulated by urban structure, as a rule the increased roughness of added objects to the landscape will cause less wind but stronger gusts. This phenomena is called the *venturi effect* (Holden, 2017). Therefore a denser city structure, i.e. a city with more objects and increased roughness will create less wind and thus less convection. However, a very rough city will cause more turbulence and more mixing of the air masses within the city (Stewart, 2021).

Finally the urban heat island is thought to be made stronger by more compact cities. Compact cities will, however, have lower greenhouse gas emissions (Stewart, 2021).

3.1.3 Radiation and energy

The main phenomena during night in the urban heat island is that the ground starts to re-radiate the heat captured during the day back into the atmosphere. This heat or “energy” takes the from of longwave radiation and it is most effectively lost on nights with clear skies and no wind (Holden, 2017).

There are three main forms of ways of heat to transfer between materials; convection, conduction and radiation. Convection is when energy is moved by the movement of the particles themselves. A common example of convection would be warm air rising in the city as it gets heated by the sun or masses of air mixing due to winds in the urban fabric. Conduction on the other hand is when heat passes through a material without moving the matter itself, much like heat would pass through a rock or in case of the city – through asphalt or concrete. Conduction also takes place in other media that aren’t solid, such as gases or liquids. However, the effect of conduction in gases or fluids is negligible in comparison to that of convection, which only is possible in gases or liquids (Holden, 2017). The final mode of heat transfer is radiation, which is very important for the city setting due to the long wave radiation. Any object that has a temperature that’s above absolute zero (-273 °C) will have some form of transmission in radiation. Higher temperature means shorter wavelength, as shown by the *Wien displacement law*. This means that the radiation coming in from the sun that has a very short wavelength (below 4 u m) will be much more high energy than the anthropogenic heat flux(up to 100 u m).The radiation is different from convection or conduction in that it can travel through vacuum and that it travels at the speed of light (Holden, 2017). There are two main types of radiation, the long-wave radiation and the short-wave radiation. The shorter wavelength is high in energy and becomes longwave when it is reflected and energy is absorbed by another medium (Stewart, 2021). The sunlight can either be direct which causes a large amount of high energy radiation to hit the ground and create a stark diurnal variation, or it can be diffuse. Diffuse means that the radiation that hits the ground will have been scattered through clouds before hitting the ground (Holden, 2017). Clear skies are the “perfect” conditions to create a strong urban heat island effect, since the heated city will cool slower than the rural area surrounding it. The diffuse radiation will on the other hand make the diurnal variation become very small. The diffuse radiation refers to clouds absorbing and scattering the solar rays, making their wavelength longer (more low energy). To describe the energy balance it can be helpful to talk about the net radiation. This is a reference to radiation (energy) deficit or surplus of a system or medium. In the case of the city the net radiation is mostly positive during the day due to the large amount of short wave radiation being received but negative during the night due to the dissipation of long wave radiation. Clouds at night will make more radiation to be recycled and less energy to escape. This will cause less of a temperature decrease and therefore a stronger urban heat island effect(Holden, 2017).

Shading is a very effective strategy to counteract the UHI effect, as more than eighty percent of the short wave radiation comes from direct solar radiation on a day with ideal conditions for a strong UHI effect. A canopy cover of leaves will transfer the energy received from the sun from the ground to the canopy's’ vegetative matter. This causes less energy to reach the ground and thereby has a cooling effect. The dominant driver for UHI is direct solar radiation while diffuse radiation is not considered a significant factor during daytime (Stewart, 2021). The shade from trees are of primary importance to counteract the effects of direct radiation (Erell et al., 2011).

3.1.4 Water and energy storage

The energy transport in the terrestrial system can be divided into three categories; radiation, sensible heat flux and latent heat flux (Stewart, 2021). Latent heat, meaning "hidden heat", refers to the energy that is required for a medium to change its state, like solid to liquid, or gas to plasma. Something can therefore gain latent heat without increasing in temperature such as 0 °C ice melting into 0 °C water. The sensible heat on the other hand refers to the heat that is felt, meaning a temperature increase. The main difference with concern from urbanized landscapes is that the latent heat flux is very much more effective at decreasing temperature than the sensible heat flux (Holden, 2017). Flux is a reference to heat transfer meaning that latent heat transfer is more effective than sensible heat transfer. The mode of transfer for both the latent heat and the sensible heat is convection (Stewart, 2021).

$$\text{BOWEN RATIO} = \frac{\text{SENSIBLE HEAT FLUX}}{\text{LATENT HEAT FLUX}}$$

Fig. 5: the mathematical formula for the *bowen ratio*

The ratio of sensible and latent heat is called the *bowen ratio* and is the sensible heat flux divided by the latent heat flux as shown above (fig. 5). The bowen ratio should be below 1 in normal conditions, i.e. the latent heat flux should be greater than the sensible heat flux (Holden, 2017 & Stewart, 2021). In moist conditions the value of the bowen ratio decreases as the temperature increases and it reaches zero at around 32-34 °C. Since latent heat flux relies on the availability of moisture, the bowen ratio can be very low in dry climates despite very high temperatures, such as the in the case of deserts. The deserts function by releasing the net radiation primarily as sensible heat in the atmosphere, translating into a bowen ratio above 1, sometimes causing shade temperatures of 50 degrees (Holden, 2017). The equivalent of the desert climate zone where is seen in much of the modern cities as impermeable surfaces, few plants and underground water storage create a situation with very little available water for latent heat flux. The trees provide moisture through their transpiration throughout the day and can be a way to increase the latent heat flux for places where impermeable ground cannot be avoided. Finally it is important to note that both *latent heat flux and sensible heat flux* depend on convection and that these two are the main forms of energy transportation in the urban system, as well as any terrestrial setting (Stewart,2021).

In situations where there is available moisture, the net radiation surplus is transferred by latent heat flux, which can alone can alone account for 75 – 80 % of all daytime energy transport. The latent heat flux is so much more effective at cooling the atmosphere that tropical ocean surfaces rarely exceed 32-34 degrees in comparison to the tropical deserts that may reach 50 degrees (Holden, 2017).

Water in itself is also interesting, since it needs an unusually high energy input to increase its temperature relative to other materials. This makes it very effective as insulation as can be seen in tropical rain-forest climates, since they have a very stable climate with a small diurnal variation, often in the range of 22-32 at the coolest and warmest part of the 24-hour period. In the case of the hot desert on the other hand, the climate is arid and the diurnal variation can be very large (Holden, 2017). This property of water is very useful in an urban setting since it has the capacity to ameliorate climate. These properties of water have been used in very hot desert climates for thousands of years (Don, 2018). It can therefore be helpful to regard the city in terms of a natural climate to understand its function and workings. In this case a very heavily urbanized city would be equal to that of a desert.

3.1.5 Admittance, storage and release

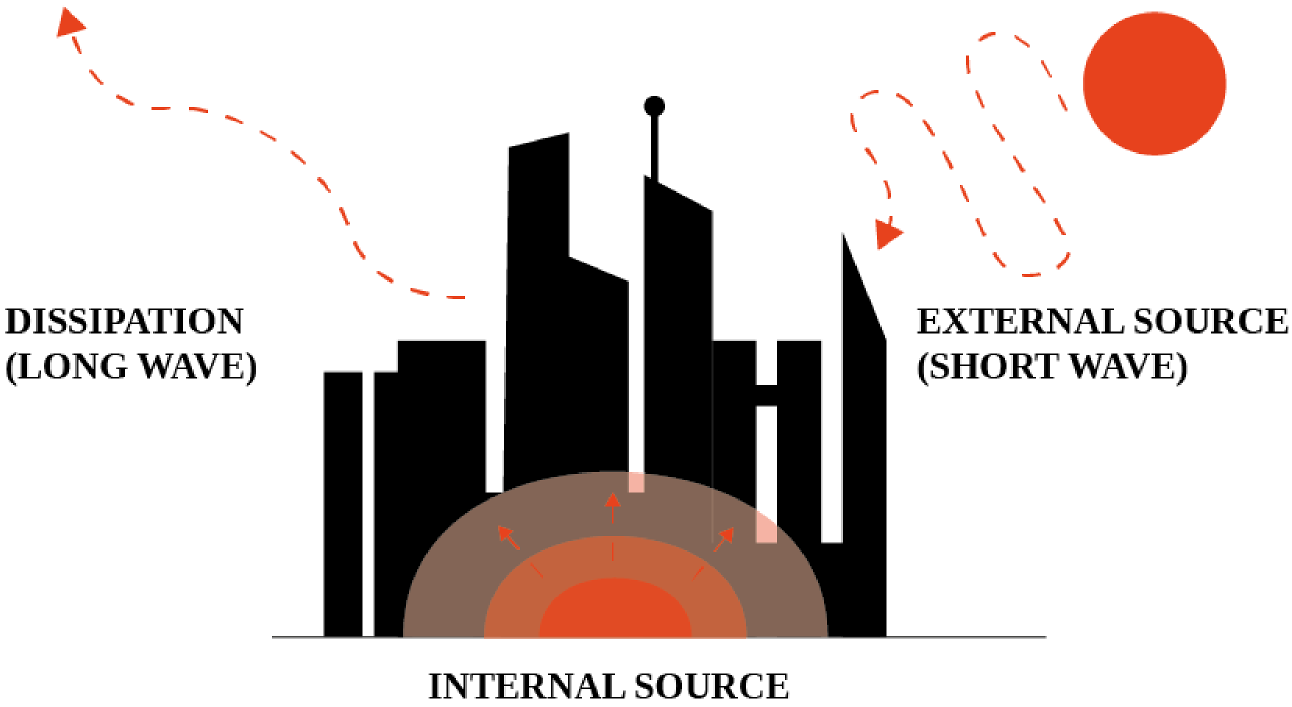


Fig. 6, the source of energy in the city and the release.

When it comes to heat storage it is very important to understand the thermal admittance values. This simply means the heat energy that a material absorbs because of large conductivity and high heat capacity. Density is a large factor for raising these thermal admittance values. This is problematic since dense materials such as asphalt or brick are needed to support the large surface pressure in the city, protecting important infrastructural systems such as pipes or subways. This is also true for stone or brick houses, owing to modern housing rather relying on thinner envelopes and more insulation to decrease the heat storage. Permeable ground will not only have a lower amount stored heat, but they will also allow for more dissipation of latent heat through heat fluxes from the moist soil and vegetation (Stewart, 2021).

The UHI effect could be boiled down to how much heat is received during the day, how much of it is stored and how effectively it is released. The releasing of heat as described before is a process that takes place both during the day and during the night. Table 1 categorizes the different properties of the city in accordance to their relevance to either; admittance (absorption), storage or release.

Firstly when it comes to received energy, the surface admittance plays a big role but there is also energy that stems from the city itself. This energy that originates within the city is called *anthropogenic heat flux*, or *heat output*. The energy is therefore received in one of two ways, the first is by shortwave radiation (surface admittance), the second one (anthropogenic heat output/flux) stems from processes in the city itself such as vehicles or other combustion such as heating houses or industry. Table 1 shows the *surface admittance* values as well as the *antropogenic heat output* for different urban structures.

LCZ (local climate zone)	**SURFACE ADMITTANCE** (*$J\ m^{-2}\ s^{-½}\ K^{-1}$*)	**ANTHRO. OUTPUT** (*$W\ m^{-2}$*)
1 – Compact highrise	1500 - 1800	50 - 300
2 – Compact midrise	1500 - 2200	<75
3 – Compact lowrise	1200 - 1800	<75
4 – Open highrise	1400 - 1800	<50
5 – Open midrise	1400 - 2000	<25
6 – Open lowrise	1200 - 1800	<25
7 – Open lowrise	800 - 1500	<35
8 – Large lowrise	1200 - 1800	<50
9 – Sparsely built	1000 - 1800	<10
10 – Heavy industry	1000 -2500	<300
A – Dense trees	???	0
B – Scattered trees	1000 - 1800	0
C – Bush	700 - 1500	0
D – Low plants	1200 - 1600	0
E – Bare rock	1200 - 2500	0
F – Bare soil	600 - 1400	0
G – Water	1500	0

Table 3: The surface admittance refers to the ability of the surface to accept or release heat, whereas the anthropgenic heat output refers to the energy generated by humans or human activity in the city, ranging from human metabolism to indoor heating. The important part of the diagram is the difference between the categories, since the units are too technical for this thesis,. Note that compact mid-rise sometimes has a higher admittance than compact high-rise, but usually very much lower values for anthropogenic heat output. LCZ is an abbreviation of "local climate zone". Data from Oke & Stewart (2012).

It becomes clear that the surface admittance is variable between the different media since heavy industry and bare rock, such as asphalted parking lots, have the highest values. When it comes to the anthropogenic heat flux the value becomes higher as the structure becomes denser and higher, with the exception of the heavy industry.

The amount of heat that is stored in the urban system is directly linked with the materials that are used. In highly urbanized areas it is often imperative to use heavy materials that can handle the large weight of vehicles and pedestrian pressure, as well as the lager houses; in some cases even skyscrapers. Dense and strong materials have a larger heat storage capacity as a rule of thumb (Stewart, 2021).

Oke and Stewart (2012) made study on a road in Vancouver that spans across many different local climate zones, which is shown here below. It's interesting to note that density of built space seems to correlate with departure of mean temperature, as is hypothesized by UHI theory.

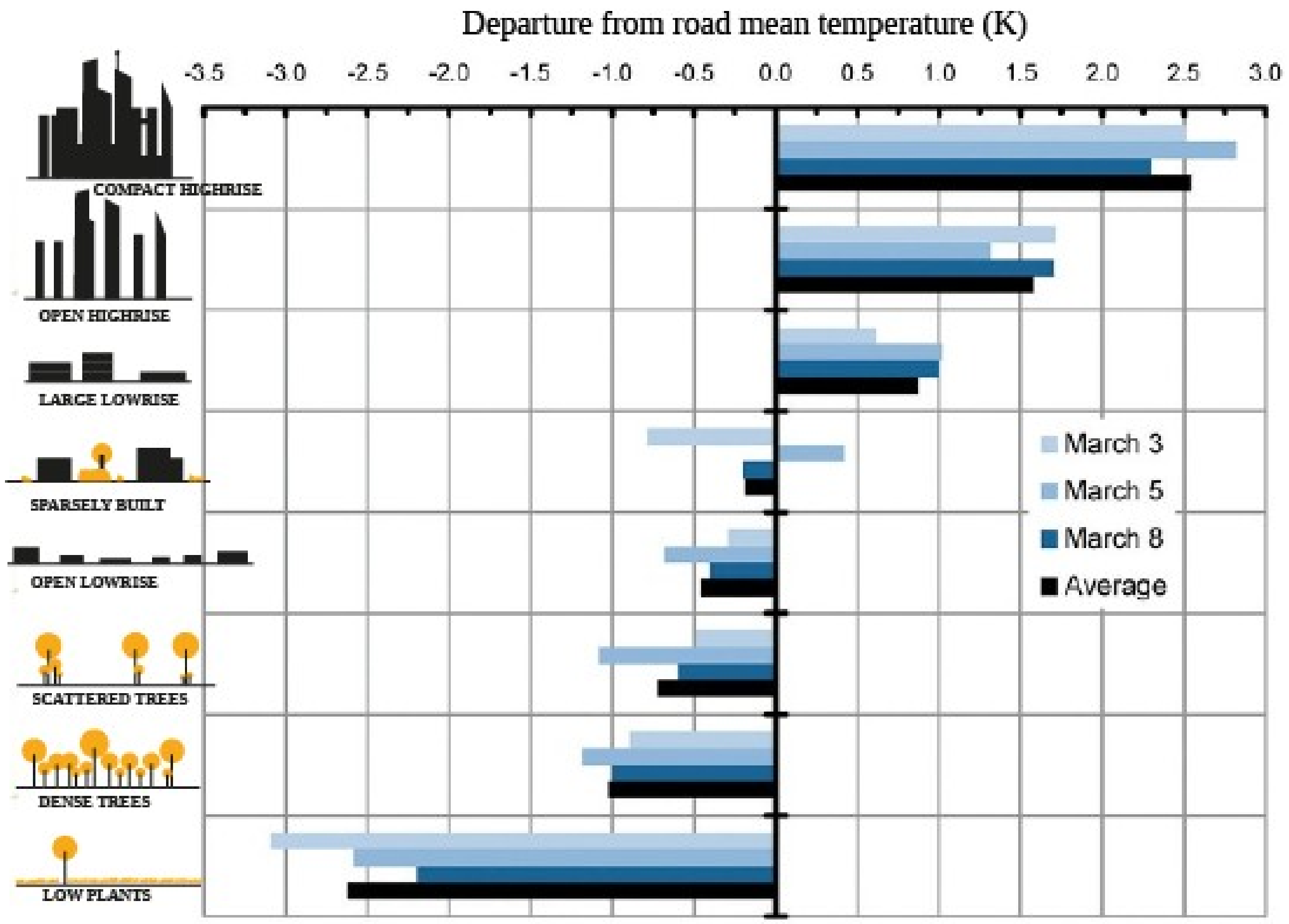


Fig. 7. The mean temperature seems to rise with city density. The reason for low plants to be the lowest might be for the large sky view factor, or it might be the fact that it might be a swamp, as it otherwise naturally would be wooded due to ecological succession. The reason for swamps to be effective at loosing heat is their large latent heat flux (Adapted from Stewart et al, 2012).

In terms of storage and admittance the asphalt surfaces are really troublesome, as shown in the graphic on the next page (fig. 8) by Stewart et al (2021). It is evident that the asphalt surface behaves as problematic as a desert surface during the day, but gives less of relief at night both in terms of surface temperature and air temperature. This is highly relevant since large areas of asphalt are sometimes constructed in the city.

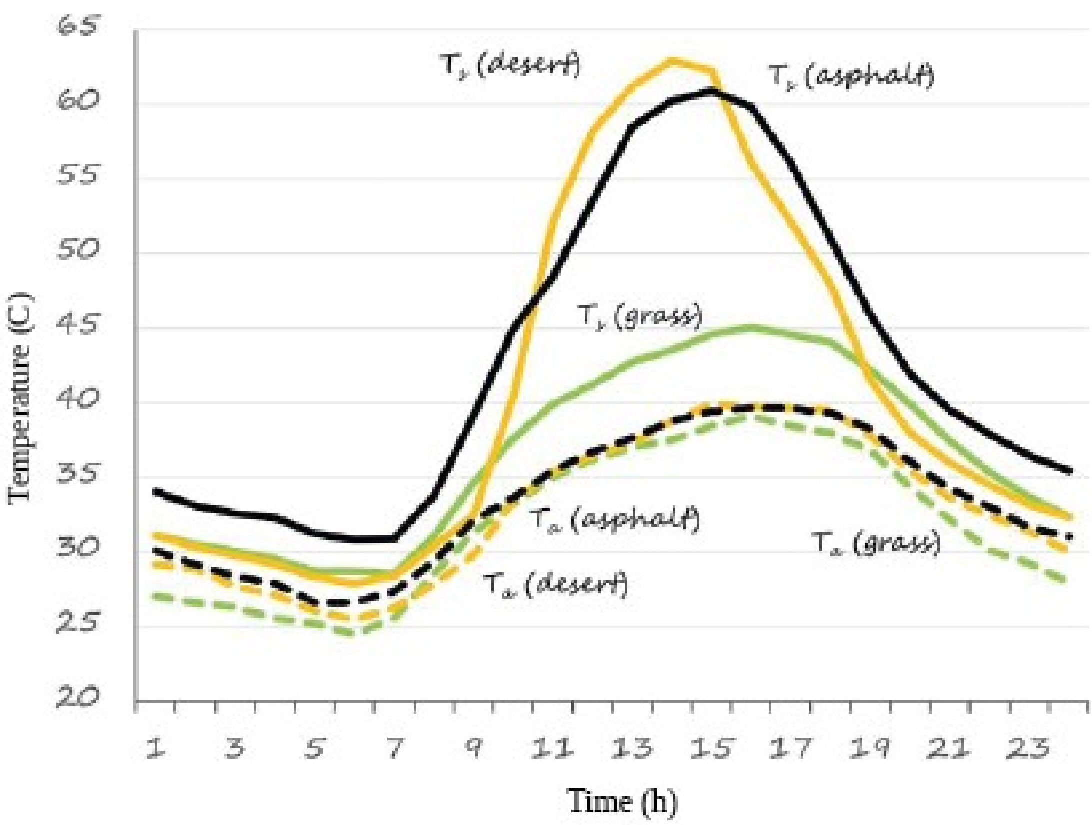


Fig 8 .The image shows the different temperatures of a grass, asphalt and a desert. The are coded with lowercase referring to the air temperature, the lowercase s refers to the surface temperature, the air temperatures are also made with a dotted line in contrast to the surface temperatures. Note how the surface temperature of the asphalt is almost as warm as a desert during the day, but sharply worse at night. When it comes to air temperatures, the grass is the coolest, the desert is second and the asphalt is worst (adapted from Stewart et al, 2021).

The *release* of energy in the form of long wave radiation at night is what is causing the elevated nocturnal temperatures in the city, both in terms of anthropogenic heat flux such as heat leakage from buildings but also from materials re-radiating the heat that has been stored during the day. How to reduce anthropogenic heat flux is a complex question and its detail is beyond this paper, but much of it has to do with building insulation and heat energy being a rest product from different processes in the city. On clear and calm nights there is a low heat flux from both latent and sensible heat due to weak airflow. This is troublesome since these conditions are also optimal for the UHI effect and the best way to tackle the problem, aside from minimizing stored heat in the first place, is to maximize dissipation of long-wave radiation.

An effective way to increase for the long-wave radiation loss is to increase the sky view factor, in order to minimize the recycling of radiation energy in the system, i.e. the radiation bouncing between the surfaces (commonly walls) of the built structures. The sky view factor is the greatest on the roofs, making them the coolest at night and since warm air has a lower density than cold air. This cooler air could potentially be used in the city as it would push up and away the warmer air on the facades and the streets. The usage of wind both in the form of local wind systems and the so called “land breeze” can be useful to mix the air in the city and to lower the temperature (Stewart, 2021) The land breeze is a wind that comes from the country side to the city as warm city air rises and creates a vacuum that drags in cool country air. This could potentially be strengthened in theory and give rise to utopic ideas such as wind corridors (Holden, 2017).

3.1.6 Summarizing the drivers of the UHI

Oke and Stewart (2012) list different properties that affect the local city climate and can be potential *drivers* of the UHI. Along with the importance of location within the city, the form of the urban geometry is also very important. This is called “canyon geometry” and is referring to the city street having a similar geometry to a canyon in nature. It is important to note that many of the properties delineated below are interlinked.

The first important property that is listed is the *sky view factor*, which can be described as the amount of sky that is visible from the ground. This is affected by the depth and the width of the urban “canyon”. The sky view factor affects radiative heating and cooling, by the amount of area that is exposed to the sun but also by how easy it is for energy to radiate back without bouncing back a second time (“being recycled”) in the “canyon”. It’s described in a factor from zero to one, where one would be an open field and zero would be a cave (Oke & Stewart, 2012). The sky view factor is a very powerful driver of the urban heat island effect. It has been shown to be able to push the city air temperatures in the urban canopy layer to be seven degrees warmer than the temperatures on the rural hinterland. During a night of low wind speeds the urban heat island effect can even be described as a function of the sky view factor, since the energy loss stems from radiation. Sky view factors of below 0.5 are typical for urban centers in Europe (Svensson, 2004).

The second property is related to the first one, and is the *aspect ratio*. It is simply the height to width ratio of the canyons, meaning how tall the buildings are in comparison to their spacing, as well as a measure of the spacing of trees. The canyon geometry and vegetative geometry is not only affecting the radiation but it is also a crucial factor for airflow. Objects will stop and funnel air and make air parcels mix as the objects create both halts and roughness (Oke & Stewart, 2012).

The third property is the *mean building height and tree height.* This, as in the case of the second property, affects the airflow and reflectivity but also the general heat dispersion above ground. It’s described in meters (Oke & Stewart, 2012).

The fourth property is the terrain roughness. This once again affects the airflow, surface reflectivity and heat dispersion above ground. The measurement is from 1-8, where eight would be a compact highrise urban core as described previously in this chapter (Oke & Stewart, 2012). The high roughness means stronger but generally less wind, such as is described by the *Venturi Effect* that can reinforce gusts into 3 times their original strength (Holden, 2017). This means that a high roughness leads to generally less airflow but stronger gusts as large quantities of wind is pushed through narrow canyons.

The fifth property is the building surface fraction. This is described in percentage of land that is covered with buildings. This once again affects airflow, reflectivity and heat dispersion above ground (Oke & Stewart, 2012).

The sixth property is the impermeable surface fraction, which is also described in percentage. This affects surface reflectivity but also the available moisture. The available moisture is also important for cooling and heating through the transfer of latent heat (Oke & Stewart, 2012).

The seventh listed property is the permeable surface fraction which has the inverse effects of the impermeable surface cover. It includes all hard surfaces where water cannot penetrate, like asphalt, cement, roofs etc. This property is also described in percentage (Oke & Stewart, 2012).

Number eight is the surface admittance. The surface admittance refers to the ability of the surface to gain or release heat, which will effect how much heat that is being stored during the day, but also how much is released. Some factors that control the surface admittance are the soil wetness (latent heat flux) and the material density (Oke & Stewart, 2012).

The ninth property is the *albedo*, or the “surface reflectivity” (Holden, 2017). This is measured during a clear midday sky and affects the radiative heating potential. The albedo will vary with color, roughness and wetness. It is described in a scale from 0.02- 0.5 (Oke & Stewart, 2012).

The last and tenth property is the anthropogenic heat flux. Sources of heat are machines, vehicles, heating of houses and even metabolism. It would seem as if the city can be described as a heat engine. The heat flux will vary greatly with population density, season, latitude and how houses are insulated (Oke & Stewart, 2012). However, if the wind is strong enough, the air of the city will be changed before it has anytime to heat up significantly. This means that there can be no UHI under conditions of very strong winds. The speeds of these winds that can undo the UHI vary depending on the size of the city, the bigger the city the stronger the winds have to be. One example is Montreal that requires 11 meters per second and another one is London that requires 12 meters per second. The *Venturi effect* in weaker wind speeds will cause turbulence in the air mixing the air masses in the canopy layer. This makes UHI effect to be more equally dispersed in the entire canopy layer (Holden, 2017).

3.2. Micro-climates in the city

Micro-climate is in this thesis defined as a set of climactic conditions that are specific to one limited environment. This could be a city street or a square that experience thermal modification due to site specific factors. From the previous part of this thesis, it becomes quite obvious that the micro-climate of the cityscape is affected by human influence. To account for the human scale it is also important to examine thermal conditions from a pedestrian perspective.

The most effective ways to decrease temperatures in city city microclimates is to increase shade and latent heat transfer. The two main ways to increase shade is by either green landscaping or by built structures. The built structures have a more opaque shade and are therefore more effective. The vegetation does however have the potential to be leafless in winter and let through light and provide winter warmth. The vegetation in itself can also have a cooling effect through the high latent heat contribution (Nasrollahi et al, 2020).

A recent study by Habibi et al (2020), studying the impact of the ancient Persian gardening techniques of an urban street in Isfahan, Iran, found that the design during the Safavid era (1501-1736) was far superior to modern designs when it comes to the support of thermal comfort. Even still, the current situation was 1.5 degrees cooler than a scenario without trees nor water. Moreover, the researchers conclude that the design during Safavid era was 7-15 times more favorable than the current and the “no trees or water” scenarios. At one of the warmest points of the day, at 14:00, the temperature of the Safavid era was 2-2.5 degrees cooler than the current situation, as well as 3-3.5 degrees cooler than the scenario without trees or water.

A review of different studies on urban micro-climate mitigation in pedestrian areas (Nasrollahi et al, 2020) found that the most effective ways to combat thermal discomfort was to plants trees for their shading capacity. It also found that the courtyard is the best urban structure when it comes to regulating thermal comfort. This is something that has been known for a long time and in use all the way back to ancient Egypt. In the urban canyon green walls showed to be much more effective than green roofs, and in very hot climates it was preferable to have a larger *height to width ratio* between buildings and streets to increase shade. In the review the authors present several examples of how much shade can effect the mean radiant temperature, as well as the actual temperature. But buildings provide shade in all seasons and it is evident that some climates need solar radiation in winter to provide thermal comfort, such as one case in of a study conducted in Shanghai. In Shanghai the researchers found that the outdoor presence of pedestrians was directly interlinked with the amount of solar radiation in winter, meaning that more radiation attracted more people.

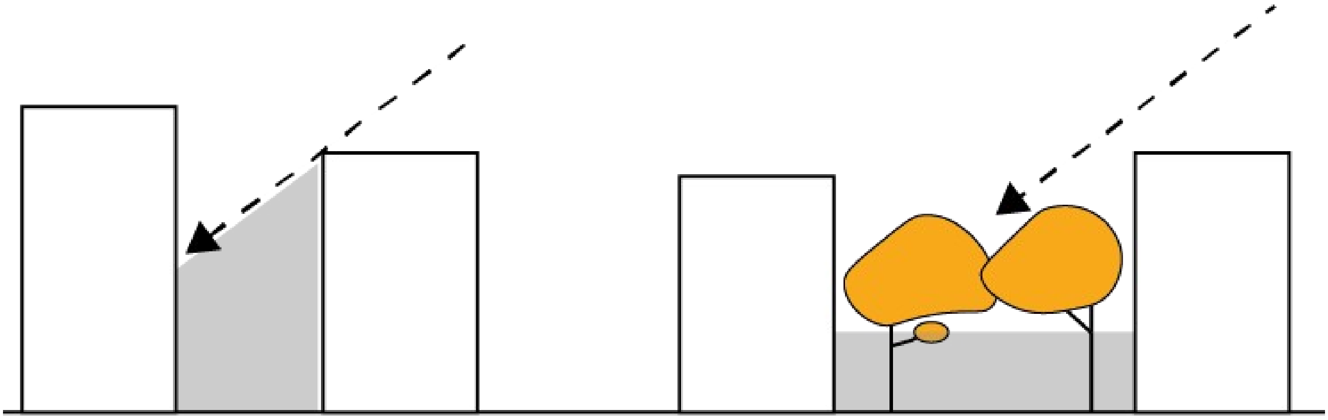


Figure 9. This illustration shows two different techniques of urban geometry to control the amount of incoming solar radiation. The canyon to the left is narrow and provides shade for a large part of the day for the pedestrians, its narrow street in comparison to the height of the buildings means that it has a high height to width ratio that is well over 2. The canyon to the right on the other hand is very wide and therefore has a low height to width ratio. Here the purpose is instead to create shade by vegetation. This shade might not be as opaque as the shade from the buildings but it could be designed to be deciduous. The benefit of using deciduous vegetation is that it adapts to the needs of each season.

In the same review there are several studies that focus on the effects of shading. During a normal summers day in Hong Kong, with an air temperatures of 29.7 C° , the surface temperatures that are exposed to solar radiation can reach 50-60 C° in contrast to shaded surfaces that would reach 30-34 C° . The review also showcases a Japanese study demonstrating that during a solar radiation intensity of 800 W/m ^{2} , the effect of a shading pergola was a 16.2 °C reduction in “universal-effective-temperature index”, whereas it was 18.4 °C from the more opaque shade of a building. The review presents another example of a study conducted in Cuba, showing that a height to width ratio of 0.5 (the street is double as wide as the heights of the buildings) had a mean radiant temperature (MRT) 20 °C warmer than a street that had a H/W ratio of 3.

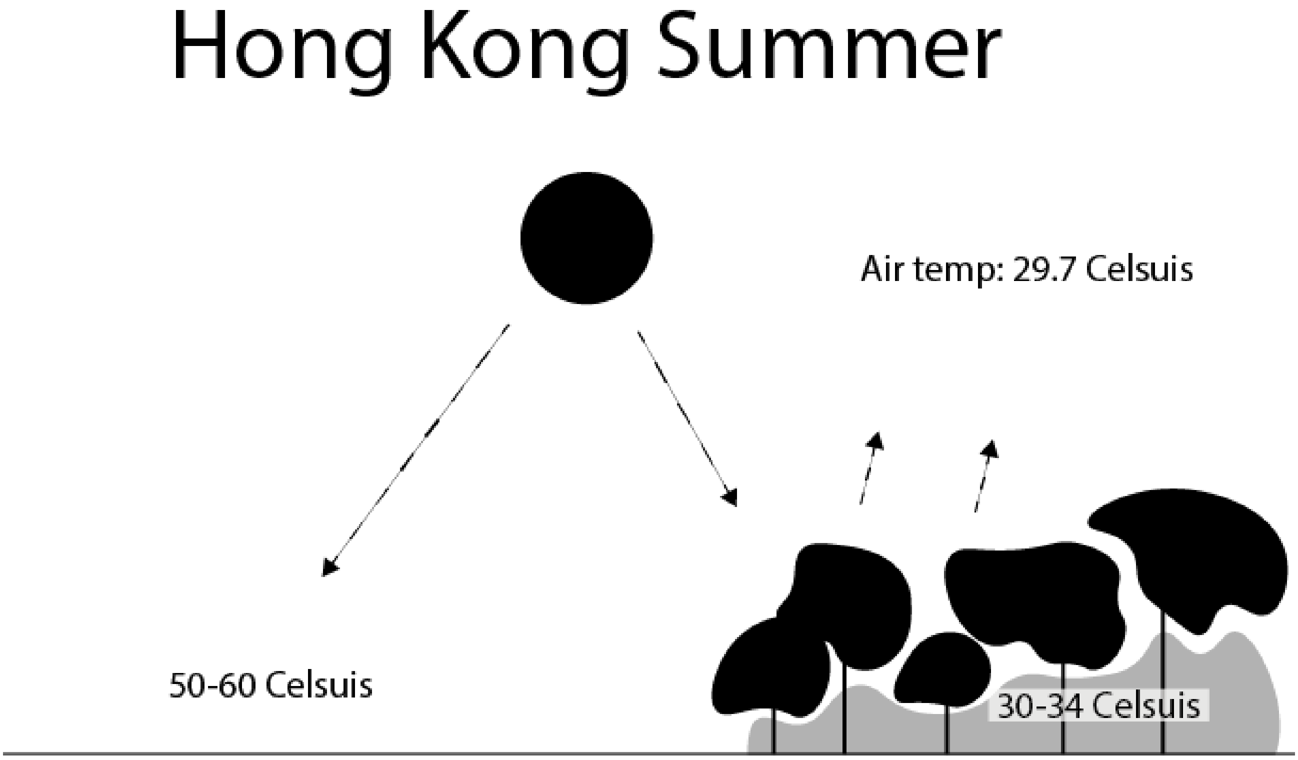


Fig 10. The difference between shade and sun exposed areas in Hong Kong, at the southerly latitude of 22° North (Nasrollahi et al, 2020). Note the radiation which is reflected back into space by the canopy.

The review furthermore presents studies on how the increased humidity can reduce air temperature and MRT. One of the studies from Bahrain found that the difference in MRT between a vegetated and a concrete area was 5 C°. This is in line with the theory of latent heat transfer that is presented previously in the chapter about the urban heat island effect.

For the Mediterranean climate in particular, there was one study (Alcazar et al, 2016) examining the effect of green roofs and urban forests on the micro-climate. The focus was on regulating the air temperature during the hot season. The study concluded that the green roofs had a moderate ameliorating effect on temperatures, but that the vegetation in the urban space had a larger impact. The vegetation was not only helpful for shading, but also for increasing soil moisture and therefore latent heat transfer. Furthermore, the potential of the latent transfer rises as humidity decreases since the air will be less saturated. This makes water and vegetation of special interest to hot and dry climates like those of the Mediterranean.

Another study (Yahia et al, 2013) conducted in the hot and dry climate of Damascus, Syria, also found that urban geometry and surface cover has a great influence on urban comfort at a pedestrian level. They found the H/W ratio and the orientation of the urban canyons to be most influential on micro-climate in terms urban geometry. The study also found that in the urban canyons, the relationship between the aspect ratio, orientation and vegetation all have a similarly strong influence. When there is no canyon on the other hand, as in the case of detached buildings, the influence of aspect ratio and orientation is rather weak. In the case of the absence of a canyon the surface temperatures and outdoor thermal comfort is rather dependent on vegetation cover.

3.3. Introduction to paradise gardens

3.3.1 Examples of early Egyptian and Persian garden traditions

The earliest clear signs of desert gardens are found in Egypt, not in Persia, even though Persia and Andalusia will be the more in focus in this investigation. Remains of gardens as old as 8000 years have been uncovered in Egypt. These gardens were not clearly designed however, and it would take until 2000 BC before garden design was practiced. It is thanks to their hieroglyphs, plans and drawings that can be found in the ancient Egyptian tombs that now we have an understanding of these gardens. This puts them into contrast with the ancient Mesopotamian gardens that have fewer records. The ideas and challenges of living in riparian desert environments however were the same since both the ancient Egyptians and the ancient Archemenids designed with water and shade to modify their microclimate. The use of water was especially prevalent, both on a smaller as well as a larger scale. A large scale example is the artificial lake at *Malkata*, created by the Pharaoh “Amenhetep III”, that was 1 by 2 kilometers wide. The extensive evidence for the use of water on smaller scales can be seen in the tomb text (fig. 11), showing a water basin surrounded by figs. The other image one more step below it (fig. 12) shows a ceremonial garden at Karnak, most probably meant to be a garden of the afterlife for the Pharaoh (Turner, 2005). The map can be interpreted with some freedom of course but something that is quite clear is the presence of multiple water bodies.

Fig 11, a water basin surrounded by fig trees (Turner, 2005).

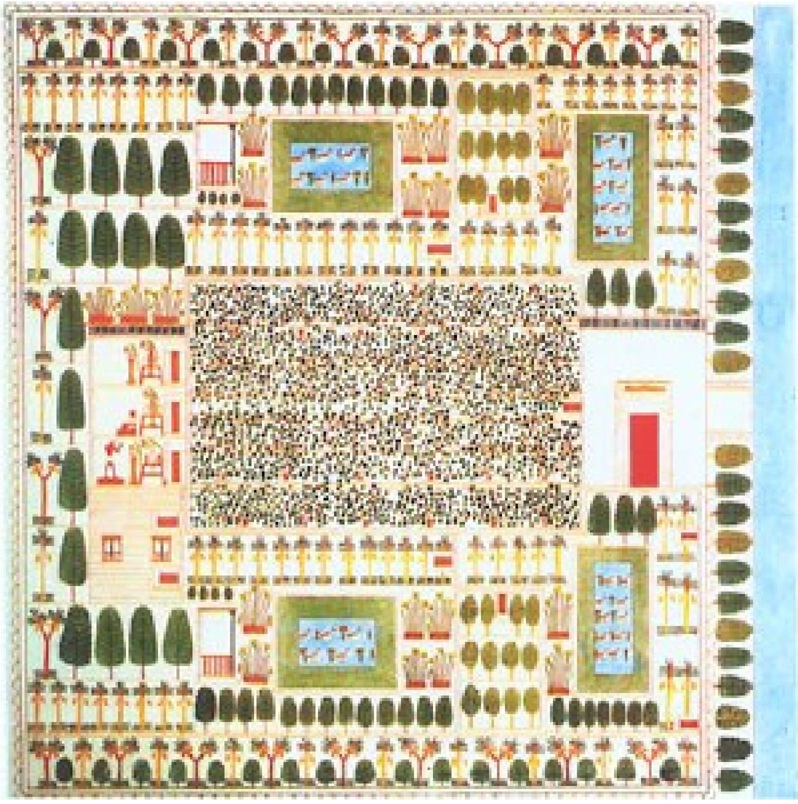


Fig. 12, a ceremonial garden with multiple water basins (Turner, 2005).

The domestic gardens of ancient Egypt were smaller than the kingdoms large palatial gardens. In the domestic gardens the emphasis instead lied on having an outdoor room not unlike the later traditions of constructing patios of Persia and Andalusia. To create shade they used vines and trees, and basins of water to improve the latent heat flux (fig. 12). There could be a potential problem with water bodies in the form of insects such as mosquitoes, to get rid of all the insects that live in the pools they used fish (Turner, 2008). Fig 13 is based on an interpretation of a domestic garden, with the help from material already provided by Turner (2005).

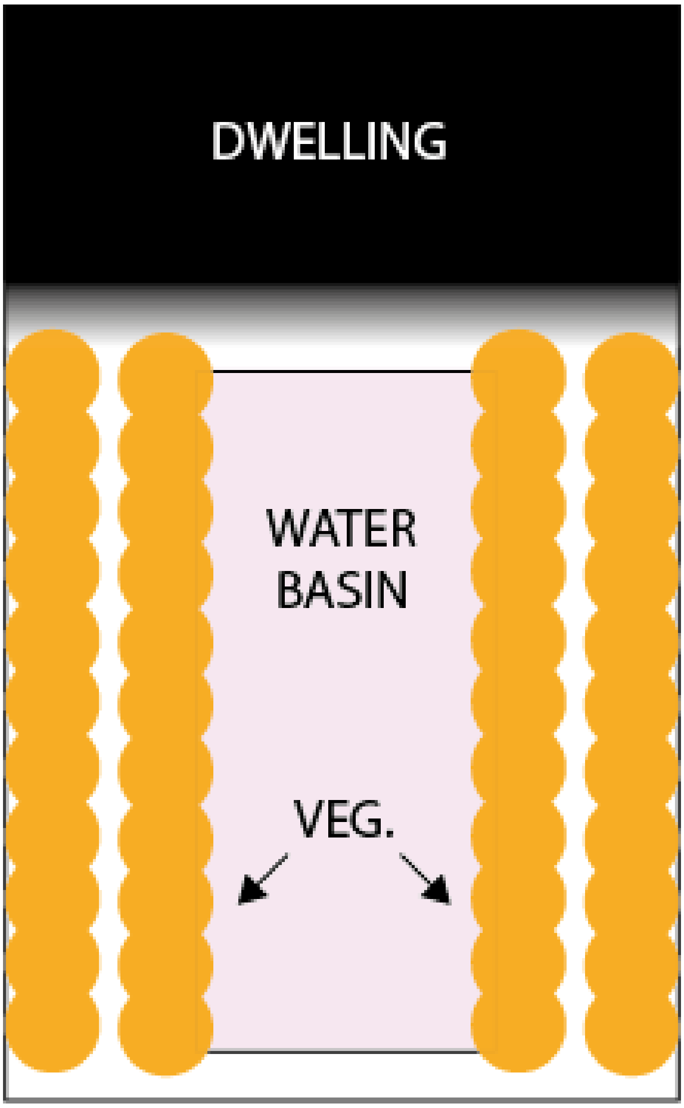


Fig. 13, A conceptual illustration of an Egyptian vernacular dwelling, house in black, sun shades in faded black, vegetation in orange and water in light purple. Material adapted from Turner (2005).

Furthermore the ancient Egyptians understood that it was important to control the radiation so that there are both places that receive solar radiation in the winter and places that receive shade in the long summer. This was accomplished with consideration to form and structure using axial lines connecting important nodes, and by including different features and vegetation such as pergolas with vines and trees. When it came to form and structure; the ancient Egyptians were interested in using axial lines that connected important nodes, like temples. These paths were often adorned with statues in formal cases, but they were also climatically adapted in the use of trees to block solar radiation (Turner, 2005).

With the introduction from the ancient Egyptian gardens, this thesis will focus on the on the gardens of ancient Persia. Since the ambition is to put the thesis into the context of Europe with further correlations to Granada, Spain, it will also focus on one of the European successors: the Moorish tradition of Andalusia. This selection comes quite natural, since Persian gardens have been influential for all the Islamic gardens according to Ruggles (2008), as she calls the garden of Pasagadae an ancient precedent for all the Islamic gardens. The Moorish garden style in the Andalusian tradition becomes most interesting in this respect due to the centuries of Arab rule in Spain. The Moorish garden tradition may not be a direct successor to the garden of Padagadae but traces of influence are discernible from the Persian traditions like in the case of Alhambra (Turner, 2005).

The ancient Persian gardens focus on creating a paradise that contrasts to the hostile outside environment by using the different resources to ameliorate the climate. The Persian garden ideal is that of a moderate climate, abundant vegetation and of soft light. To create these moderate micro-climates, they had to transport water from other places far away, changing the hostile and arid climate (Ruggles, 2008). In the context referring of modifying micro-climate, it is helpful to understand the etymology, i.e. the origin of words, since the origin of the word paradise stems from the old Persian word “paraedizo”. It’s original meaning translates into something like “enclosure” or “walled garden” (Turner, 2005).

The most important factors for the desert gardens are therefore water and shade, the water creates mist that increases evoporative cooling and the shade decreases received solar radiation on the ground (Faghih et al, 2012). The four elements of fire, wind, water and soil are also central to the Persian garden tradition. Water is especially important, since the goddess of the ancient Zoroastrian religion, Anahita, is the goddess of all water and thought to have the power of purification (Farahani et al, 2016). The connection between power and water is something that survived through the ages, and it can be seen in the lions court of the Alhambra gardens, where the central lion fountain also being a symbol of power (Ruggles, 2008).

3.3.2 Geometry and layout in relation to religion and mythology

One of the most important structures of the Persian and later Islamic gardens was the Chahar Bagh. This type of garden is often associated with the division of a garden in four parts by a cross-sectional water-course. Some garden techniques that are related to the Chahar Bagh are; a cross axial path surrounded by sunken beds, central fountain, central watercourse and water basins. The shapes of the water basins were rectilinear in the beginning, but transformed into more curvilinear and stellar patterns as time went on (Ruggles, 2008).

The origin of the Chahar Bagh, the traditional Persian garden, has connections with one of the ancient Persian religions, Zoroastrianism. It separates the universe into four parts, four seasons and four elements. These elements are: water, wind, fire and soil (Faghih et al, 2012). There is also a tradition of dividing the world into four corners, which was inspired by geometrical traditions of ancient Mesopotamia (Farahani et al, 2016). These versions of divisions in four bear a striking conceptual resemblance to the Chahar Bagh, which is a quadripartite garden structure.

The ancient Persian gardens were furthermore divided into parts that were meant as pleasure gardens and parts that were meant as productive gardens. These productive gardens thus were not accessible to the public (Khalilnezhad, 2017). In the sense of microclimates, it makes little difference if the trees are made for production or pleasure in terms of latent heat transfer, since all trees transpire water. When it comes to shade on the other hand there is a difference, as we can compare the smaller fruit trees such as pomegranates to bigger trees in the pleasure garden, such as the very common cypress or plane trees (Khalilnezhad, 2017). The ancient garden of Pasagadae (see section *Garden structure and wind*) is likewise believed to have multiple purposes as it is speculated that it served as both a hunting ground and a fruit garden (Fallahi et al, 2020).

Trees were widely used in the Persian gardens, since they decrease incoming radiation but also have a symbolic connection with the heavens. The evergreen trees were especially important since the trees of heaven were said to be forever green and forever fresh. The evergreen cypress was seen as a symbol of immortality, and the flowering almond was seen as a symbol of the regeneration of the earth in spring (Farahani et al, 2016).

There are contemporary studies of these four fold gardens, exploring the perspective of viewing them as fractals. As nature produces a symmetrical hierarchy of repetition, some human traditions have done so as well; like the Chahar Bagh. This fractal nature might originally has been meant to represent divinity but it was also meant to represent ideals such as fairness and equality since they are divided *equally*. According to Patuano et al (2021) the Persian gardens contain a very high degree of self-replication, scale in-variance and that they have a high fractal dimension. The researches also speculate in the effects of applying these design ideas to and urban fabric, making for a more just city as equality was one of the original ideals of the Chahar Bagh.

3.3.3 Geometry and layout and its influence on micro-climate

The sky view factor for the gardens themselves is of little interest since the trees mostly block radiation from ever reaching the ground in the first place. However, the walled enclosure of the gardens meant that most of the incoming radiation that was redirected out to atmosphere instead of being captured within the garden space (Ruggles, 2008; Fagigh et al., 2012) The large water basins being used in Andalusia (Campbell, 2018) make for an elevated sky view factor since they created a large area that was without buildings, as well as adding latent heat transfer. The most important factor for the amount of sky visible is the relation in between the height of the structures and their spacing.

Garden structure and wind

An example of a very old garden can be found in the ruins of the palace of "Cyrus the Great". It was built 559 years BC in Pasagadae, which was the name of the capital of the Archaemenid empire in what is today Iran. The royal garden has a rectangular bed, that shows some evidence pointing towards that the garden might have had a cross-axial water course, dividing it in four parts, fitting with the general idea of Chahar Bagh. Moreover, the evidence for the sight-lines dividing the space into a four part geometry even if there was not cross-axial watercourse. There is also conclusive evidence for stone water channels with regularly spaced rectangular basins on three sides of the basin, making a case for the cross-axial water course as a hypothetical form of irrigation (Ruggels, 2008). These channels were made of limestone blocks that were over 1 square meters wide, and the channels themselves were found to be 25 centimeters wide and 12,5 centimeters deep (Campbell, 2018).

The central cross axis was often used as a means of irrigation outside of its symbolical and ornamental value. They were often connected with a water reservoir, and when these waterways were flooded, they provided moisture to the vegetation beds. This might also be the origin of the sunken beds, since the water needs to stay in the beds and not escape into other parts, especially in dry climates where water is precious. The water flow to these channels was controlled by rocks that were stopping the water, and the irrigation usually continued for a couple of hours (Ruggles, 2008). Irrigation was so important that it’s speculated that this is the origin of the four divided structure (Farahani et al, 2016).

The four divided garden can also be found in the Palatine gardens, starting to appear in 8th century. The very first one is the Umayyad garden at Rufasa in what is today Syria. After this there is also evidence for a quadripartite garden in the Andalusian “palace city” built 936 near to what is today Cordoba (Ruggles, 2008).

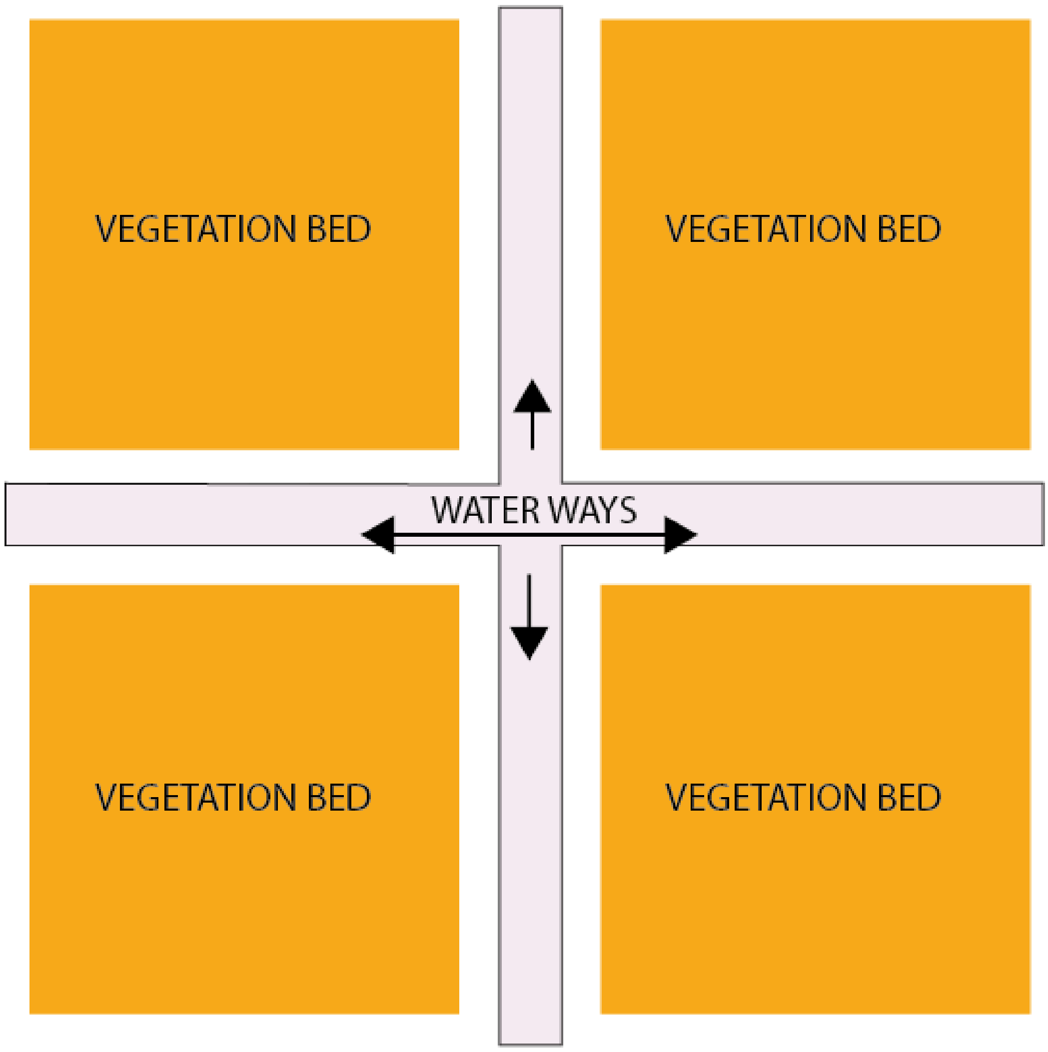


Fig. 14, A conceptual illustration of the traditional Chahar Bagh, showing a striking resemblance to for example the “Casa de contratación”, (Fig. 24) (Adapted from Ruggles, 2008).

The early shapes of the paradise gardens were rectilinear squares or sometimes rectangles and later change into more curvilinear and stellar shapes (Shahidi, 2010; Ruggles, 2008). These shapes, or constellations, were not rigid in comparison to the western gardens that follow the perspective principles. Instead they were more adaptable to the site and local environment they were in, as shown in Bagh-e fin (Farahani et al, 2016). The sizes of the paradise gardens and the Moorish gardens differ, but in the Alhambra, the aim was for the garden to be surveyed from one view, in order to reach “maximum delight” without letting the eyes wander (Hussain, 2014).

One study set in the city of Shiraz, Iran about the effectiveness of 9 different traditional Persian gardens patterns in means of lowering mean radiant temperature, found that the Chahar Bagh of Pasargadae was the least effective (Ojaghlou et al, 2019). The most effective of all the nine structures in the study is shown in fig. 15.

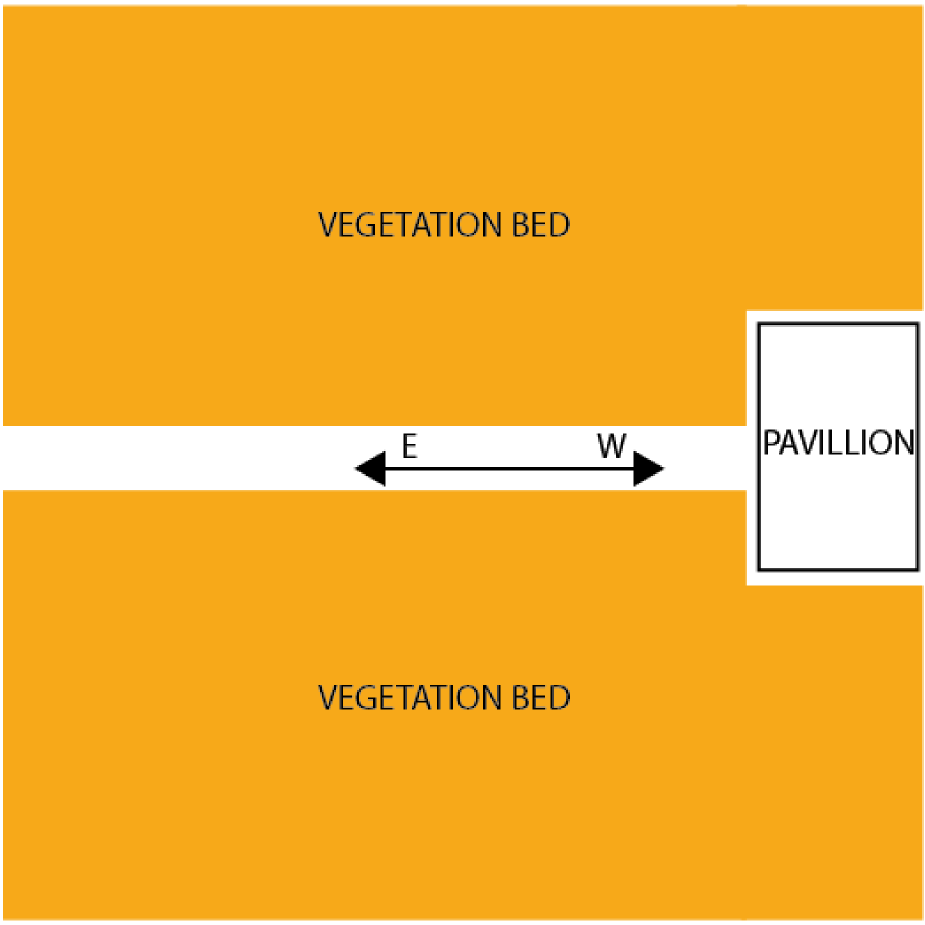


Fig. 15, A conceptual illustration of the most effective structure for micro-climate, based on a study by Ojaghlou et al. (2019).

Wind, as discussed in the previous part of this chapter, is crucial for heat dispersion. A bio-climactic analysis of García-Pulido (2018), with focus on the Aljiares palace in Alhambra found that winds and ventilation had great importance for both active and passive cooling.

The structure of Andalusian housing often used a patio as a means of ventilation and thermoregulation. The patio accumulates the cool night air and works as an insulation from the heat during the day. Due to its lush vegetation cover and large amounts of water, it has been shown to be as much as 12 degrees cooler and a 15% higher humidity than the outside. The *venturi effect*, which is also previously discussed in the chapter on the UHI, as well as the *stack effect* were used to cool the buildings. Both rely on cooler air from the outside coming in, as well as warmer air from inside dissipating out (García-Pulido, 2018). The effectiveness of the patio is of special interest since a city square could potentially be viewed as the patio of a whole city block. There are also other quantitative studies (Soflaei et al, 2016) that show that the patio effectively cools buildings.

In the Persian gardens wind also played an important role and it was influenced by the gardens being walled or patios. The gardens often used evergreen trees as wind break, as seen in the garden of Shah Zadeh, Mahan-Kerman (Tajaddini, 2011).

Surface materials and solar radiation

For the original Chahar Bagh, the four partite garden, the large part the surface was covered by plants, since the only paved part was a central walkway/water flow.(Ruggles, 2008) In Pasagade 2600 years ago these channels were made of limestone, and in the later gardens of Andalusia they were often made of stone, but sometimes marble or even clay (Campbell, 2018).

A large part of the ground materials of some of the palaces in Andalusia were actually only made up of vegetation depending on how the “ground layer” is defined. Since the sunken beds were set so low that the green carpet of the crown layer would be at the same level as the path (Ruggles, 2008).

Fig. 16, Patio de los Naranjos (Cordoba), showing the same idea of irrigation as in Seville (fig. 20) but with a different ground material. This material is also common in the Alhambra and the city of Granada. Here the water channels are also open, in contrast to Seville.

One study from the Alhambra using x-ray and chemical analysis reveals that the most common building materials were made up of calcite, dolomite and quartz, and to some extant oxides, sulfates and clays (Oliveira et al, 2019). Another study researching the earthen walls of the Alhambra found that the main binding material was clay, and that the outer layers consisted of calcareous materials(CaOH2) (Lanzon et al, 2020).

There is also evidence that the Sassnians (224-651 BCE) extensively used timber and stones for construction of their temples. The only tree found to have been used in the contruction of these palaces was the cypress (*Cupressus sempervirens*), which also had other importance in the ancient Persian culture. There is also some speculation that wood was an important material for the earlier Archemenid empire that built Pasagadae (Djamali et al, 2017). Pasagadae itself however was dominated by micritic limestone that were made up of calcite, goethite and quartz, but varying in color from dark to white stones, according to mineral analysis (Emami et al, 2018). The abundance of calcite is usually a sign that the material used is limestone, something that can be seen in other places as well, such as the temple of Anitha, the *water goddess* mentioned before, in Kangavar (Bamoos et al, 2020).

In the Alhambra the people protected themselves from the heat by constructing with materials with a large thermal inertia (García-Pulido, 2018). The high thermal inertia makes the buildings stay cool throughout the day but the large amount of heat stored in the walls of the housing keep radiating out into the city space throughout the night (García-Pulido, 2018). This type of design in a dense city area that suffers from heat would be unadvised, since the heat dissipation at night would worsen the urban heat island effect. Even this type of city lets in less radiation in the first place, there will always be streets of parts of streets that face north-south direction that will let in radiation, that will radiate back during the night.

3.3.4 Water

Fountains

Fountains were important in the gardens of both Andalusia and Persia and often formed a focal point, as seen in the court of lions in Alhambra. The central position is an inherited feature from the Persian gardens, but were also essential from a practical point of view since they provided cooling (Campbell et al, 2018). The fountains of the ancient Persian gardens and those of Alhambra differ in their workings and their appearance, but they all provide important mist and latent heat transfer as discussed previously in this chapter. The Persian gardens gardens were fed by the Qanat. They engineered nozzles to make the water cascade out with relatively low pressure as seen in Bagh-e fin (Ruggles, 2008). In Bagh-e fin the fountains are described as bubbling out more than being a real cascade (Campbell et al, 2018). The Alhambra today on the other hand has jet fountains, as shown here in a photograph of the Acequía court (Fig. 17). The original jets of the Acequia court were fewer and also less strong since they were also fed by mountainous Qanats. The modern jets were added by the mid 20^{th} century by the architect *Prieto Moreno* (Ruggles, 2008). The original fountains from the Moorish period were aided by nozzles to give a stronger pressure that could make the cascades reach higher, as they were said to reach ten feet (3+ meters) by Andrea Navagero in the 14th century (Campbell et al, 2018). Persia did also use jets in their later gardens of the Safavid period (1500-1736), as the Hazar Jarib garden of Isfahan was decorated with 500 jets (Fekete et al, 2015).

Fig. 17, The Acequía court, here all the historically incorrect jets installed by the architect Prieto Moreno can be seen. A fountain in the shape of an open lotus flower is also visible in the foreground, as well as pot plants. The Acequía court probably also had sunken beds by some 20 centimeters, adorned with herbs and shrubs. A photo of the flower beds can be found in the appendix.

Flowing water is a powerful tool in the Persian and Andalusian gardens not only because of their obvious aesthetic appeal, but also in the form of climactic regulation since flowing waters create mist. Flowing waters as well as fountains also create special sounds that are pleasant for the user (Shahidi, 2010). Harvey (1974) describes it as a “rumorous sound” and points to the gardens at Generalife, where the runlets had been reduced to the tops of the parapet walls as seen in the picture below. This way the water can still freshen the atmosphere but require smaller quantities.

Fig. 18, The runlets on parapets as seen in Alhambra. Note how the visitors are invited to run their hands through the water and cool off.

Pools

The mirror reflects peripheral environments and thus it expands the view of the landscape and the architecture (Shahidi, 2010). An excellent example of a mirror is that in the court of the myrtles in Alhambra, Spain, as shown in the photograph below. The common use of a central basin in the middle of a patio is called an “Alberca” (Harvey, 1974).

Fig. 19, Court of myrtles, the large water basin both reflects the architecture, but also provides both latent heat transfer and large sky view factor, and thereby bettering the microclimate.

The idea of a basin is to create an elevated pool that reflects the environment, both people and architecture. The basins at Alhambra and Generalife were often made in marble or stone, usually made from only a single piece. There was a tradition of sculpting the basins into the form of open lotus flowers and this can be seen in many places in the Alhambra (Campbell, 2018).

In Andalusia the concept of still pools has been widely used, and was often a used as a space for reflection. This can be seen in the “court of myrtles” in Alhambra. Another example is the giant pool now in ruins in *Al-munjat al Rumminiyya*, outside of Cordoba. This pool was built in the 10th century and was very large, 49.7 by 28 meters with a depth of 3 meters (Campbell et al, 2018). This amounts to a volume of 4174,8 cubic meters at full capacity, almost double that of an Olympic swimming pool that has a volume of 2500 cubic meters.

In ancient Persia the pools often served as a reserve for watering the garden, but also for settling dust or cooling the microclimate. The pools vary in their shape and form, and the most common were; rectangles, squares, circles, octagons, cross, lobe and many times the form was related to the nearby building. The pool walls were often made in dark marble or granite to match the water of the pools, which was commonly dark and shallow to best reflect the buildings. The important Persian architect *Pirnia* said that the walls of a pool should be higher than the pool itself. This way the water creates the illusion of an endless pool when it overflows. The pools were often situated along the longer axis of the Persian gardens (Fekete et al, 2015).

Channels

A very important reason why the Arabs and the Persians managed to make the desert bloom is because of irrigation. As rain might not fall for long periods of time in the desert the soil dries up and is not able to soak the water when it does fall. This state of no soil-moisture is also the case of many urban centers since we use asphalt and other dense materials as a carpet for large parts of the city. The Arabs, however, made this into their advantage by transporting water underground in a system of channels called “Qanat” (Ruggles, 2008). The idea of constructing channels is hardly something new, but transporting water underground in order to provide moisture for shade giving plants could be essential. This is especially true during the summer months in a city like Granada, where rainfall is so scarce that evaporation cannot be afforded. There is also possibility of connecting some waste water to these “Qanat”, and as the soil moisture increases the possible selection of plant species will also increase.

The system of qanats that were laid out in Archemenid empire, 5th century before Christ, is still used today in Iran. The Qanat of Qassabeh is of a particularly large with its depth of 340 meters and length of over 31 kilometers (Campbell, 2018).

The other form of irrigation that was used by the Persians was the wadi, which is a seasonally fed stream that was connected to orchards and the like. These were usually barraged by rocks in case the current would grow too strong (Ruggles, 2008). This could provide an inspiration for open water management in the city.

Other types of open channels that weren’t fed by seasonal streams were also used, often constructed in stone, clay or marble. It could be just to show the movement of water or to irrigate vegetation as seen in Patio de los Naranjos, Seville. Here the water is lead from the central water feature to orange trees through brick channels as seen in figure 16. There is some evidence that these channels in Seville might one day have been made out of stone (Campbell et al, 2018).

In the very beginning of channel design in Persia the channels were narrow and shallow, but later with the evolution of design they became wider. This changed the structure of water, allowing for zigzag or wave patterns that gave the impression of more movement (Fekete et al, 2015).

Fig 20, Patio de los Naranjos (Seville), the water flows in channels from the fountain to the orange trees, the stems of which are visible in the square plantings. Note the ground material (brick) in comparison with Patio de los Naranjos in Córdoba (Fig. 16).

Waterfalls

Some gardens had strong topographical features, that in turn gave a reason to create terraces. When the water flows from one (upper) level to the other (lower), it creates an impressive cascade as can be seen in Mahan Garden in Kerman (Fekete, 2015). This is a great way to increase the amount of mist in the local micro-climate since it does not require propulsion or a specially designed nozzle like a jet would. It would be only the natural flow of the water without any redirection needed.

Andalusian zoomorphic spouts

The gardens of the Andalusia of course differ from the gardens of ancient Persia and Egypt, and all the photographic material below comes from Andalusian gardens. One thing in particular that the Andalusian gardens are famous for is their usage of *zoomorphic* spouts and fountains, meaning fountains that are shaped like animals. Many of them them were made in bronze and because of this only a few have survived through time since they were melted as soon as they became out of fashion. Some however still exist, like the lions in the court of lions in Alhambra. An important difference from the current fountains at the court of lions is that there are indications that the water did not use to exit the mouths of the lions in a jet, but rather slowly “pouring out” as described by *Lalaing* in 1504 (Campbell et all, 2018).

Fig. 21, zoomorpic fountain, in the Alhmabra. Note the channels dividing the court in four, as is common in the Chahar Bagh. Notice the very high albedo of the ground material, which can cause glare.

3.3.5 Vegetation

Trellising

There is evidence that trellising was used in the pleasure gardens, as seen in the manuscripts from the *Bayad wa Riyad*. The trellises were originally structures for the vines to climb, so that the fruit wouldn't stay on the ground and rot. As the vines climb, they create fresh and living green walls. In the Andalusian manuscripts these green walls are shown together with their fruit, flowers, singing birds, water basins and domed kiosks. These trellises can also be used to create green roofs, supplying valuable shadow in addition to their granted gifts of wonderful smell and color (Ruggles, 2008).


Fig. 22, Trellising of Nerium oleander in Alhambra.

Trees

There were two main categories of trees: those who gave fruit or those who provided shade (Khalilnezhad, 2017; Farahani et al, 2016). The shade was in fact so important that all paths were designed to be as narrow as possible to minimize sun exposure. The typical shade tree would be the cypress (*Cupressus sempervirens*), that was especially common along the waterways in order to minimize evaporation (Farahani et al, 2016). This way trees were often placed along the main axis, being usually pines, cypress or planes (Shahidi, 2010). Cypresses can also be very long lived, with the example of Alhambra, where some cypresses are said to be over 600 years old (Harvey, 1974).

The aesthetic part of the larger trees was also very important, as they were meant to draw the visitors eyes up from the ground and the sunken beds. The most common trees in the Andalusian gardens were cypress as mentioned before, but also date palms and oranges (Ruggles, 2008).

In Andalusia there is also a history of using poplar as the main tree for avenues, as these are often called ”Alameda”, stemming from the Spanish word for poplar “Álamo” (Harvey, 1974).

According to the “treaty of agriculture” written Nasrid agronomist Ibn Luyun, the ideal positioning of vegetation is where it blocks the midday sun. This is something that is still in use to this day in his home city of Granada, which is also the home of the Alhambra and Generalife (García-Pulido, 2018).

Fig. 23, A path accentuated by Cupressus sempervirens in the Alhambra. Note the water runlets along the sides.

Planted beds

Sunken beds were widely used, both in the Chahar Bagh but also in the Andalusian garden adaptations. They provided not only visual stimulation, but also delicious scents such as jasmine and roses. This is readily shown in the courtyard of “Casa de contratación”, in Seville, Spain (fig. 24). In many cases the plants in the sunken beds were planted at a depth of half a meter or more, so that they could grow to maturity before reaching the ground level of the visitor. This way the flowers of the plants could form a carpet mosaic not unlike that of a textile carpet lain on the ground or that or a large water basin. The fact that the sunken beds never rise above ground level also allows the visitors gaze to uninterruptedly perceive other parts of the garden. The flowers of the sunken beds, often narcissus, saffron crocus, chamomile, anemone, margaritas, roses and violets, were mostly planted low enough for visitors to see them from above as dashes of color in different shapes in the otherwise green carpet (Ruggles, 2008).

The sunken beds were often not only meant for visual enjoyment of the visitors, but they also provided crops to some extent, as was the case in Alhambra (Hussain, 2014). Their origin might have been a rational response to the need of irrigation. The flowering oranges were especially important for gardens of Alhambra since they gave both beautiful white blossom, perfumed the air and gave fruit (Ruggles, 2008).

Fig. 24, Casa de la contratación, Seville, with the sunken beds are visible, but the ground level “carpet mosaic” of leaves and flowers has been exchanged for taller orange trees. Note also that the central waterway is dry.

3.3.6 Conclusion garden techniques

In connection with the urban heat island theory, there are two main ways that the desert gardens combats heat. First of all they try to minimize the amount of radiation received by shading, then they try to increase the latent heat flux with water, as well as creating large sky view factors for these places, like in the case of the large pools of the Alhambra or ancient Egypt. Finally, they try to create structures that maintain an abundance of water all year around the shade giving plant life. Having a history spanning 8000 years, the desert peoples discovered a number of different ways to do this, and in the result (table 7) I present the techniques that are of interest to this thesis.

4. Result

4.1. Urban heat island

From the literature study it can be concluded that the urban heat island is affected by the amount of energy being received and stored in the urban system, the amount of energy that is generated within the urban system itself and finally how effectively the energy escapes. An illustration of a simplified urban energy system can be seen in figure 6.

Reception and storage of energy

FACTOR	EFFECT	SOURCE
H/W ratio (aspect ratio)	Controls incoming radiation	(Oke & Stewart, 2012)
Sky view factor	Controls incoming radiation	(Oke & Stewart, 2012 ; Svensson, 2004)
Albedo	Controls energy absorption	(Holden, 2017 ; Oke & Stewart, 2012)
Building surface fraction	Controls incoming radiation	(Oke & Stewart, 2012)
Surface admittance	Storing energy in the urban system	(Oke & Stewart, 2012)
Mean tree and building height	Controls incoming radiation	(Oke & Stewart, 2012)

Table 4, Showing energy is being externally received and stored

Generation of energy

FACTOR	EFFECT	SOURCE
City size and density	Controls the amount energy being created	(Holden, 2017; Oke & Stewart, 2012)
Anthropogenic heat flux	Controls the amount of energy being created	(Holden, 2017 ; Oke & Stewart, 2012)

Table 5, showing how energy is being generated within the urban system

Dissipation of energy

FACTOR	EFFECT	SOURCE
Surface admittance	Controls the rate of dissipation	(Oke & Stewart, 2012)
Sky view factor	Controls the amount of “recycled radiation”	(Oke & Stewart, 2012 ; Svensson, 2004)
Wind conditions	Controls the removal of latent and sensible heat	(Holden, 2017 ; Stewart, 2021)
Bowen ratio	Controls the amount of latent heat	(Holden, 2017 ; Stewart, 2021)
H/W ratio	Controls the amount of “recycled radiation”	(Oke & Stewart, 2012)
Terrain roughness	Controls the overall wind amount	(Oke & Stewart, 2012; Holden, 2017; Stewart, 2021)
Building surface fraction	Controls roughness and sky view factor	(Oke & Stewart, 2012)
Impermeable surface fraction	Impacts the bowen ratio	(Oke & Stewart, 2012)

Table 6, showing the factors that control the dissipation of energy in the urban system

Spatial structures

Furthermore, it has been shown that a denser city would have a more important urban heat island effect. This makes the following structures the most effective at causing urban heat islands; compact high-rise, compact mid-rise and heavy industry. The heavy industry has strong impact mainly because of its large antropogenic heat flux. Here below a graph can be shown of the different structures.

In terms of classifying the site of Puerta real in the different city structures presented by Oke and Stewart (2012) (fig. 2, 3, 4), it has many characteristics from compact midrise (2). It is seen here below in the graph mapping these city structures. The only structure that has both larger anthropogenic heat flux and surface admittance is heavy industry, as can be seen in figure 25 here below.

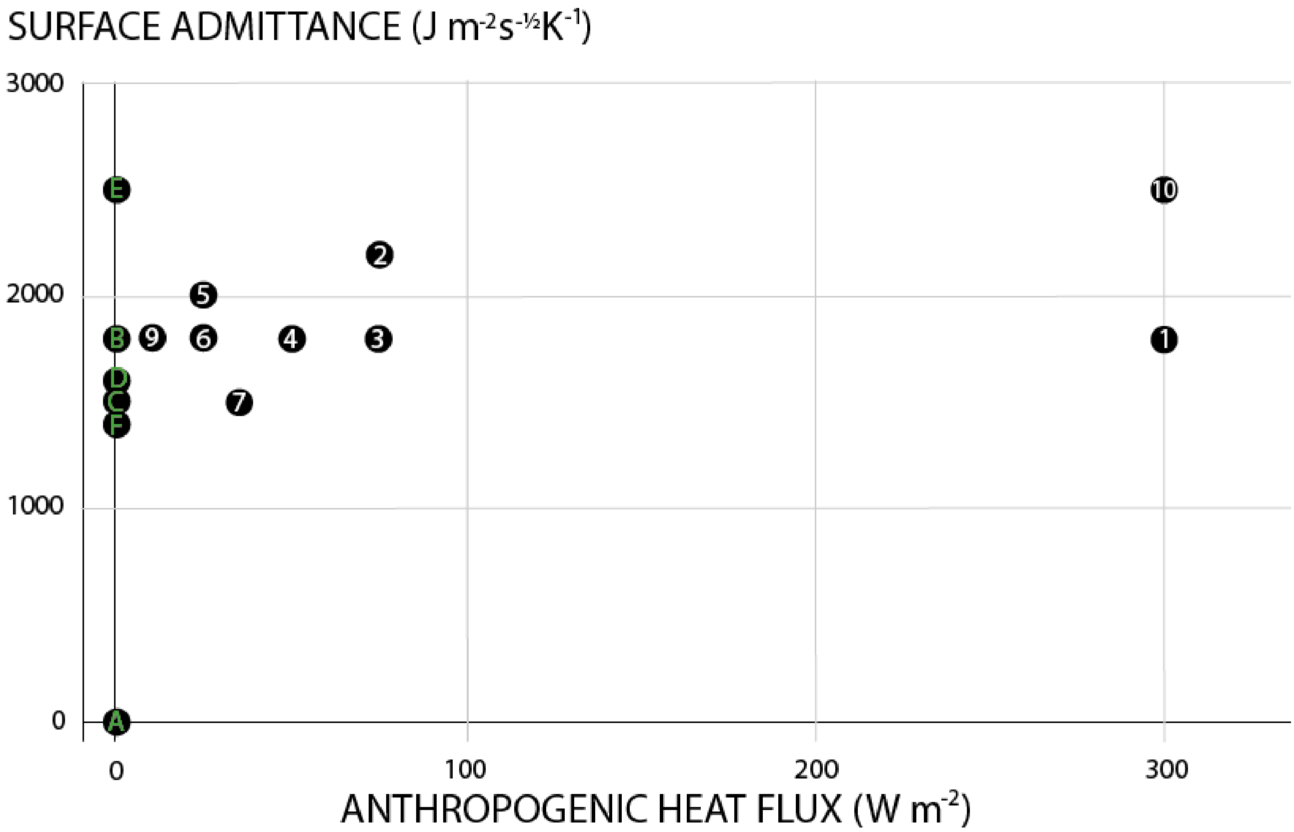


Fig. 25, the different city structures presented by Oke & Stewart(2012) and also data adapted from their work. In theory, being further to the upper right on this diagram would imply a larger urban heat island effect. The built structures have white letters while the vegetative structures have green letters. It should be noted that the values for 4 and 8 are the same, as well as G and C. This is why neither G nor 8 are visible above.

Microclimates

The main point that can be drawn from the desk study of micro-climates is that the two most important factors are shade and latent heat transfer. The difference between shade and sun exposure can be stark, and in some cases lethal, e.g the 60 °C temperature in the sun on a normal summers day in Hong Kong as seen in fig. 10 (Nasrollahi et al, 2020). There are two main ways to increase shade in the urban fabric, either through an increase in the H/W ratio, or by vegetation. Buildings give a more opaque shade and reduction in radiation, but fail to let through light in summer. In cooler climates the winter sun is directly linked to the amount of time people spend in public spaces (Nasrollahi et al, 2020). The climate of Granada requires both summer shade and winter sun (AEMET, 2021).

Green walls are more effective than green roofs at cooling the city, any urban greenery in the streets is has also been found more effective than green roofs. When it comes to the urban structure, the patio has been shown the most effective at lowering temperatures (Nasrollahi et al, 2020).

4.2. Paradise gardens

All paradise garden techniques that have been identfied

TECHNIQUE	SOURCE	EXTRA
Fountains	(Campbell et al, 2018 ; Ruggles, 2008 ; Fekete et al, 2015)	See fig. 17; 20
Still water	(Shahidi, 2010 ; Campbell, 2018 ; Fekete et al, 2015)	See fig. 19
Open channels	(Campbell, 2018; Fekete et al, 2015)	See fig. 16; 21
Partially open or closed channels	(Campbell et al, 2018 ; Ruggles, 2008)	See fig 20
Cascades	(Fekte et al, 2015)	
Water runlets on parapets	(Shahidi, 2010 ; Harvey (1974)	See fig. 18
Tree shade	(Khalilnezhad, 2017; Farahani et al, 2016)	See fig. 23
Trellising shade	(Ruggles, 2008)	See fig. 22
Sky view factor through pools	(Shahidi, 2010 ; Campbell, 2018 ; Fekete et al, 2015)	See fig. 19
Blocking midday sun with vegetation and architecture	(García-Pulido, 2018)	See fig. 15
Structures that create venturi winds	(García-Pulido, 2018)	
Using east west Chahar Bagh structures	(Ojaghlou et al, 2019)	See fig. 15
Using patios as a thermal regulator	(Soflaei et al, 2016 ; García-Pulido, 2018)	
Creating stack winds for ventialtion of housing	(García-Pulido, 2018)	

Materials with high thermal inertia	(Bamoos et al, 2020 ; Lanzon et al, 2020 ; García-Pulido, 2018)	

Table 7., a list of the different techniques identified from the paradise gardens.

4.3. The selection of garden techniques for the intervention

There are two main foundations that have been guiding the selection of garden techniques for the intervention, namely the *theoretical background* and the *conditions of the site*. They are presented here below.

Site conditions

The main conditions that affect the site are the climate conditions and the spatial conditions. These two are also interlinked, as the theoretical background affirms the role of urban geography as a driver for the urban microclimate. The climate conditions from both meteorological data and the open layout makes the area prone to heat.

Another important factor is the amount of space available. It is true that the area is open, but it is open because it needs to allow for large amounts of traffic. This traffic is both in the form of pedestrian and vehicular mobility. Subsequently there is minimal amount of space for the intervention, meaning that techniques that take up large areas are not feasible.

Urban geography of the city can be changed, but in the case of this intervention this option has been left out. Instead the possibility of working with the current structure has been the condition for the reasoning.

Theoretical background

The theoretical background on *microclimates* and *urban heat island* serves as a pin pointer to understand how the urban energy system works and what factors affect heat in the urban system. The most important factors were found to be *increasing latent heat flux* (water) and *decreasing radiation* (creating shade). The materials are also factors in the urban system but it is quite unrealistic to imagine a complete change the architecture of the site, it is also outside the scope of this thesis. Another important note is that one of the goals of intervention is also to allow for winter sun.

FACTOR	LIT. SOURCES	GARDEN TECHNIQUES
Latent heat flux	(Holden, 2017 ; Stewart, 2021)	Channels, sunken beds, fountain, impermeable ground
Tactile water	(fig. 16 ; fig. 18 ; Fig. 21 ; Harvey, 1974)	Open runlets, fountain
Shadow	(Fig. 9 ; Fig 10. Nasrollahi et al, 2020; Yahia et al, 2013)	Deciduous pergola, palm trees
Winter sun	(Fig. 9 ; Nasrollahi et al, 2020)	Deciduous pergola

Table 8. showing what theoretical factor that is being changed, and which garden techniques are used to do so. The aim of *identifying garden techniques for this urban space* can therefore be considered solved and presented here above in the table.

Discarded garden techniques

From the table (7) some techniques had to be discarded because of spatial or practical limitations. These are as follows; still water (in large quantities), creating larger sky view factor through large pools, using chahar bagh structures, manipulating the urban geometry to create winds and anything related to housing material or insulation.

The techniques above have been discarded because they are either outside the realistic spectrum of an intervention, or because there is simply not enough space for them.

4.4. Application to Puerta real – *the climactic effect of the techniques on a real site*

Fig. 26, location of site within Granada, with the Alhambra in the right upper-hand corner (Google maps, 2022).

Fig. 27. A zoom of fig. 26 (Google maps, 2022).

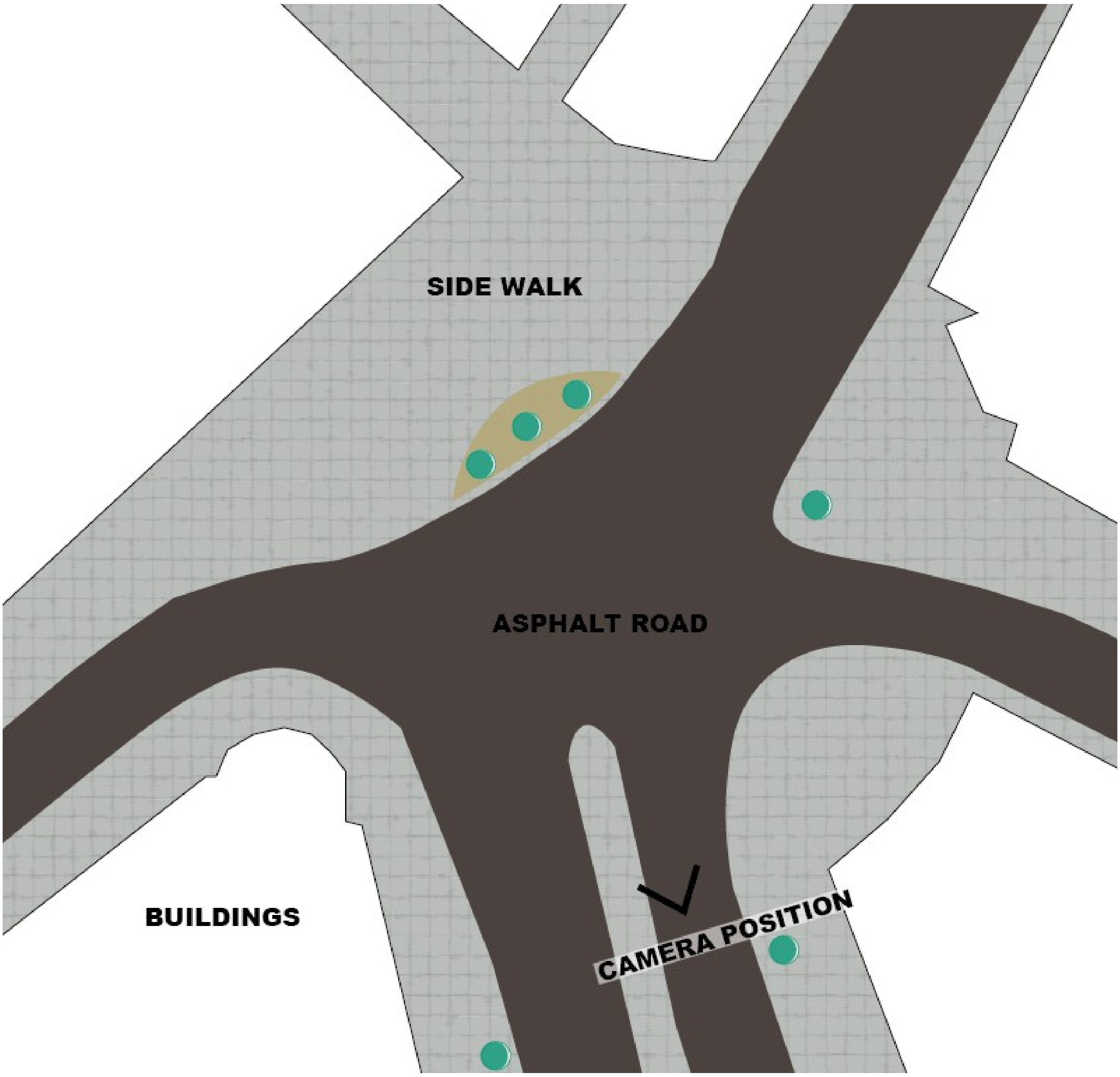


Fig. 28. The site before intervention. The camera position is important to understand the render of the finished site (fig. 38) and the video.

4.4.1 Channels

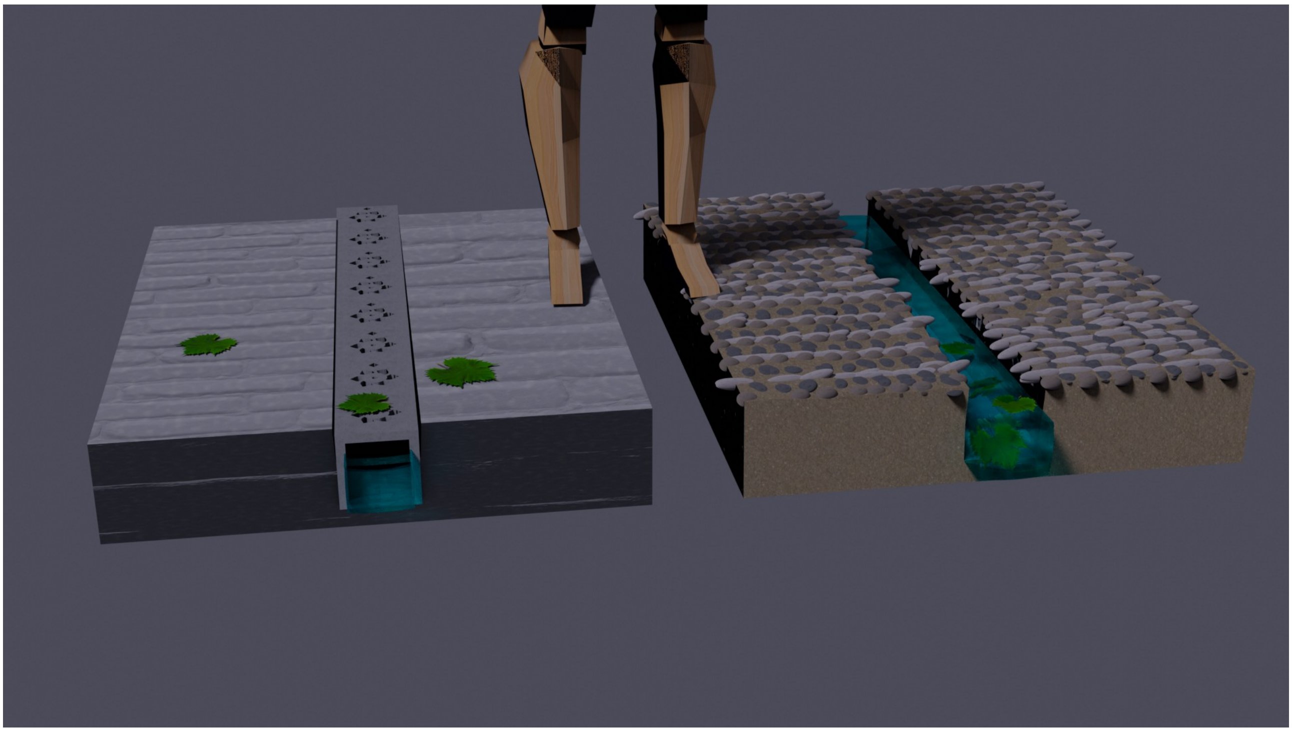


Fig. 29, two types of different ground materials that are proposed.

A first and fundamental technique that can be used to lower surface temperatures is the implementation of channels that connect the vegetation beds. There are two main versions of channels showed in the theoretical part, one type found in *Patio de los naranjos* (fig. 20) in Seville, and the other one in *Patio de los naranjos* in Cordoba (fig. 16).

The surface material to the right is of the same type as is found in Cordoba, with open channels and a mosaic of pebbles as a surface material. The pebbles and open channels create a large surface roughness and is not very accessible for people in wheelchairs etc. This material is therefore best placed on the on surfaces that experience vehicular traffic, such as a road. The open channels will have a higher evaporation rate than the partially closed channel presented above, and will be a counter act the heat generation from the passing combustion engines. The larger roughness will most probably also have a slowing effect on traffic. It is also important to note that the open channels will have a more important accumulation of organic material and will be need to be rinsed regularly. The closed channels will therefore be in the pedestrian area. They also have a fitting lotus pattern design by the author.

The channels will connect all the vegetation beds (of the pergolas/palm trees) as seen on the map of the site (fig. 36). This will make any watering easier, as it can be practiced in the same way like it was by the ancient Persians, Egyptians and Andalusian cultures.

An important note is that these channels were not included in the *Leonardo simulations*, instead extra water was added to the area with the fountain to compensate.

4.4.2 Fountains, parapets and sunken beds

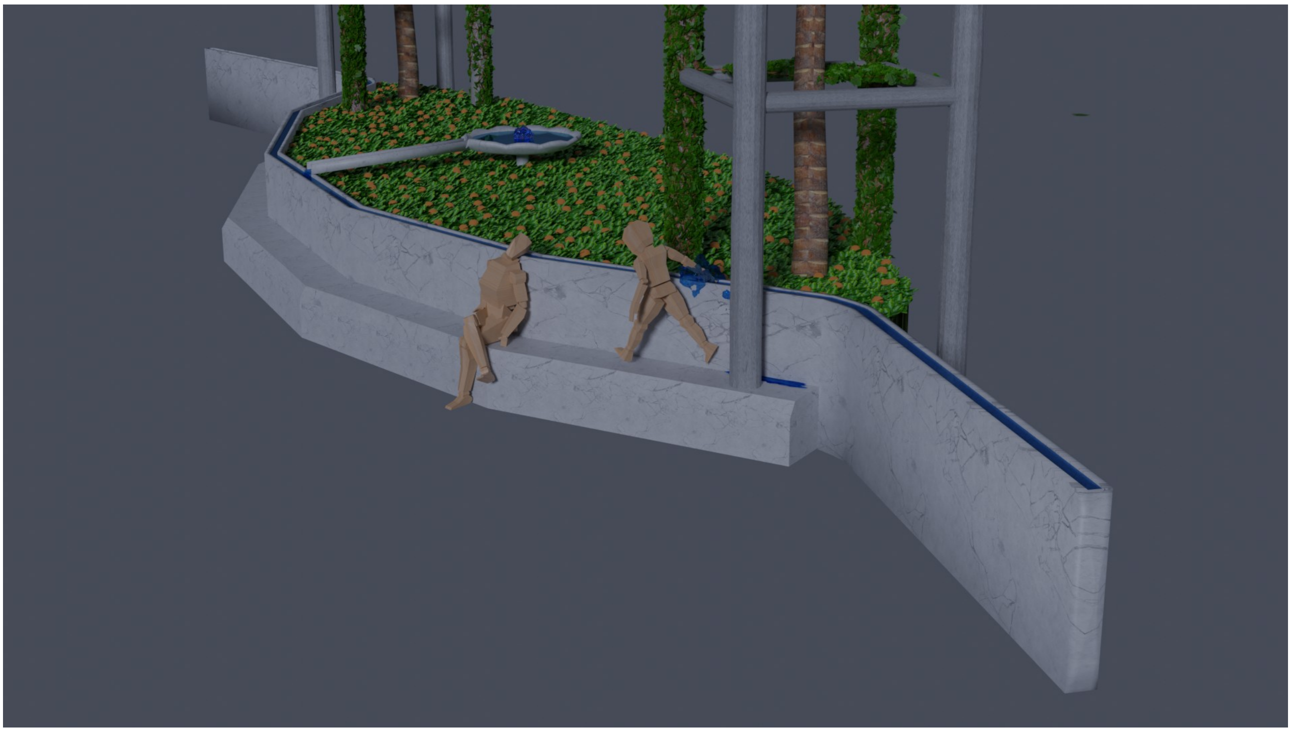


Fig. 30, Proposed implementation of vegetation beds, lotus fountain and a parapet with a water course.

There are a number of garden techniques shown in this render (fig. 30), these will be explained here below.

Behind the seating and parapet, a lotus fountain can be seen, not unlike either one of the many lotus fountains in the Alhambra (fig. 17). The main idea is to use the cooling potential of latent heat transfer, this is not only done by the cascading of the fountain itself but also by the water pouring down from the channel onto the parapet.

The next important part of this intervention is the mosaic of oranges and their fruit, in the height clearly visible from above by adults passing by. The render shows the planting during autumn but it should be noted that the flowers in spring are perfectly situated in height to perfume the air of the people seated. The transpiration of the leaves also creates more latent heat transfer, as well as giving shade to the ground and thus protecting it from drying up.

In the foreground a child can be seen using the parapet just as the people do in the Alhambra (fig. 18). It is important to note that this can also be used for play for children, aside from its microclimactic benefits. These benefits are different types of latent heat transfer, such as putting water on your body (commonly hands) or simply by being near a water body that is a source of evaporation. The parapet is also placed in such a manner that it divides the pedestrian area from the road. The placing of this part of the intervention can be readily shown in the map of the site (fig. 36).

4.4.3 Trellising summer and winter

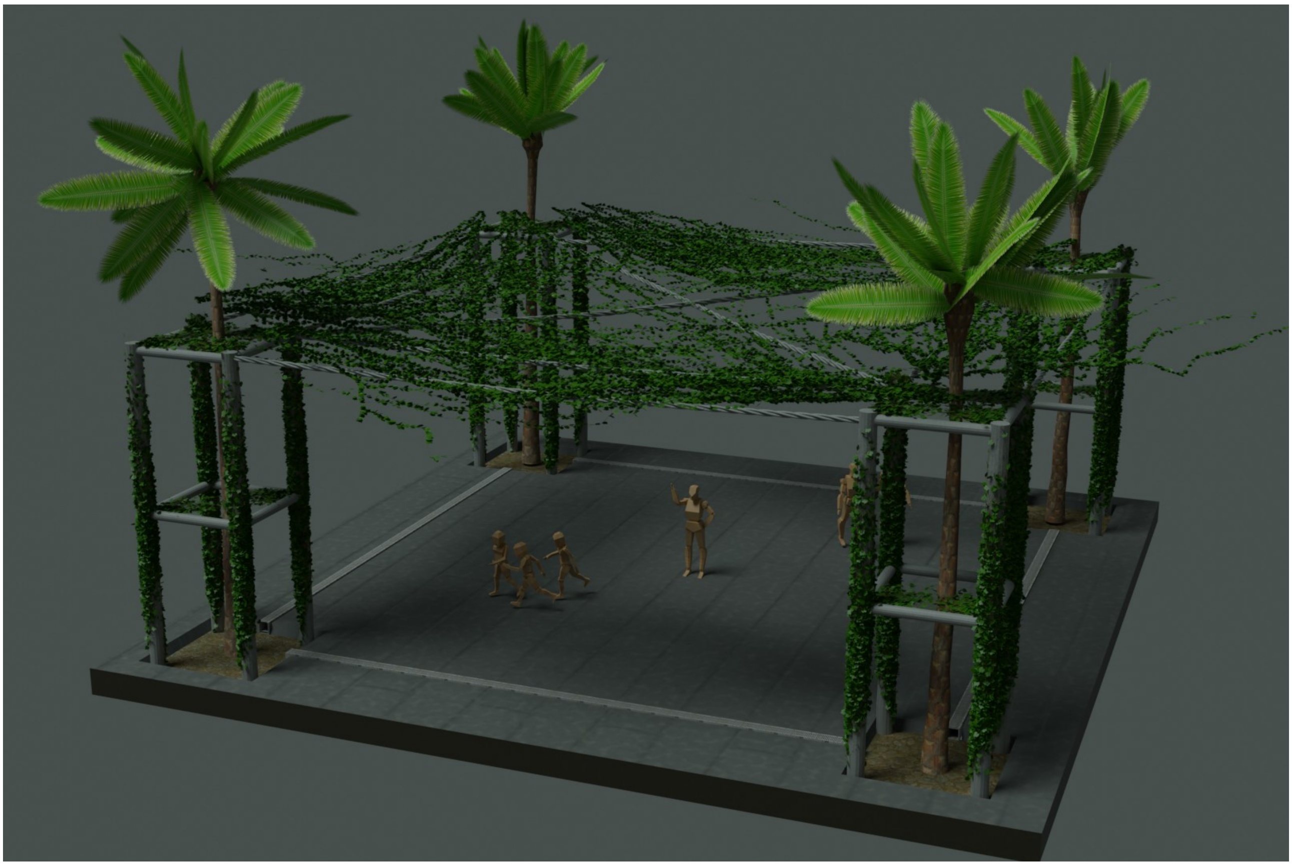


Fig. 31, Trellising giving shade and latent heat transfer in summer.

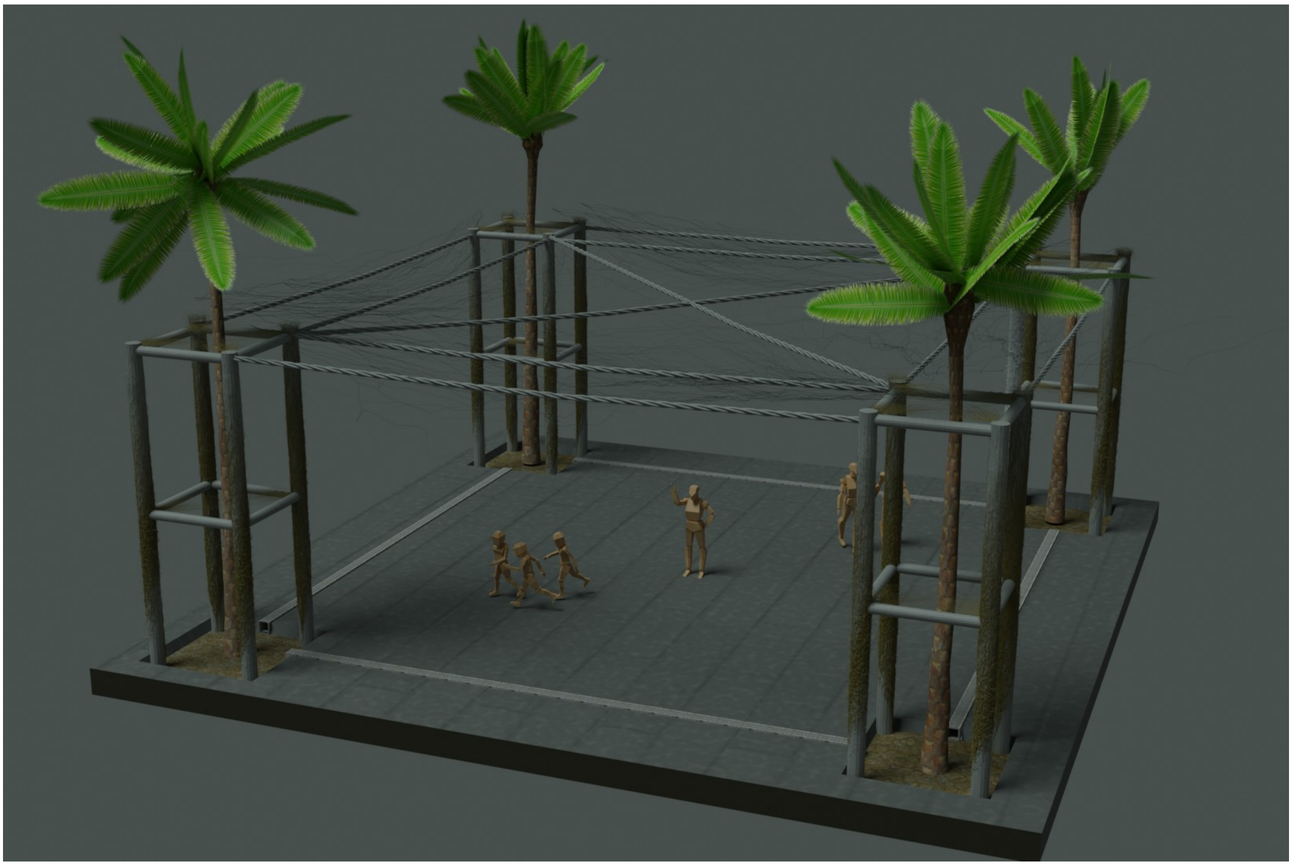


Fig. 32, trellising letting sunlight come through in winter.

The idea for the pedestrian area is for them to be provided bio-shade, by which I’m referring to *shade by organic matter*. This is an area that needs to make use of its modest amount of space as well as the need for sunshine on chilly winter days. Trellising, a tradition in Persian, Egyptian and Andalusian gardens, is therefore used since it takes up little space. These trellising structures also allow for the for the age old tradition of planting date palms, since they can fit in the space within them. The structures are connected by metal cables that provide support for the essential climbers. The shading is thermally dynamic (deciduous), providing dense shade in summer and little to no shade in winter. The difference in sun exposure is made visible in the luminosity of the reflections on the scale figures in the renders (fig. 31 and fig. 32). Both of the renders are made with the supposed full luminosity of a sun. Here the channels connecting the vegetation beds are also visible.

4.4.4 Trellising in main vehicular intersection

Fig. 33, interventions on the intersection.

This render shows the vehicular intersection on the other side of the parapets and orange plantings. This space uses the same ideas as presented in the other renders, with shade and water filled channels. It is important to note the surface material and the semi-visible open channels connecting the vegetation beds. The cars are only put to get a sense of scale and understand the function of the road.

4.4.5 The results of the ENVI-met simulations

Model 0

Fig. 34, the area before the project has been initiated.

This (fig. 34) is the area before an intervention has been made, showing a square in summer that is practically totally without shade. The ground is also made out of asphalt, something that is changed in Model 1. The design and colors of all these interpretations are stylized and are not meant to photo-realistic. To understand the camera position, see fig. 28.

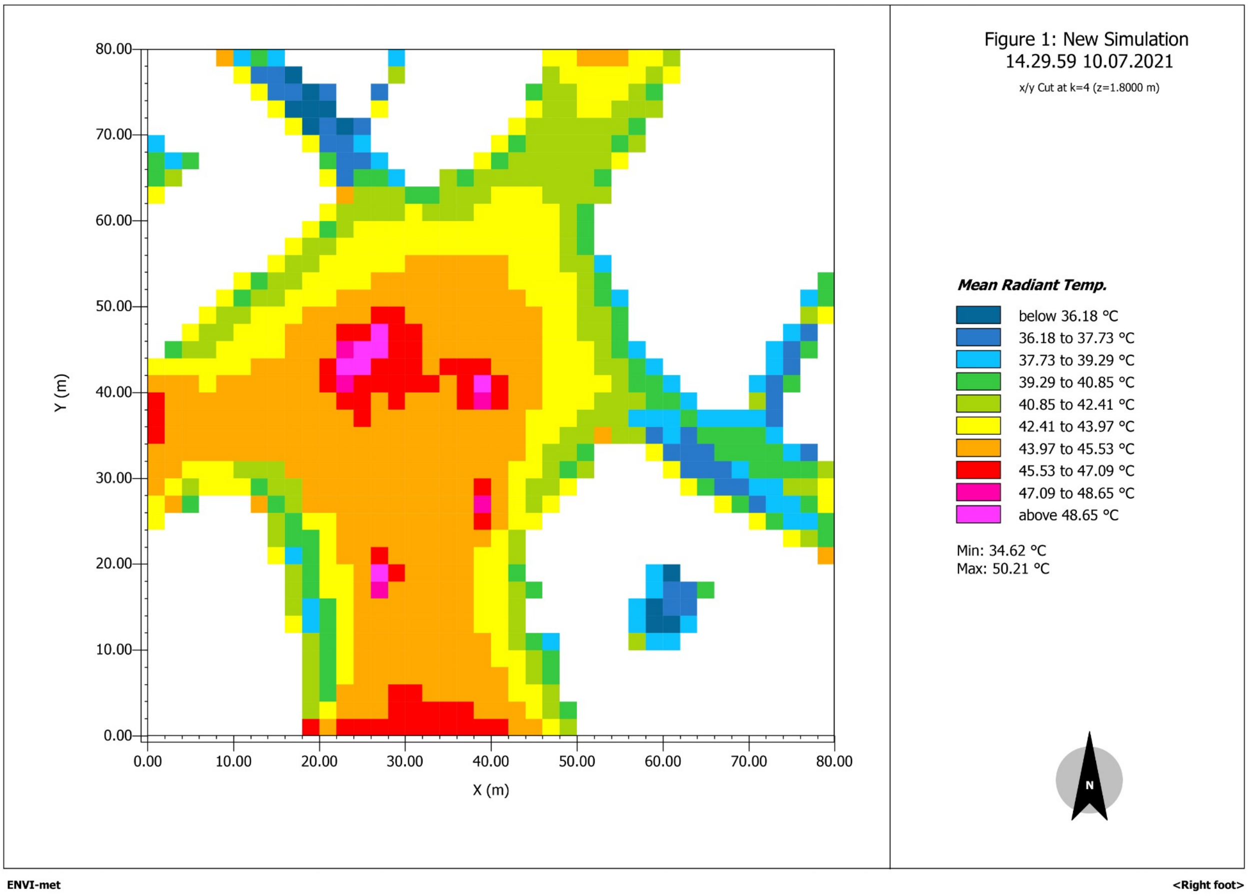


Fig. 35, the MRT values for Model 0. The white bodies are the houses.

MRT max: 50.21 °C

MRT min: 34.62 °C

A very large part of the area has an MRT of 43.97 °C to 45.53 °C, and some part in the middle exceed 48.65 °C. It is very clear that the opaque shade of the narrow streets have a very strong effect that leaves some areas with a MRT value of below 36.18 °C, this is also visible as the absolute warmest part of the area is the one that is most exposed.

Model 1

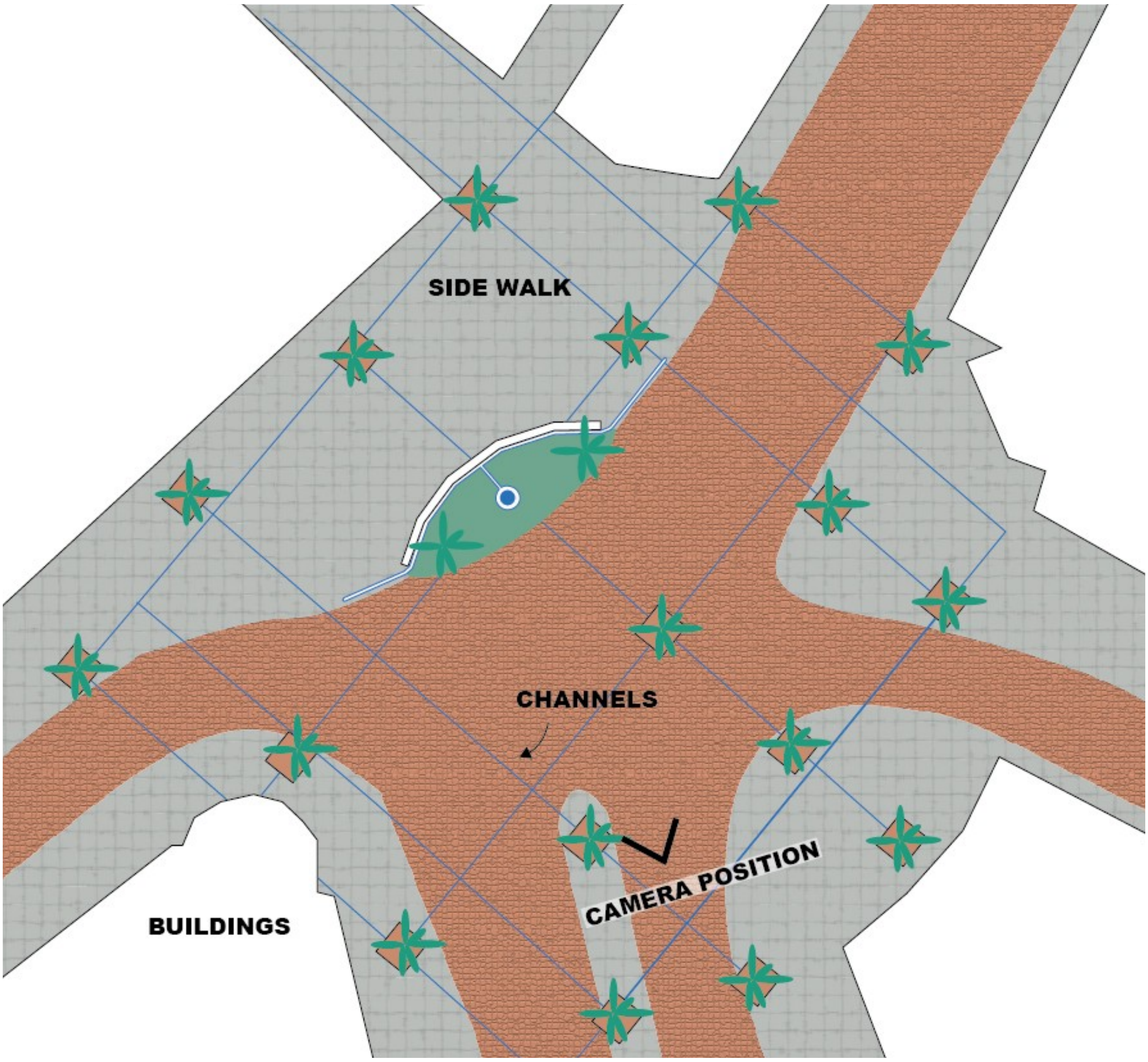


Fig. 36. A plan of the site after the intervention, highlighting the channels

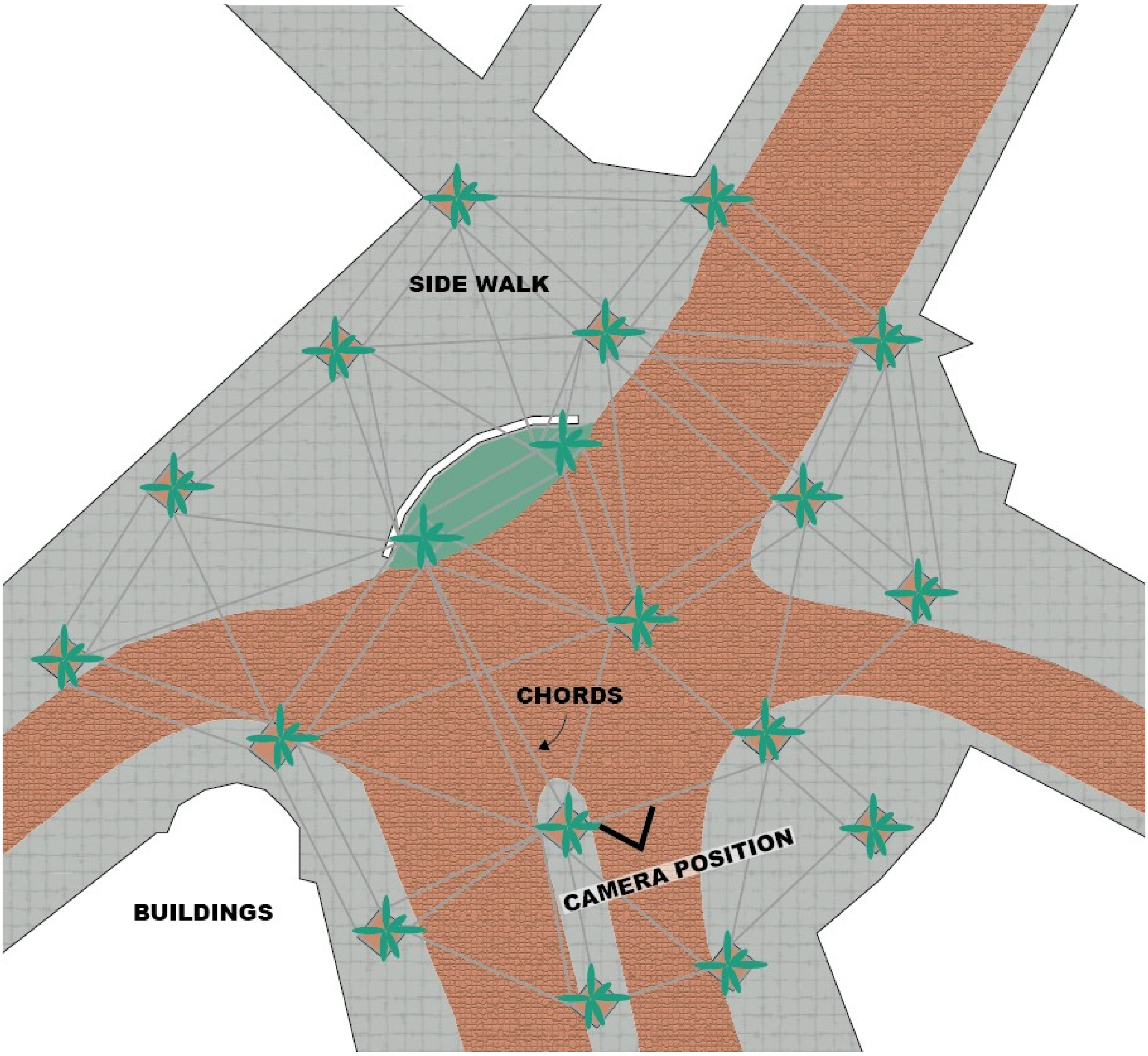


Fig. 37. A plan of the site after intervention, showing the metal chords and structures holding up the climbers, i.e. the pergola.

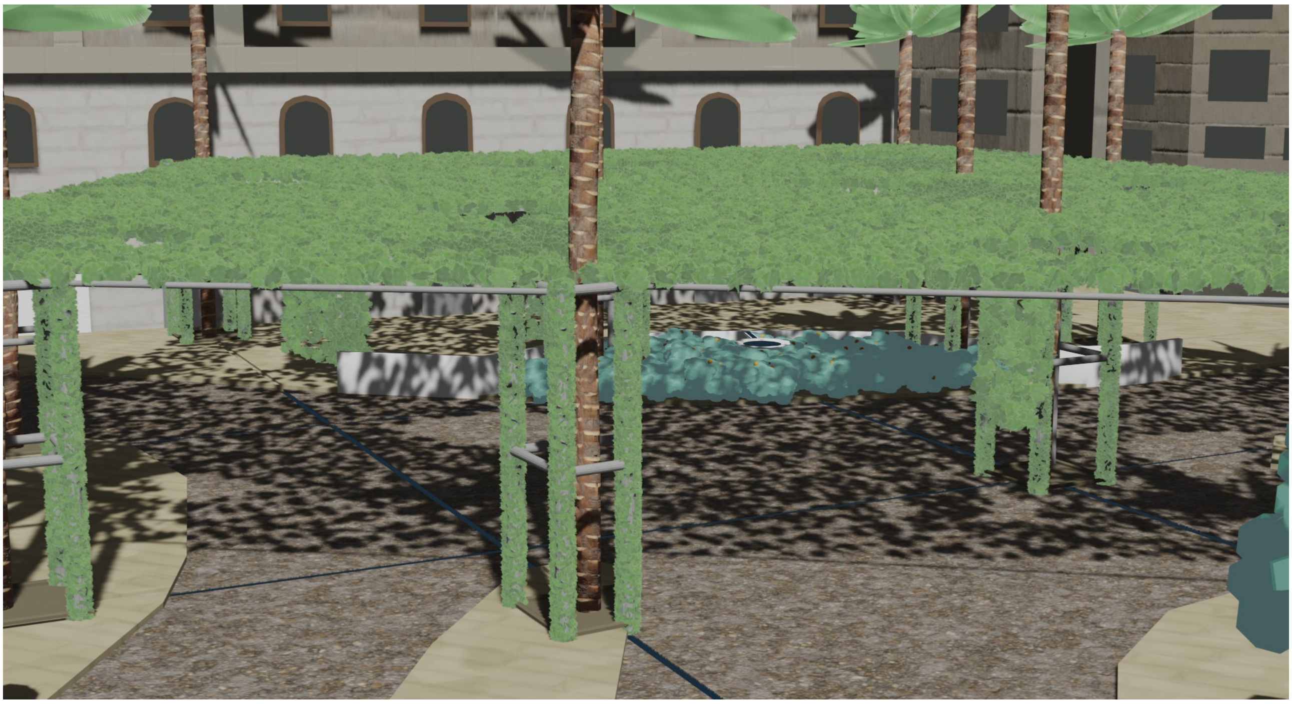


Fig. 38, a visualization of model 1

Here (fig. 38) the shading potential has almost reached its maximum. It should be noted that the climbers hanging down need to be trimmed in areas with traffic, but in pedestrian areas they can be left to create different types of ambiances. The height of the canopy is set to be 5.5 meters for a most traffic to able to pass.

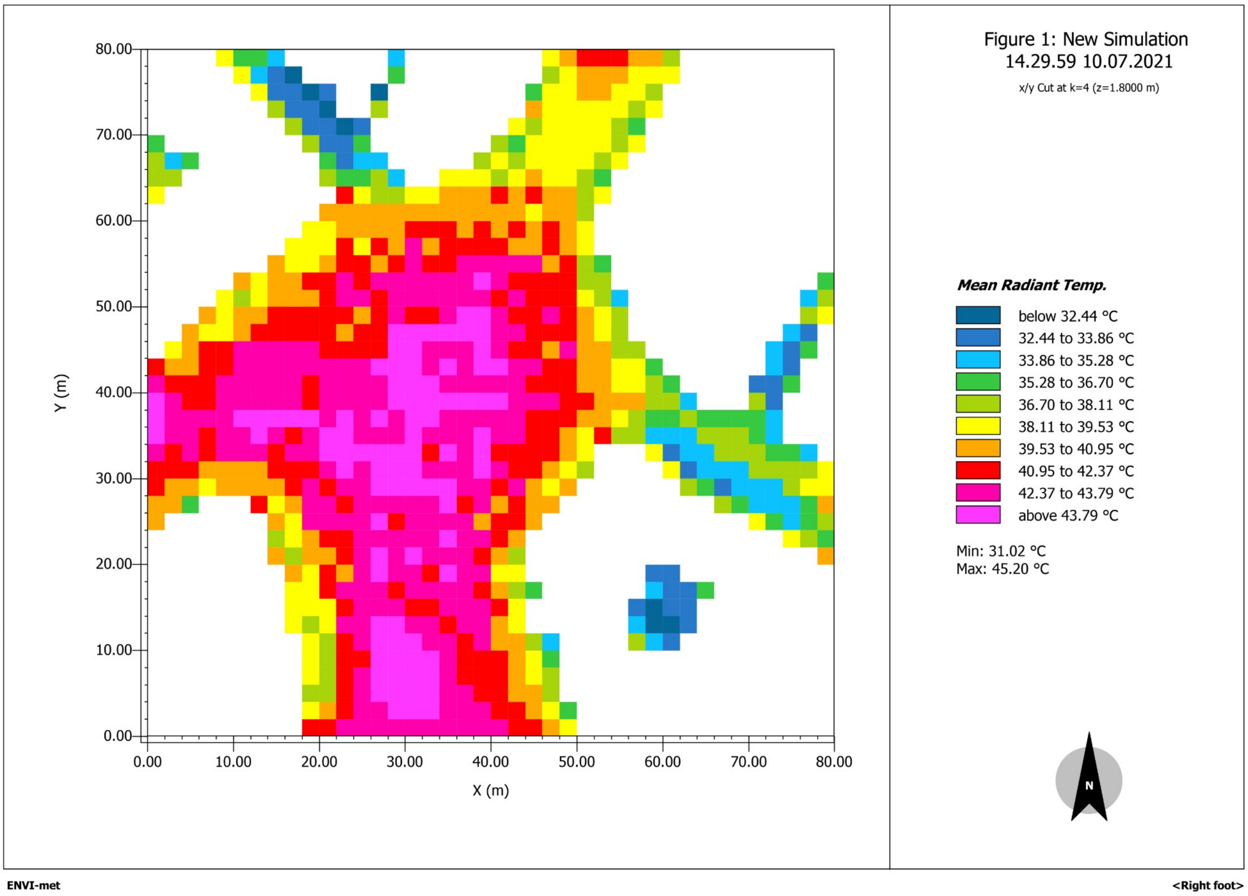


Fig. 39. The MRT values of the site after the intervention.

Here (fig. 39) the values are more equally distributed around in the square. It is also notable that the lowest MRT (31.02 °C) considerably lower than the air temperature which is 34.8 °C. Furthermore, most of the pedestrian areas have an MRT lower than 40.95 °C. Before the intervention the MRT the pedestrian area can rise to a MRT of 44.37 °C.

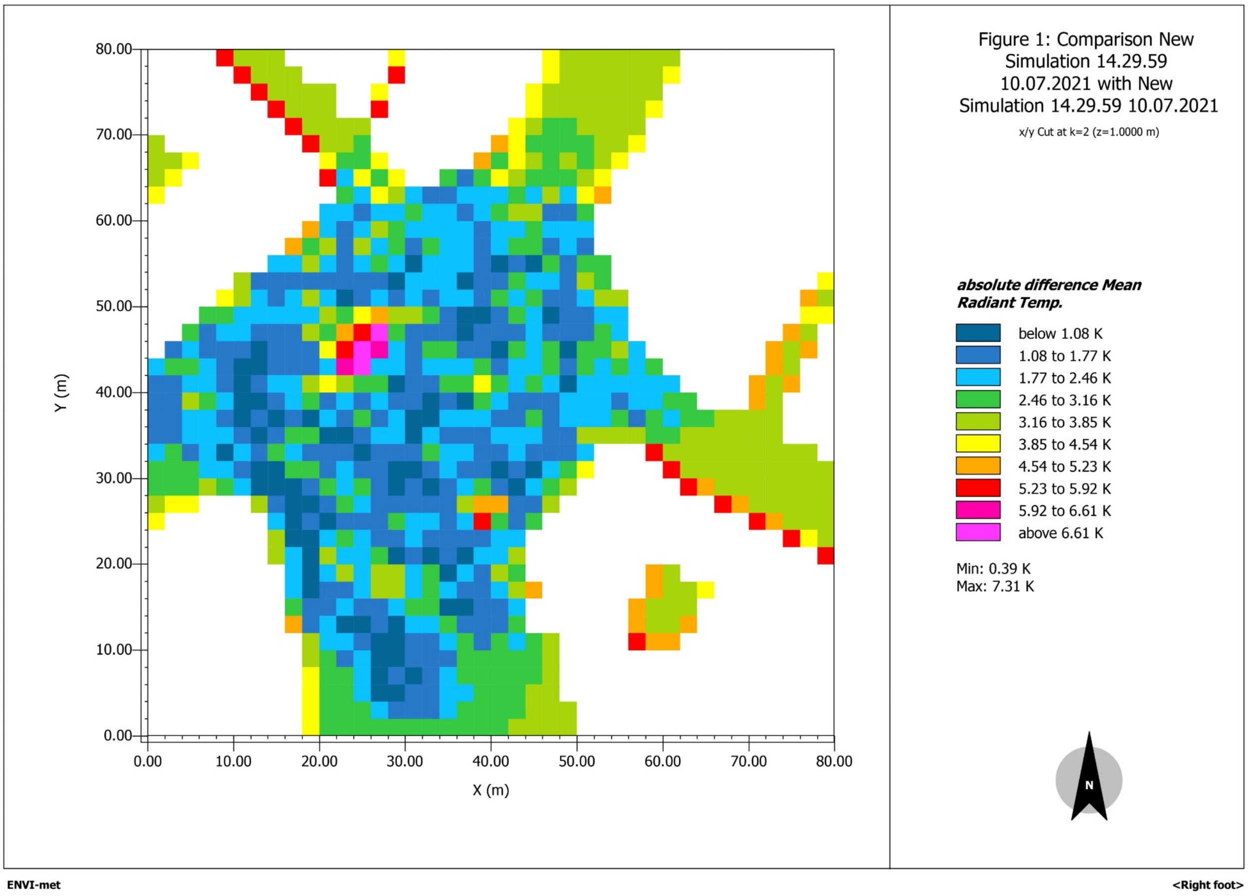


Fig. 40. This is an ENVI-met simulation showing the difference in MRT casued by the intervention, i.e. comparing Model 1 and Model 0.

Summary climactic effects

In the simulation of the intervention temperatures were brought down by 7.31 degrees centigrade. This could play a huge difference since the maximum MRT at the initial site was 50.21 degrees centigrade. The change in PET was 3 ºC in the max value and 1.9 ºC in the min vaule. The change in MRT max value was 5.01 ºC between intervention and no intervention.

MRT	**PET**
50.21 ºC (Model 0 max.)	43.9 ºC
34.62 ºC (Model 0 min.)	35 ºC
45.2 ºC (Model 1 max.)	40.9 ºC
31.02 ºC (Model 1 min.)	33.1 ºC
42.9 (50.21 – 7.31) ºC (Comp. and model 0)	39.6 ºC

5. Discussion and conclusions

5.1. The urban heat island and microclimates

In the end, the energy is the most important factor in the urban system. The amount of energy that is held within the city often correlates with the prevalence of dense and heavy materials. In heavily urbanized areas it is often imperative to use heavy materials that can handle the large weight of vehicles and pedestrian pressure. Other examples of heavy structures are lager houses and in some cases even skyscrapers. Dense and strong materials have a larger heat storage capacity as a rule of thumb (Stewart, 2021). Therefore the general heat storage capacity of city space could be viewed as a function of the population density since more people on less space will require taller and heavier housing. That is especially problematic since this is true of the anthropogenic heat output as well, creating a situation with large amounts of stored energy in addition to our anthropogenic output. This is coupled by the prospect of the urban heat island is being made stronger by more compact cities. On the other hand compact cities will have lower green house gas emissions (Stewart, 2021). This begs the question, how dense can we build before the urban heat island effect makes the city unlivable?

The urban heat island has been observed in winter in Montreal with a maximal effect of 12 degrees centigrade (Oke, 1971). Another example is London, where heat losses can have an effect of 200 watts per square meter. This is so high that it’s even greater than the daily average solar effect during winter. This said, it is important to note that the temperature in the city can vary greatly depending on where in the city the measurement is taken, as a park will normally be cooler than a built up area (Holden, 2017).

Prolonged exposure to heat has an adverse effect on human comfort and health, one paper (Matthews, 2017) found that even if we meet the goal of keeping climate change below 2 degrees centigrade, 350 million inhabitants of mega-cities will suffer deadly heat by mid-century (Earth institute, 2020). This is coupled with a very varied heat tolerance among populations in the world, in the case of Europe the difference between north and south can be stark. This is both due to human factors such as being “used to heat”, cultural factors such as taking a siesta during the hottest hours or simply the insulation of the housing. In the example of housing, the optimum outside temperature for housing in Finland is 14 degrees whereas it is 25 degrees in Greece (EEA, 2020).

The air conditioner is a very common appliance that is used during extreme heat. Unfortunately, the air conditioner works by taking heat from inside the house and transporting it to the outdoor city space. This makes the city space even hotter on days that are already sweltering. This can be deadly during heatwaves for poor communities without access to housing in climates such as the middle east or the like (Dawson, 2017).

Since the city can be divided into different climate zones, which of these zones are best for human health and comfort? This of course depends on where you live, as the urban heat island might be beneficial in really cold climates. However, the climates that have no risk of deadly heat waves in the near-term, nor in the future; are few. This is especially true for vulnerable groups such as the elderly (EEA, 2020).

The literature studies on microclimates and the urban heat island has shown that the most effective ways to combat heat is to minimize admittance and storage of energy while at the same time maximizing the loss of energy at night. Effective ways to decrease the received energy are to block much of the incoming radiation by shading and increasing cloud cover, as well as minimizing anthropogenic heat flux. Effective ways to minimize the stored energy is to chose the right types of materials in the city, like avoiding asphalt and dense materials when it is possible. Finally, the release of energy has to do with many factors, but the most effective ways to maximize energy release is to maximize wind flow, minimize the recycling of radiation from the urban canyon geometry, provide moist zones to lower the Bowen ratio (and thereby temperature). But this begs the question of *bio-shade* since the worst affected areas might be too dry for vegetation. But if we water ornamental gardens for the sake of beauty, we can water vegetation for the sake of a livable microclimate.

5.2. Paradise gardens

Basins are prevalent in the desert garden traditions and they are good at cooling an area. Unfortunately they take up a lot of space and are therefore not fit for dense urban space. In an urban area that has a lot of traffic, pedestrian or otherwise, it will be severely compromising to integrate a large pool or a basin. This is why they will be difficult to use as a tool for combating the urban heat island and warm microclimates, since the places that would need them most usually have the lowest amount of available space. There might be some solutions to this in the form of basins of the depth of a couple of centimeters. This way the areas can be walked and they still provide latent heat flux. It should be noted that these areas might be expensive to construct and maintain, and if they don’t have enough roughness they will be very slippery.

There are many unknown garden techniques that will be discovered as time passes and more archaeological excavations are made. In this sense this list of techniques that has been presented is non-exhaustive from a future point of view. It is also non-exhaustive in the sense that only the most common techniques have been considered. Furthermore none of these techniques have been analyzed for their own proper climate effects. As an example; the effects of shading trellising and the effects of small water channels along the ground have not been compared nor quantified. The study only gives a broad direction of the effect of these techniques, but does not in any way go into detail in each one of them.

5.3. The intervention

First and foremost this proposal is meant to serve as a prototype of how garden techniques can be used to modify microclimates. Therefore some very specific site restrictions have not been considered, because it would not be helpful for the goal, which is oriented at the possibility of universal application. One of these factors is the ability to plant larger trees in the area, as there is an overbuilt river called *Darro* just underneath the site. This would complicate construction of this project but it would also supply the area with easy access to water. Furthermore, the central plantation in the middle of the road (fig. 36) will have a complicating effect on traffic since it will limit the space, although the actual paths of traffic would not change.

The idea to use trellising on a larger scale high above the ground can seem utopic, when considering the large intervention needed. This being said, these types of interventions are not unknown to the south of Spain. Only about 300 metes from the site in Granada something similar (fig. 41) can be found in a patio called “Corral del carbón”.

Fig. 41, Corral del carbón, showing how trellising can be used on a larger scale to create shade.

This thesis has also simplified some of the existing vegetation, as there are some valuable older tree specimen of pomegranate (*Punica granatum*). In a real proposal these would preferably be integrated into the project. Since the absolute main focus is the microclimate these specimen are not shown in the renders or the maps.

There can be some opinions on the rate of this intervention, referring to the time it takes before the intervention becomes effective. The project is thought to be as cheap as possible, to be economically feasible in more areas of the world. There are however some “quick-fixes” in the meantime, like putting up shade sails. This type of intervention is common in Andalusia's capital Seville, where large blankets are put up between houses to give shade to the streets(see on site version, fig. 42). It is also known that trees grow faster in areas with larger growing season if they have adequate access to water, meaning that the vegetation would give effect faster in Spain than for example Norway.

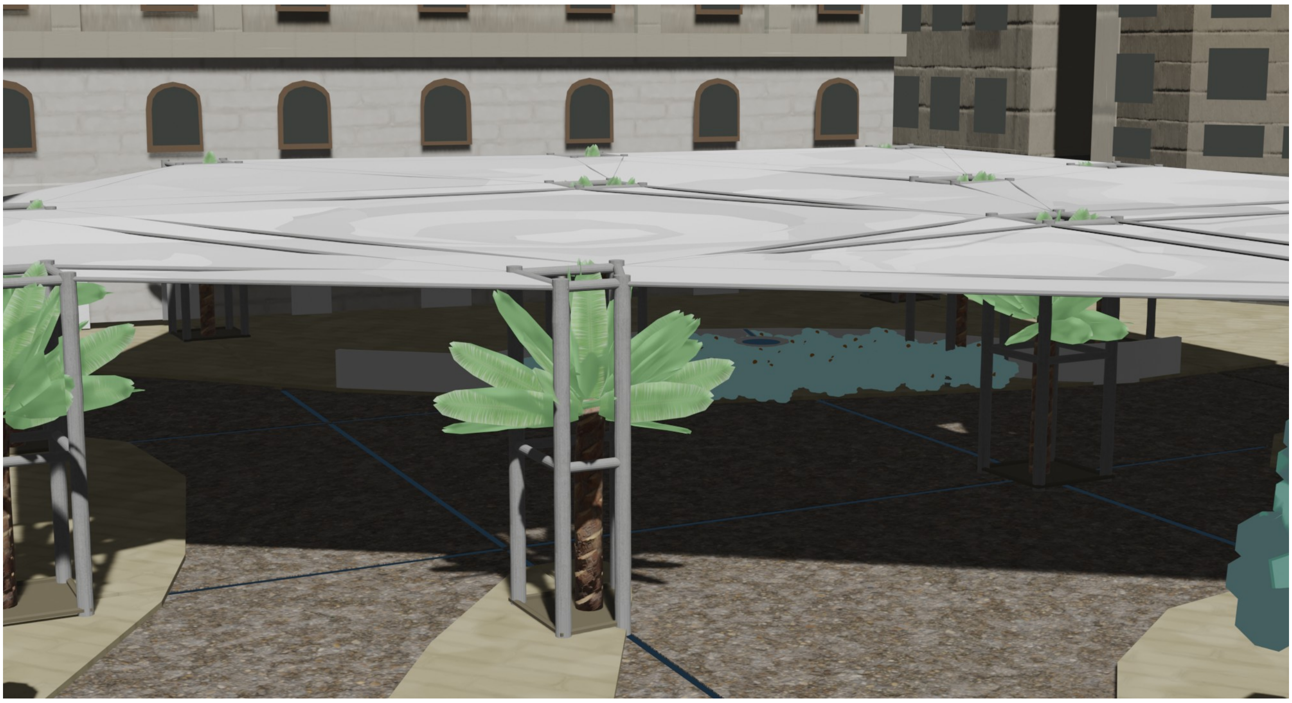


Fig. 42. An idea for putting up shade sails before the climbers have been established.

The height and design of the pergola was set to ensure that both the large trucks can pass and that the climber will be able to have grip on the structure. Hence the surface of the pergola is uneven and the height is set to 5.5 meters. This is higher than most trucks and takes the inevitable untightness of the steel chords into account, as they will expand and contract with different thermal conditions.

5.4. ENVI-met

There are some important limitations to the use of ENVI-met that decrease the scientific accuracy of the study. The first one is the low amount of pixels available in the free beta version of ENVI-met. This does not only limit the geometrical accuracy, but it also makes it impossible to incorporate objects that are smaller than the chosen pixel size of *2 x 2* meters with any precision. In the case of the many channels, parapet runlets or the fountain in the proposed intervention, this creates a large source of inaccuracy. It has been compensated by mapping out the extra amount of water in the area around the runlet since the channels couldn't be mapped out. This creates a stronger local effect in terms of latent heat transfer.

Another inaccuracy in the analyses of the models stems from the available trees in ENVI-met. The lack of orange hedges in the correct size made for the use of an unspecified hedge with the height of 2 m for the ENVI-met model 1. This is even more acutely inaccurate in the case of the climber plants that should have been put up as trellising, these climbers are substituted by an extra addition of palm trees that give shade. This creates a different shade intensity since climbers and palm trees let through different amounts of light. Another effect of the added biomass (stems) will be the change in thermal inertia as well as the change in change in heat flux in the form of circulation. Furthermore there were no models of the pomegranate trees and these had to be substituted by "Wild fruit trees", like all other vegetation inexactness this also effect shade and evotranspiation rates.

Both of these problems can be solved by buying the fully liscenced version of the program, as this will both allow for more pixels as well as a tree editing extension within ENVI-met called *albero*. The lack of accuracy makes the study less precise, but the results of the thermal calculations by ENVI-met can be seen as a generalized indication of the thermal effects of an intervention of this type. The generalization makes the study of the site less credible, but it still shows an example of the effects of latent heat flux and shade in an environment like that of a Mediterranean city.

The water modeling in ENVI-met is as said before heavily limiting for the temperature study because it centralizes the effect of the latent heat flux. This might lead to a similar general reduction in temperature as a whole, but it will make the max and min temperatures more extreme. This would make the min and max values of model 1 too extreme, making the intervention seem less effective than it actually is.

5.5. Final conclusion

The temperature difference between the site before and after the full potential of the intervention is 5.01 ºC in MRT. The resulting conclusion is that this type of intervention, using the techniques of the desert cultures, can be very effective at modifying microclimate. The only limit to the effect of the techniques would be the scale of implementation. The effects of shade and increased latent heat flux have a scientific basis for their effect on the urban system. The remaining question is: how can shade and water be added to the urban system without taking up too much space? These desert cultures have proven to have a great set of techniques for this integration of water and shade into urban space.

The answer to the questions on what techniques are best fitted and if they have any effect on the microclimate can therefore be regarded as *answered*. Their effect on the microclimate is hypothesized in the theoretical background and it is also proven by the calculations in ENVI-met.

The general increase in vegetation will also require an increase in permeable ground. This will lower the amount of stored heat and facilitation heat dissipation.

5.6. Suggestions for further research

A first suggestion for further research would be to investigate the urban heat island in Mediterranean cities with focus on different microclimates such as treeless squares or parks with fountains. Personally I would like to dive even deeper into the ancient desert cultures, looking into more examples climate modification.

As pointed out before, there are no quantitative studies on energy effects for the different techniques, this could provide a mapping framework that could give them a “bio-climactic value”, something that could provide a similar function as the current idea of ecosystem services. Just as an ecosystem service is valuable the combating of heat waves is.

It would be very interesting to see more work on garden techniques from tropical cultures, in connection to combating heat in the humid tropical climate zone. The ancient Maya civilization is one example of a good place to look since it’s both ancient and situated in a tropical climate (Yucatán, Mexico).

6. Sources:

Alcazar, S. S., Olivieri, F., & Neila, J. (2016). Green roofs: Experimental and analytical study of its potential for urban microclimate regulation in Mediterranean–continental climates. *Urban Climate*, 17, 304–317. https://doi.org/10.1016/j.uclim.2016.02.004

Beaumont, P. (1971). Qanat systems in Iran, *Hydrological Sciences Journal*, 16:1, 39-50, https://doi.org/10.1080/02626667109493031

Campbell, J., & Boyington, A. (2018). Fountains and water: The development of the hydraulic technology of display in islamic gardens 700-1700 CE. *Studies in the History of Gardens and Designed Landscapes. 38(3),* 247-267 . https://doi.org/10.17863/CAM.50855

Dawson, A. (2017). *Extreme cities: the peril and promise of urban life in the age of climate change.* NYC: VERSO

Djamali, M., Chaverdi, A. A., Balatti, S., Guibal, F., & Santelli, C. (2017). On the chronology and use of timber in the palaces and palace-like structures of the Sasanian Empire in "Persis" (SW Iran). *Journal of Archaeological Science, Reports, 12,* 134–141. https://doi.org/10.1016/j.jasrep.2017.01.030

EEA - European Environment Agency (2020). *Urban adaptation in Europe: how cities and towns respond to climate change.* European Environment Agency. URL: doi:10.2800/324620

Earth institute (2020). *Potentially fatal combinations of humidity and heat are emerging across the globe.* Columbia University. URL: https://phys.org/news/2020-05-potentially-fatal-combinations-humidity-emerging.html

Emami, M., Eslami, M., Fadaei, H., Karami, H. R., & Ahmadi, K. (2018). Mineralogical–Geochemical Characterization and Provenance of the Stones Used at the Pasargadae Complex in Iran: A New Perspective. *Archaeometry, 60(6),* 1184–1201. https://doi.org/10.1111/arcm.12395

Erell, Pearlmutter, D., & Williamson, T. J. (2011). *Urban microclimate : designing the spaces between buildings* (1st ed.). Earthscan. https://doi.org/10.4324/9781849775397

Faghih, N., & Sadeghy, A. (2012). Persian Gardens and Landscapes. *Architectural Design, 82(3), 38–51.* https://doi.org/10.1002/ad.1403

Fallahi, E., Fallahi, P., & Mahdavi, S. (2020). Ancient Urban Gardens of Persia: Concept, History, and Influence on Other World Gardens. *HortTechnology, 30(1)*, 6–12. https://doi.org/10.21273/HORTTECH04415-19

Fekete, A. & Haidari, R. (2015) Special aspects of water use in Persian gardens. *Agriculture and environment(7)* 82-88 https://doi.org/10.1515/ausae-2015-0007

García-Pulido, L. J. (2018). The Alijares Palace (Qaṣr al-Dishār) at the Alhambra: a bioclimatic analysis. *Journal of Medieval Iberian Studies, 10(1),* 46–71. https://doi.org/10.1080/17546559.2016.1140905

Google. (n.d.). (Puerta réal, Granada, Spain). Retrieved January 10, 2022, https://goo.gl/maps/yavriDsg29jYHD2G8

Guerreiro, B. S. & Dawson, R. J. & Kilsby, C. & Lewis, E. & Ford, A. (2018). Future heat-waves, droughts and floods in 571 European cities. *Environmental research letters 13(3)*. DOI: https://doi.org/10.1088/1748-9326/aaaad3

Habibi, K., Hoseini, S. M., Dehshti, M., Khanian, M., & Mosavi, A. (2020). The Impact of Natural Elements on Environmental Comfort in the Iranian-Islamic Historical City of Isfahan. *International Journal of Environmental Research and Public Health, 17(16),* 5776–. https://doi.org/10.3390/ijerph17165776

Harvery, J. (1974). Spanish gardens and their history. *Garden history, 3(1),* 7-14 https://doi.org/10.2307/1586307

Holden, J. (2017). *An Introduction to Physical Geography and the Environment*(4th edition). Pearson.

Hussain, F. A. (2014). *The Gardens of the Alhambra. In Gardens & Landscapes in Historic Building Conservation*. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118508107.ch43

Höppe, P. (1999) The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *International journal of biometeorology*. https://doi.org/10.1007/S004840050118

Khalilnezhad, S. M. (2017). Distinctive features of productive landscapes in Persian gardens. *Acta Horticulturae*,*1189(1189)*, 35–38. https://doi.org/10.17660/ActaHortic.2017.1189.6

Kabisch, Strohbach, M., Haase, D., & Kronenberg, J. (2016). Urban green space availability in European cities. *Ecological Indicators,* 70, 586–596. https://doi.org/10.1016/j.ecolind.2016.02.029

Kántor, & Unger, J. (2011). The most problematic variable in the course of human-biometeorological comfort assessment — the mean radiant temperature. *Central European Journal of Geosciences*, *3(1)*, 90–100. https://doi.org/10.2478/s13533-011-0010-x

La Agencia Estatal de Meteorología (1 November, 2021). *Valores climatológicos normales. Granada Aeropuerto.* URL: http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos/valoresclimatologicos?l=5530E&k=undefined

Lanzon, M., De Stefano, V., Molina Gaitan, J-C., Bestue Cardinel, I., Guiterrez Carillo, L. (2019). Microstructural and physical changes induced by deposition of Ca(OH)(2) nanoparticles in original and reconstructed samples. *Construction & Building Materials, 232.* https://doi.org/10.1016/j.conbuildmat.2019.117202

Matthews, T. & Wilby R. & Murphy, C. (2017). *Communicating the deadly consequences of global warming for human heat stress*. Columbia Univeristy, New York.
URL: *https://www.pnas.org/content/114/15/3861.short*

Mahmoudi Farahani, L., Motamed, B., & Jamei, E. (2016). Persian Gardens: Meanings, Symbolism, and Design. *Landscape Online, 46,* 1–19. https://doi.org/10.3097/LO.201646

Nasrollah, N., Ghosouri, A., Khodakarami, J., Tlaeghani, M.(2020) Heat-Mitigation Strategies to Improve Pedestrain Thermal Comfort in Urban Environments: A Review. *Sustainability*, 12(23) DOI: https://doi.org/10.3390/su122310000

Oke, T.R (2012) Local Climate Zones for Urban Temperature Studies. *Bulletin for American Meteoroogical Society 93(12)*, 1800-1900. https://doi.org/10.1175/BAMS-D-11-00019.1

Oke, T.R & Stewart, I.D. (2012) Datasheet for local climate zones- supplement for Local Climate Zones for Urban Temperature Studies. *Bulletin for American Meteoroogical Society 93(12),* 1800-1900. https://doi.org/10.1175/BAMS-D-11-00019.1

Ojaghlou, M., & Khakzand, M. (2019). Thermal Comfort Characteristic of 5 Patterns of a Persian Garden in a Hot-Arid Climate of Shiraz, Iran. *Journal of Landscape Ecology, 12(3), 1–33.* https://doi.org/10.2478/jlecol-2019-0016

Oliveira, M. L. ., Dario, C., Tutikian, B. F., Ehrenbring, H. Z., Almeida, C. C. ., & Silva, L. F. . (2019). Historic building materials from Alhambra: Nanoparticles and global climate change effects. *Journal of Cleaner Production, 232, 751–758.* https://doi.org/10.1016/j.jclepro.2019.06.019

Patuano, A., & Lima, M. . (2021). The fractal dimension of Islamic and Persian four-folding gardens. *Humanities and Social Sciences Communications, 8(1),* 1–14. https://doi.org/10.1057/s41599-021-00766-1

Ruggles, D. F. (2008). *Islamic gardens and landscapes*. University of Pennsylvania Press. https://doi.org/10.9783/9780812207286

Shahidi, M. & Bemanian, M & Almasifar, N & Okhovat, H.(2010) A Study on Cultural and Environmental Basics at Formal Elements of Persian Gardens (before & afer Islam). *Asian Culture and History, 2(2),* 133-147. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.674.2334&rep=rep1&type=pdf

Soflaei, F., Shokouhian, M., & Mofidi Shemirani, S. M. (2016). Investigation of Iranian traditional courtyard as passive cooling strategy (a field study on BS climate). *International Journal of Sustainable Built Environment, 5(1), 99–113.* https://doi.org/10.1016/j.ijsbe.2015.12.001

Svensson, M. (2004) Sky view factor analysis – implications for urban air temperature differences. *Meteorological applications, vol. 11(3), p. 201-211.* DOI: https://doi.org/*10.1017/S1350482704001288*

Tajaddini, L. (2011). Review of the Characteristics of Mahan Garden: One Type of Persian Gardens. *World Academy of Science, Engineering and Technology(56)* 1581-1584 https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.294.3883&rep=rep1&type=pdf

Turner, T. (2005). *Garden history- philosophy and design 2000 BC – 2000 AD*. Routledge. https://doi.org/10.4324/9780203589335-9

Yahia, M. W., & Johansson, E. (2013). Influence of urban planning regulations on the microclimate in a hot dry climate: The example of Damascus, Syria. *Journal of Housing and the Built Environment, 28(1)*, 51–65. https://doi.org/10.1007/s10901-012-9280-y

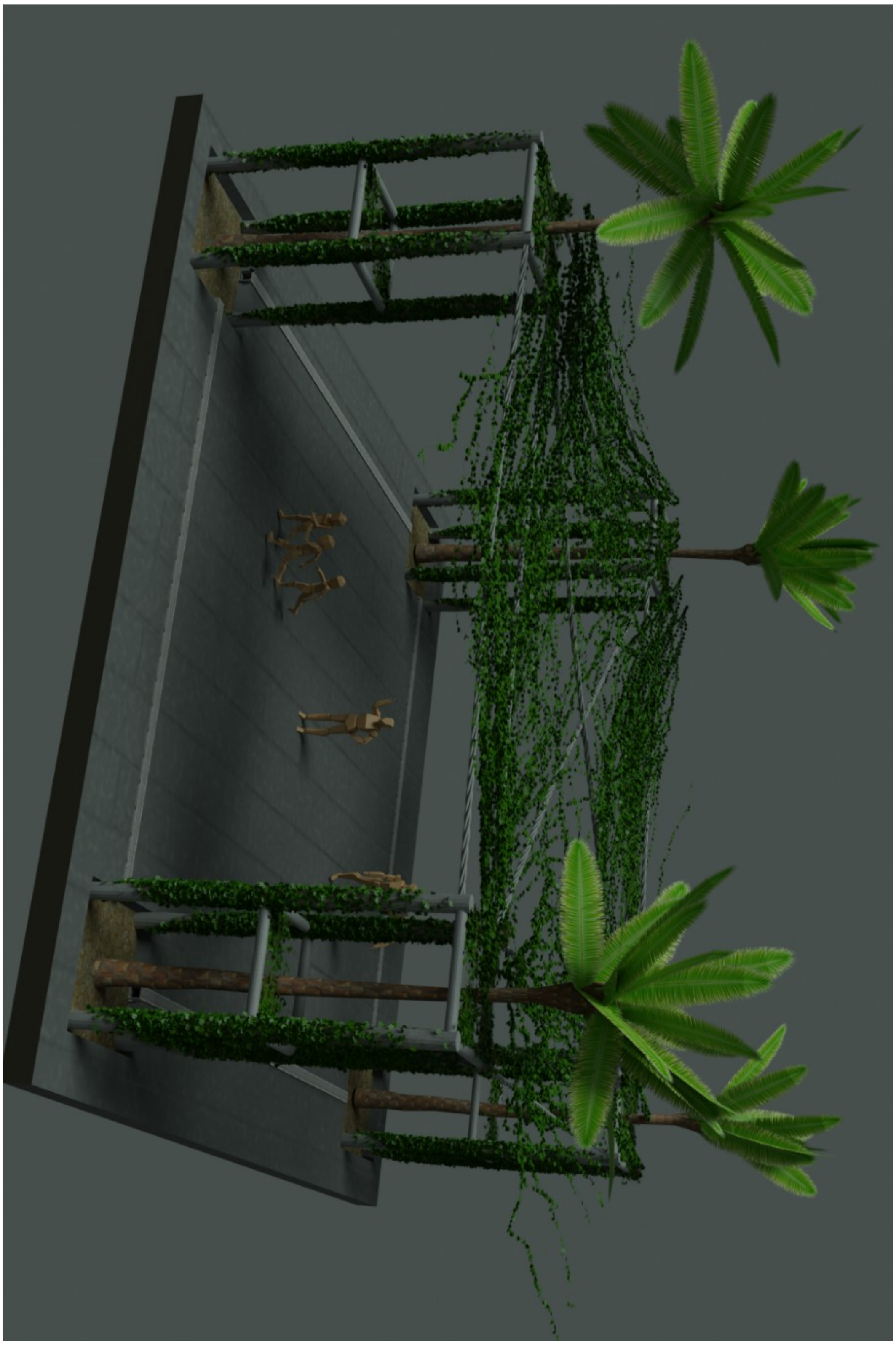
Zimmerman, N. (22 July 2016) *Sponge City: Berlin plans for a hotter climate*. Deutsche Welle https://www.dw.com/en/sponge-city-berlin-plans-for-a-hotter-climate/a-19420517

7. Appendix

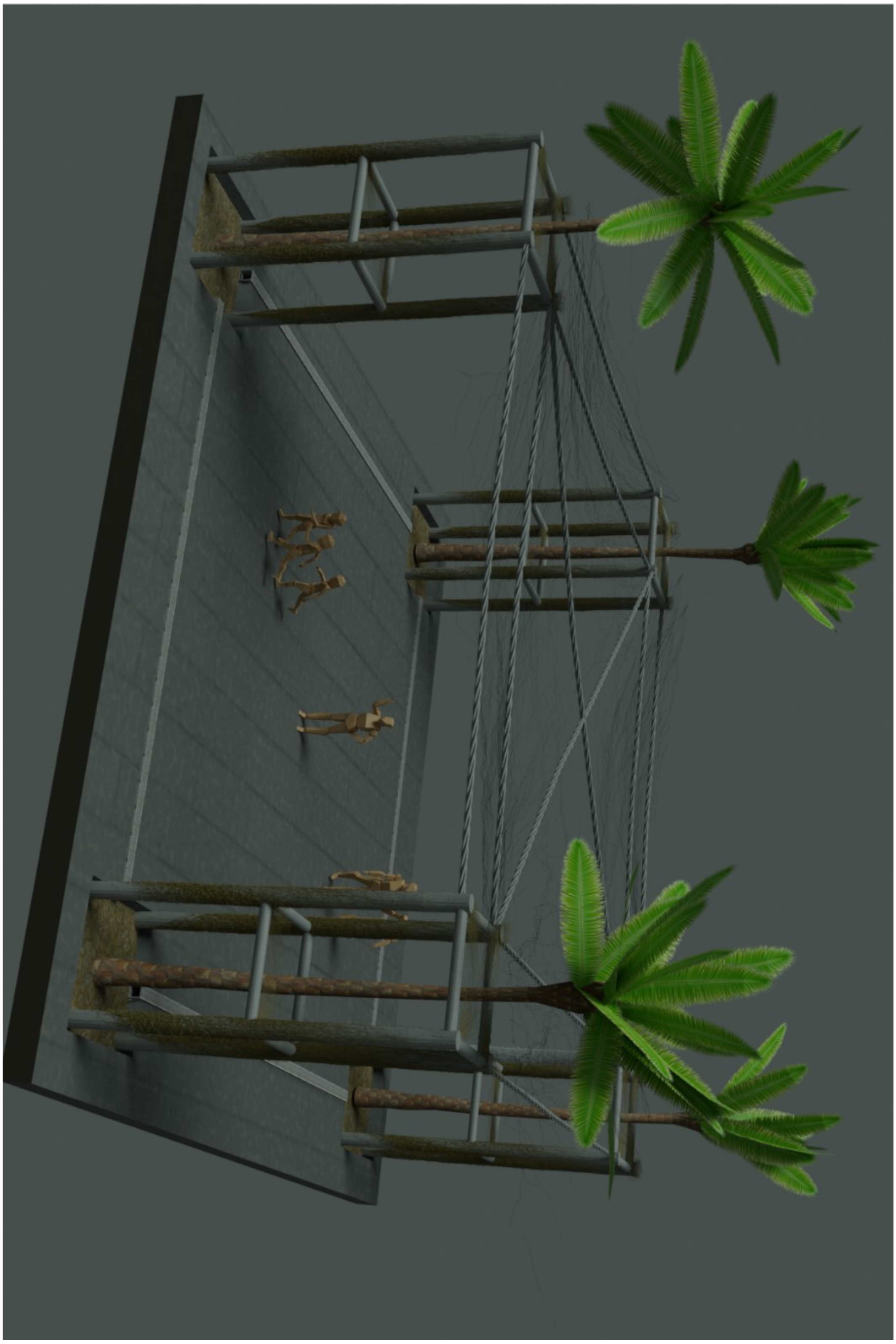
Video link

https://www.youtube.com/watch?v=rFOxKkoSOKI

Trellsing 1



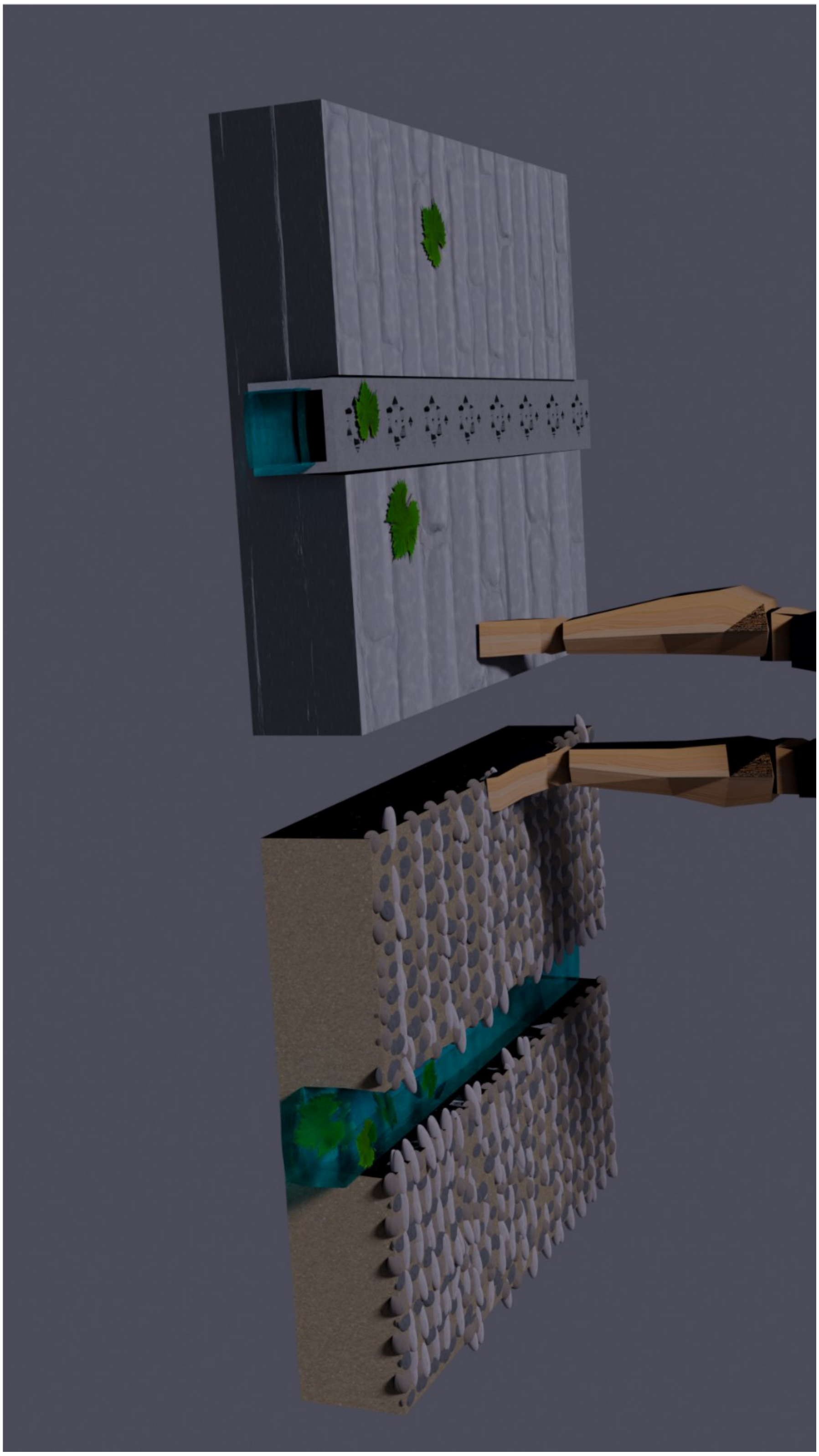
Trellising 2



Fountain

Center

Channels



Urban trellising in Granada

Flower beds in Acequía court, Alhambra