ACE Architecture, City and Environment

E-ISSN 1886-4805

Water Sensitive Urban Design: Construction Systems, Materials Choice and Use Criteria to Improve Surface Temperatures

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Received: 24-06-2023 | Final Version: 14-10-2024

Abstract

Water sensitive urban design stormwater and rainwater management construction systems (hereinafter, WSUDs) contribute to the resilience of areas to water when they are implemented in urban development and they enable recovery of the water cycle. However, these systems can increase surface temperatures in a context of rising planet temperatures. This article aims to establish criteria for choosing and using WSUDs that lower surface temperatures in a climate of hot and dry summers. It summarizes the main results of seven years (five years of measurements) of WSUD surface temperature records. The methodology is mainly based on manual and in situ measurements, at a detailed scale, under the green canopy, with a thermographic camera and other devices that measure complementary parameters at the same scale (light meter, anemometer, hygrometer). The conclusion is that there are two main groups of WSUDs and materials, depending on their thermal performance: those that contain and retain water and those with a faster infiltration speed, with surface temperatures above the environmental ones during hot summers. Parameters that clearly influence surface temperatures are the specific heat of the water, in the first group, and the shade of the building and the green area, the albedo, the thermal inertia and the granulometry in the second one.

Keywords: WSUD; climate change; surface temperatures; water management

Citación

Pérez Cambra, M.M. et al. (2024). Water Sensitive Urban Design: Construction Systems, Materials Choice and Use Criteria to Improve Surface Temperatures. *ACE: Architecture, City and Environment*, *19*(56), 12391. https://doi.org/10.5821/ace.19.56.12391

Criterio de elección y uso de los materiales y sistemas constructivos del Diseño Urbano Sensibles al Agua para la mejora de las temperaturas superficiales

Resumen

Los sistemas constructivos implementados por el diseño urbano sensible al agua (en adelante, WSUDs) que gestionan las aguas pluviales contribuyen a la resiliencia de áreas, al urbanizarlas, en relación al agua y permiten recuperar el ciclo del agua. Sin embargo, estos sistemas pueden aumentar las temperaturas superficiales en un contexto de incremento de la temperatura del planeta. El objetivo de este artículo es establecer un criterio de elección y utilización de los WSUDs que reduzcan las temperaturas superficiales en un clima de veranos cálidos y secos. El manuscrito resume los resultados completos de siete años de estudio (cinco de mediciones) de temperaturas superficiales de WSUDs. La metodología se basa principalmente la medición in situ manual, a escala de detalle y bajo las copas de los árboles, con una cámara termográfica y otros dispositivos que miden parámetros complementarios a la misma escala (luxómetro, anemómetro, higrómetro). La conclusión es que existen dos grandes grupos de WSUDs en función de su comportamiento térmico: los que contienen y retienen agua y aquellos de infiltración más rápida que los anteriores, con temperaturas superficiales siempre superiores a la ambiental durante los veranos calurosos. Los parámetros que influyen son: el calor específico del agua, en el primer grupo y la sombra de la edificación y del verde, el albedo, la inercia térmica y la granulometría en el segundo grupo.

Palabras clave: WSUD; cambio climático; temperaturas superficiales; gestión del agua

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E-ISSN 1886-4805

1. Introduction

In the current context of climate change, 30% of Europe's population is affected by water stress in an average year (European Environment Agency, 2021), with increasing floods (Martínez Santafé et al., 2019). Water management solutions that recover the water cycle can contribute to reducing drought impact (City of Melbourne, 2014) and tackling undersized drainage infrastructures due to overpopulation and constant growth of urban areas (United Nations, DESA, Population Division, 2018) and floods.

Water sensitive urban design (WSUD) is an approach that integrates all of water cycle management into urban planning and design (City of Melbourne, Urban Water, n.d.). Australia has some areas with similar pluviometry and temperatures in summer to the site measured in this study: Barcelona. Barcelona has a warm temperate dry climate with hot summers, and a Csa climate ("World Maps of Köppen-Geiger Climate Classification," 2013). Thus, Australian WSUD solutions are focused on resolving similar problems in both areas with a Csa climate. Consequently, the WSUD concept is used in this research.

WSUD includes several strategies (City of Melbourne, 2014), such as those based on stormwater and rainwater management, also known as sustainable urban drainage systems (SUDS), best management practices (BMP), "mejores prácticas de control" (MPC), "buenas prácticas ambientales" (BPA), "técnicas de drenaje urbano sostenible" (TEDUS) and low impact development (LID). WSUD strategies have been applied by municipalities, as in the monitored cases studies of Melbourne, to reduce water consumption (City of Melbourne, 2014; Melbourne City Council, 2009). Strategies have been included in the BMP database (ASCE, USEPA et al., 2024) in the US, Europe (Izembart Helene, 2003; Kabisch et al., 2017) and Spain (Andrés-Doménech Ignacio et al., 2021). WSUDs can contribute to mitigating harmful climate change effects on the water cycle. However, compound extremes are currently increasing due to climate change worldwide (Istomina M.N. et al., 2023). Such extremes include floods and droughts that require compound solutions. Recent analyses of the hydraulic conductivity of some infiltrating characteristic materials (Alhama, Iván et al., 2023) indicate that some of them do not work properly thermally unless strategies are implemented to convert them into cool surfaces. Guides and studies have been compiled to reduce surface temperatures worldwide. Examples are: A Practical Guide to Cool Roofs and Cool Pavements (R20 Regions of Climate Action, 2012), Heat Island Cooling Strategies (U.S. Environmental Protection Agency, 2023), Cool Pavements: State of the Art and New Technologies (Kappou, & et al., 2022). Five heat island cooling strategies have been described: 1) increasing tree and vegetation cover, 2) installing green roofs, 3) installing cool – mainly reflective – roofs, 4) using cool pavements (either reflective or permeable), and 5) utilizing smart growth practices. This article is focused specifically on the thermal behavior of WSUD rainwater management construction systems (WSUDs) and their characteristic materials. WSUDs were registered for five years and studied for seven years in Barcelona.

1bf.

This manuscript includes recordings of vegetation cover, tree shade, blue-green roofs and cool pavements (reflective and permeable). These strategies for generating low surface temperatures coincide with the aforementioned heat island cooling strategies (Climate Protection Partnership Division in the US Environmental Protection Agency's Office of Atmospheric Programs, 2017).

Global surface temperatures are forecast to rise in a likely range of between 1.2ºC (minimum SSP1-1.9) to 3.0ºC (maximum SSP5-8.5) until 2060, a mid-term period (IPCC, 2021: Summary for Policymakers, in: Climate Change 2021: The Physical Science Basis. Masson-Delmotte, V.P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. et al., 2021). In this context, surface temperatures of WSUDs for a warm temperate dry climate with hot summers become a crucial factor to create resilient cities, not only to mitigate climate change effects related to water, but also to mitigate surface temperature increase.

To help reduce surface temperatures (Ts), the main issue of the research is whether there are any criteria to consider when choosing a WSUDs or decreasing Ts below the environmental temperature

E-ISSN 1886-4805

(Te), especially in a warm temperate dry climate with hot summers. Te is air temperature or environmental temperature and is measured one meter above the surface. Ts is surface temperature.

The second question is how to use WSUDs with recorded surface temperatures above environmental temperatures to improve their thermal performance during hot and dry summers.

The research is divided into two phases. The first lasted the first three years and was focused on how water retention in infiltrating surfaces or water harvested in the construction system with direct or indirect contact with it can affect surface temperatures (and granulometry influence).

The second phase lasted four more years and focused on the thermal study of WSUD construction systems without water retention capacity (with electrical conductivity equal to zero), and the parameters that can further modify their surface temperature like green and building shades, albedo, granulometry (due to heat kinematics) and thermal inertia.

2. Methodology

The parameters recorded to explain surface temperatures, the tools and the methodology during the two phases were as follows.

Table 1. **Parameters, tools and methodology**

	1st PHASE-tools	2nd PHASE-tools	Measured Parameters
In situ measurements	Thermal camera	Thermal camera	Surface temperature
In situ measurements	Light meter	Light meter	Albedo
In situ measurements	Anemometer	Anemometer	Wind speed
In situ measurements	Hygrometer	Hygrometer	Relative humidity of the material
Calculations	Thermal inertia	Thermal inertia	Thermal inertia

Source: own elaboration.

To check surface temperatures, Landsat8 was considered. However, the resolution was not high enough for the research purposes (120x120 m in 10th and 11th bands, the thermal ones). Besides, the thermal behavior analyzed in this article relates to WSUDs under the canopy and is focused on WSUD materials. It requires detailed scale tools.

The tool available to record surface temperatures on a detailed scale was a thermal camera, which recorded surface temperatures of the WSUDs' characteristic construction systems manually and hourly (dates and times listed below). The effect of shade was measured in built WSUD areas.

The albedo was recorded manually and hourly with a light meter (also on loan from the UPC). A light meter measures radiance reflected by the brightness of the surface, recorded and divided into the recorded sun. It is an approximation that gives coherent results when it is related to surface temperatures (Pérez Cambra, Martínez Santafé,Maria Dolors, & Roca Cladera, Josep, 2022). The hourly recorded albedo for each material is presented in the statistics hourly, except in Figs. 26a) to 31, which show the average albedo. Recent summer recordings of albedo and surface temperatures, shown in this paper, follow the trend analyzed in the PLEA Congress (Pérez Cambra et al., 2022). Surface temperatures increase in relation to low albedos and vice versa.

The anemometer was useful to measure wind speed manually and hourly. However, the values were mainly nearly zero, which is not relevant during the summertime. That is why they are not shown in this summary.

Water contained in the material was initially measured with a hygrometer to determine electrical conductivity. Substrates showed values the day after rain, but this was not the case of manufactured surfaces and gravel. They showed a value of zero on the hygrometer. Consequently, the study is divided into materials that can retain water and materials that do not (gravel, draining concrete, rubber, etc.). In addition, when water is retained, the rest of the parameters (albedo, etc.) do not alter the effect of water on WSUDs' thermal behavior.

A hygrometer was used to explore the possibility of measuring the water vapor contained in the materials' air voids and in the air touching the surface. This instrument is generally used to measure water vapor contained in air, as an approximation. No other more precise tool is available. The hygrometer was used manually and hourly. The results revealed coherent relationships between the low water vapor contained in the materials' void and higher surface temperatures, and vice versa (Pérez Cambra et al., 2022; Pérez Cambra M. & Roca Cladera, 2018). Vales of the average 24-hour air relative humidity were taken from Meteocat.

In the second group of construction systems (materials that do not retain water), parameters like albedo or granulometry were measured. The same material (draining concrete, rubber and gravel) was always considered and parameters were recorded on the same day hourly and manually.

Finally, the only parameter that was not recorded but was calculated was the thermal inertia of gravel, using the formula:

$$I = \sqrt{k\delta c} \quad \left[\mathrm{J \cdot m^{-2} \cdot K^{-1} \cdot S^{-\frac{1}{2}}}\right]$$

k: root of thermal conductivity $\left(\frac{\mathrm{W}}{\mathrm{m\ ºK}}\right)$

δ: density $\left(\frac{\mathrm{kg}}{\mathrm{m^3}}\right)$

c: specific heat $\left(\frac{J}{Kg\ ºK}\right)$

This formula (Instituto de CIencias de la Construcción Eduardo Torroja, ICCL, & Instituto de la Construcción Eduardo Torroja, 2007; Veto & Christensen, 2015). was used to explore whether thermal inertia can affect the material surface temperature when the albedo or granulometries (gravel of different types) varied for the same material. Thermal inertia was not calculated for materials with different components that were already produced because there could be errors in the composition.

Therefore, the parameters described in this paper are surface temperature, which can be modified by water retention, shade, albedo, granulometry (which can also affect water retention) and thermal inertia.

Regarding the chosen dates, infiltrating surfaces were thermally recorded during some of the warm and cold months of the year, except for a few preliminary recordings. This analysis is focused on measurements during the hot summer months in a Csa climate. Measurements in winter, our coldest climate, during the first phase were also recorded for comparison.

A first hypothesis was that if WSUDs infiltrate water, the surface temperatures (Ts) should decrease due to evaporation, especially in systems that retain water or are next to it. To explore this question, temperatures were always recorded on two days: a wet day, that is, 24 hours after a rainy day; and a dry day, that is, 24 hours after a day without rain. As rain is scarce in Csa summers, there were not many opportunities to repeat the measurements. However, they were repeated during the year of research and showed a WSUDs pattern of thermal behavior. Measurements were recorded from sunrise to sunset, when radiance had disappeared. Thus, the results show how much heat was gained by the materials during the day, to be released during the night.

In the first phase, some of the WSUDs and materials that did not retain water (with electrical conductivity of 0, for example draining concrete) showed a similar trend in winter and in summer (when Ts was compared to Te). Consequently, in the second phase, the focus was on systems that do not retain water, and the measurements were only recorded in summer (site #5, Architecture School, materials on the terrace).

Some preliminary measurements were also taken in early autumn, when it is still warm (10 and 15 days' maximum after the end of summer). These measurements in early autumn were just to confirm previous results and trends from summer 2016 for some of the WSUDs, and to see what could happen in Summer 2022 for the rest of the WSUDs.

Table 2. **Measurement dates**

1st PHASE - 3 first years	2nd PHASE - 4 last years
A. Can Cortada: 41º26'04.0"N 2º09'04.7"E	**A. Can Cortada: 41º26'04.0"N 2º09'04.7"E**
08/24/2016 - Dry Day - Summer	10/05/2021 Wet Day Early autumn
08/31/2016 - Wet Day - Summer	(verifying 2016 measurements)
02/15/2017 - Wet Day - Winter	10/01/2021 Dry Day Early autumn
02/21/2017 - Dry Day - Winter	(verifying 2016 measurements)
C. La Fábrica del Sol green-blue roof	**D. Cristóbal de Moura WSUDs (Nbs green axis)**
Green/Blue Roof N41º 22' 55.857"E 2º11'30.584"	**41º24'34.3"N 2º12'15.9"E**
09/14/2016 - Wet Day - Summer	10/05/2021 – Wet Day - Early autumn
09/12/2016 - Dry Day - Summer	(preliminary measurements prior to 2022 ones)
02/16/2017 - Wet Day - Winter	10/01/2021 - Dry Day - Early autumn
02/23/2017 - Dry Day - Winter	(preliminary measurements prior to 2022 ones)
B. Architecture School of Barcelona	**E. Architecture School of Barcelona**
Blue roof prototype-courtyard: 41º23'1.288"N 2º6'48.571"E	**Materials on terrace:**
10/20/2017 - Wet Day - Early autumn	**41º23'03"N 2º06'50"E**
09/20/2017 - Dry Day - Summer	11/05/2021 - Dry Day - Winter
02/09/2018 - Wet Day - Winter	07/20/2022 - Dry Day - Summer
02/15/2018 - Dry Day - Winter	
01/30/2018 - Wet Day - Winter	
01/31/2018 - Dry Day - Winter	
03/06/2018 - Wet Day - Winter	
03/09/2018 - Dry Day - Winter	
05/31/2018 - Wet Day - Winter	
06/18/2018 - Dry Day - Winter (almost Summer)	

Source: compiled by authors. Note: Grey color means it is not described in this article.

The measurement of surface temperature for each of the WSUDs took place in five scenarios to determine the effect of using water on the overall thermal effect of the systems.

Figure 1. **Scenarios of temperature records in Barcelona**

Figure 2.1. **Can Cortada "A"**

Figure 2.2. **Cristóbal de Moura "D"**

Source: Barcelona Municipality website map. Compiled by authors using Google Earth and own pictures. Numbers are the same as in Tables 2 and 3.

The criteria for choosing locations was to find similar infiltration construction systems in different areas of the city. The first system that was selected is Can Cortada (#1), a water sensitive urban design through infiltrating basins, structural soil pit trees and grey draining concrete. In the south of the city, Cristóbal de Moura (#4) shows a similar water strategy with infiltration basins and brown colored draining concrete. The only WSUD that harvests water is the blue roof of La Fábrica del Sol (already built), taking as a reference the case of Fawkner Park (Melbourne City Council, 2009).

Firstly, Can Cortada was analyzed. Systems that could retain more water showed better thermal performance. The second construction system was La Fábrica del Sol, to verify the water effect on Ts. Surface temperatures related to vapor contained in substrates' voids were found in the WSUD's thermal behavior (Pérez Cambra M. & Roca Cladera, 2018). After verifying the results, a blue roof prototype was built in the Barcelona School of Architecture (ETSAB) courtyard that is similar to La Fabrica del Sol. The results are summarized in the same conference paper. To check some characteristic materials that did not retain water found in Can Cortada, Cristóbal de Moura built materials and construction systems were recorded, as were other characteristic materials that were used to build WSUDs on the ETSAB terrace.

There are several ways to classify WSUDs. One of the first schemes divides WSUDs into three types: a) those that reduce rainwater runoff through source control techniques: porous pavements, infiltration trenches and infiltration basins; b) permeable conveyance systems: French drains and swales (dry and wet); c) surface collected water passive treatment systems before discharge onto land or into a watercourse, involving filter strips, detention basins, retention ponds and wetlands (Scottish Environment Protection Agency, SEPA, 2000).

The measured WSUDs are in Barcelona. Built examples of some of them were used and the materials measured are common in the construction of most WSUDs.

Table 4. **WSUDs measured and type of WSUD**

1st PHASE, 3 first years	Type of WSUD
A. Can Cortada WSUDs: Figures 3 & 4. Infiltration depo or basin (Nbs)*:	
1.gravel (41.434057, 2.152310),	a) source control techniques*
2.grass (41.434075,2.152357),	
3. draining concrete(41.434101, 2.152362).	
4. Structural soil pit trees: Figure 12b, 4' sunny soil pit tree (41.434558, 2.151749); Figure 12c, 4"shaded (41.434748, 2.151943); Figure 12d, 4 shaded and sunny (41.434691, 2.151867)	a) and b) in this case
5. Draining concrete (grey): Figure 12.b, 5' sunny (41.434561, 2.151761); Figure 12.c, 5" shaded (41.434748, 2.151946); Figure 12.d, 5 shaded and sunny (41.434696, 2.151872).	b) permeable conveyance systems
B. Architecture School of Barcelona, Figure 10	
6. Blue roof prototype (41.38370, 2.113518)	a) source control techniques
C. La Fábrica del Sol green-blue roof, Figures. 6, 7 & 8.	
7. Blue roof (41°22'56"N 2°11'30"E)	a) source control techniques
8. Green (Nbs)/blue roof (41°22'55.762"N 2°11'30.193"E)	

2nd PHASE, 4 last years	Type of WSUD
A. Can Cortada WSUDs:	
Infiltration depo or basin (Nbs): Figure. 16 9. sunny gravel (41.434057, 2.152310), 10 shaded gravel (41.434120, 2.152051), 9' shaded draining concrete (41.434167, 2.152222), 10' sunny draining concrete (41.434101, 2.152362)	a) source control techniques
4. Soil pit tree Fig. 12 (41.434691, 2.151867).	a) and b) in this case
D. Cristóbal de Moura WSUDs (Nbs green axis) Figure 18	
11. Infiltration depo (sand) (41.409089, 2.203837).	a) source control techniques

12 and 15. Draining concrete (light brown color) (41.409086, 2.203817), (41.409306, 2.204130).	a) source control techniques
13. and 16. Substrate (41.409057, 2.203824), (41.409322, 2.204137)	
14. Infiltration depo (gravel) (41.409358, 2.204190)	a) source control techniques
E. Architecture School of Barcelona, Fig. 21 (41.38389, 2.11383); one material next to the other	
Different types of gravel for WSUD construction	gravel useful in building
Volcanic	a) source control techniques: all types b) permeable conveyance systems: French drains, swales (dry and wet) c) detention basins, retention ponds, wetlands
17.18.19. Natural volcanic stone (dark grey) 5-10 mm/10-20 mm/25-50 mm	
20.21.22. Red volcanic stone (dark red) 5-10 mm/10-20 mm/25-50 mm	
Metamorphic	
23.24.25. Pink metamorphic stone (6-12 mm/12-24 mm/24-40 mm)	
26.27.28. Red marble stone (10-20 mm/20-30 mm/24-40 mm)	
Sedimentary	
29.30. Yellow sedimentary stone (6-12 mm/12-24 mm)	
31.32.33. Black sedimentary stone (6-12 mm/12-24 mm/24-40 mm)	
34.35.36. Rubber: grey, green, red color	a) source control techniques
37.Draining concrete: grey	a) source control techniques b) permeable conveyance systems green swales (dry and wet), filter strips
38.Structural soil (Can Cortada)	
39.Substrate 1: with coco fiber	
40. Substrate 2: with compost	

Source: own elaboration. Numbers are according to numbers in figures.

Nbs (nature-based solutions) refers to the use of nature in tackling challenges such as climate change, food security, water resources or disaster risk management, encompassing a wider definition of how to conserve and use biodiversity in a sustainable manner (Balian, E., Eggermont, H. & Le Roux, X., Eggermont, H., & Le Roux, X., 2014). Except for the built WSUD construction systems, the rest of Fig. 1 materials were bought (all gravel types, compost, coco fiber or silica sand) and the blue roof prototype was constructed for the research. Some materials were kindly donated (sand, reused bricks, substrate, green, red and other colored recycled rubbers, and draining concrete).

To determine the WSUD materials' thermal performance, hydraulic conductivity associated with granulometry was evaluated. This is related to the classification of soil types according to their permeability coefficient (Berry, Peter L. & Reid David, 1993; González de Vallejo, Luis I., Ferrer, Mercedes, Ortuño, Luis, & Oteo, Carlos, 2002). Such a measure of thermal performance could be plausible. However, in this case, natural soils' temperatures are compared with the temperatures of manufactured materials. This rule does not work to compare materials of different compositions. Composition is a factor that affects hydraulic conductivity. In fact, non-manufactured materials with similar granulometry but different compositions can show different hydraulic conductivity, for example topsoil and "albero" sand (Alhama, Iván, et al., 2023). They had different surface temperatures during this research.

3. WSUD surface temperature results and discussion

The main goal of the first years was to compare surface temperatures in different materials and WSUD construction systems built in Barcelona, to determine the criteria for the best WSUD thermal performance. Temperatures were recorded in Can Cortada in 2016 and La Fábrica del Sol during that summer, 24 hours after rain from sunrise to sunset (also 24 hours before rain).

3.1 Systems which retain and/or store water. Can Cortada

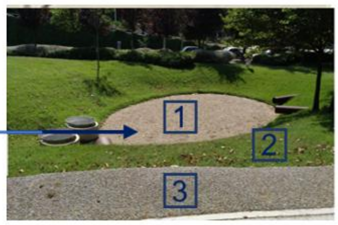
Can Cortada is a residential area surrounded by an open space built with WSUD where rainwater is infiltrated and conveyed through structural soil pit trees (to the lowest point), draining concrete and infiltration basins at the lowest point, and from there to the subsoil. It is in the north of the city, with an average altitude of 115 m, according to an urban planning information portal (Portal de Información Urbanística [PIU], Ajuntament de Barcelona, 2024). This site is close to the green mountain range that delimits the north of the city (Fig. 1). It is a "fresh" area in Barcelona, which is barely affected by the urban heat island effect (Roca J. & Arellano, B., 2020). However, it is still hot during the day in summer. For instance, some surface temperatures can reach 52.7ºC while the Te is 37.9ºC (Figs. 5.1. and 5.3). Is it possible to reverse this situation using any WSUD material or construction system? Below are some examples of the most relevant cases.

Infiltrating surfaces and materials that could retain water (e.g. vegetated surfaces) performed differently to those whose electrical conductivity was zero (like draining concrete and gravel).

Figure 3. **Infiltration basin in Can Cortada**

Source: own image.

Figure 4. **Infiltration basin**



Source: own image. Note: Note 1. gravel 2. grass 3. draining concrete

Figure 5. **Infiltration basin measurements**

Figure 5.2.1. **Grass on a wet day** | Figure 5.2.2. **Grass on a dry day**

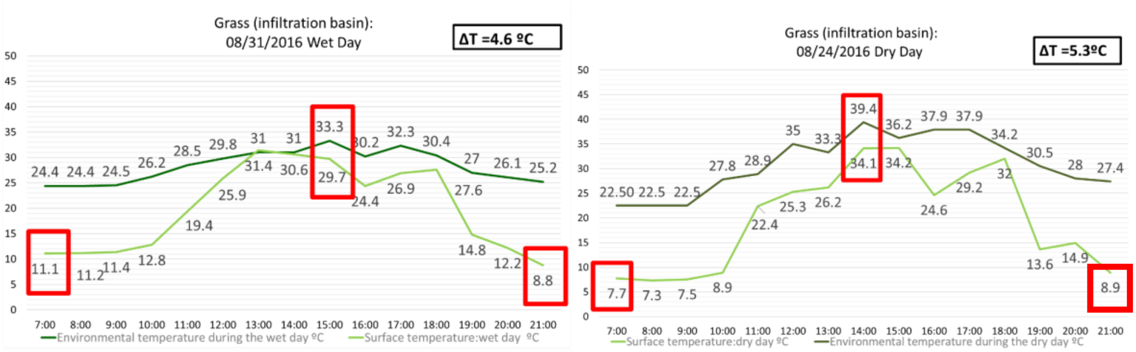
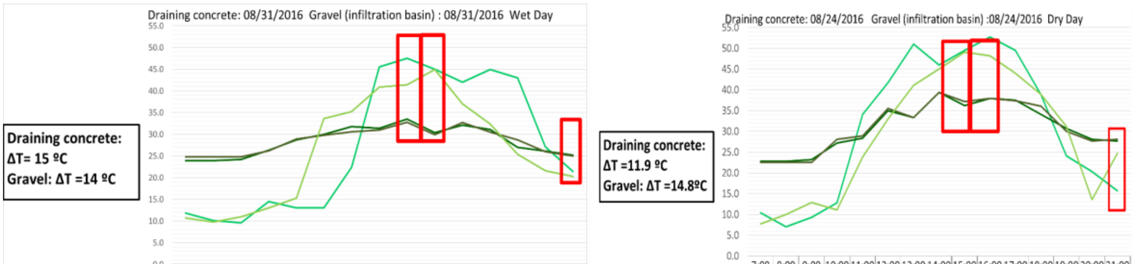


Figure 5.1. **Draining concrete and gravelwet day** | Figure 5.3. **Draining concrete and gravel on dry day**



	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00
Gravel (inf. basin): Ts wet day ºC	11.8	10.1	9.6	14.5	13.0	13.0	22.4	45.5	47.5	45.0	42.0	44.9	43.0	27.1	21.4
Gravel (inf. basin): Te wet day ºC	23.9	23.9	24.2	26.3	28.7	30.0	31.8	31.4	33.5	30.4	32.1	31.1	27.0	26.1	25.2
Draining concrete: Te wet day ºC	24.8	24.8	24.8	26.2	28.9	29.8	30.6	31.0	32.8	29.9	32.7	30.5	28.7	26.0	25.0
Draining concrete: Ts wet day ºC	10.7	9.8	11.0	13.0	15.3	33.6	35.2	40.9	41.4	44.9	37.0	32.4	25.4	21.6	20.3

	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00
Gravel (inf. basin): Ts dry day ºC	10.4	7.0	9.3	12.8	34.1	41.7	51.0	46.0	49.5	52.7	49.5	38.8	24.1	20.3	15.7
Gravel (inf. basin): Te dry day ºC	22.8	22.8	23.2	27.2	28.4	35.0	33.3	39.4	36.2	37.9	37.5	34.1	30.7	28.1	27.7
Draining concrete: Te dry day ºC	22.5	22.5	22.5	28.1	28.9	35.5	33.3	39.4	37.2	37.9	37.4	36.1	30.0	27.7	28.1
Draining concrete: Ts dry day ºC	7.7	10.0	12.9	11.1	23.8	33.0	41.1	45.0	49.1	48.2	44.0	38.9	31.2	13.6	24.7

Source: own elaboration.

Grass: The Ts of the infiltration basin was lower than the Te. When Te was at a maximum, the temperature gradient (Te-Ts) was 4.6ºC on the wet day (Figure 5.1) and 5.3ºC (Figure 5.3) on the dry day.

In contrast, the grass Ts at sunset on the dry day was 8.9ºC and on the wet day it was 8.8ºC. Sunrise Ts on a dry day was 11.1ºC and sunrise Ts on a wet day was 7.0ºC. This means there was no heat to release during the night on the dry day and a temperature gradient of 4.1ºC was released during the night on a wet day.

In contrast, systems that do not retain water (for instance, Figs. 5.1 and 5.3), such as draining concrete and gravel, always reached Ts higher than Te during the hottest hours of the day.

The temperature gradients of draining concrete and gravels, between sunset and sunrise of the dry day and the wet day, are much higher than those of grass (Figs. 5.1, 5.3 and 5.2). Thus, draining concrete and gravel can release more heat during the night than grass.

Grass in the infiltration system was the only material to show electrical conductivity, while draining concrete and gravel had values of zero, even 24 hours after rain.

The next year, when the blue roof prototype at the ETSAB courtyard was measured, we also recorded grass on a surface close to it (measurements on 20 September and 20 October 2017). This was explained at the CTV'18 Congress (Pérez Cambra M. & Roca Cladera, 2018). Ts was below Te, as in the previous year in Can Cortada.

The first hypothesis to explain a Ts lower than Te for vegetated systems was water retention, due to the high specific heat of water. Water is the substance that has the highest specific heat. It requires 1 cal to increase 1.0ºC 1 g of mass (or 4.16 joules).

According to the papers *"Capacidad de Retención de Agua Disponible (CRAD) para las plantas en suelos del Alto y Medio Aragón"* and *"Efectos de la materia orgánica sobre el suelo",* porosity and granulometry and other parameters such as depth and organic matter (due to water retention) can also affect Ts (Soriano Soto, María Desamparados, 2020; Valero Sancho, Agostín Loís, 1999).

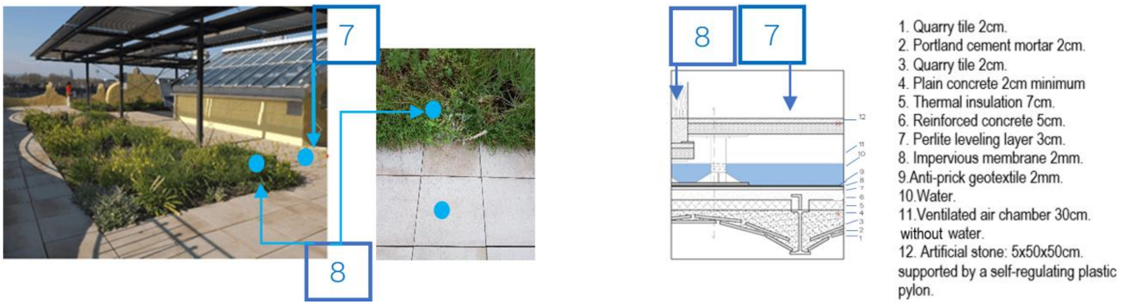
The "grass" planted in the Can Cortada infiltration basin is a mixture of two species: Zoysia japonica (drought resistant) and Festuca arundinácea (the grass with the deepest roots of all the cold climate grasses and with most resistance to heat and drought). In summer, Zoysia japonica predominates and in winter, Festuca arundinácea. The roots can reach depths of 30-60 cm.

The thermal behavior of the WSUDs built in Can Cortada (infiltration basin, structural soil pit tree, draining concrete) were checked for the third time some years later, with new records in the early autumn of 2021. The same trend was followed: only vegetated systems had surface temperatures above the Te (the substrate of the infiltration basin surface temperature was under that of Te). Could the main difference between these WSUDs be that vegetated areas, like those of the infiltration basin, retain water more than other WSUDs materials and construction systems? Could water have this powerful effect?

To answer this question, the surface temperatures of La Fábrica del Sol, a public building with a green/blue roof, were also measured that summer, to see whether water proximity could affect the surface temperatures of the artificial stone. According to "Total watermark, city as a catchment" (Melbourne City Council, 2009), a blue/green roof is one of the rainwater management construction systems included in WSUD, like the quantified example of Fawkner Park shown in the cited publication. A part of the blue roof is built with artificial stone. This artificial stone surface has no evapotranspiration possibility on its surface and it is not a granulometric subsoil. As soon as permissions were received through an agreement with Barcelona City Council, surface temperatures were recorded on the green/blue roof (location "C" in Figure 1, 7 & 8 construction systems in Table 4 and Figures 6, 7 & 8) in the permitted hours. All records were made 24 h after rain and 24 h after no rain during the summer.

E-ISSN 1886-4805

Figure 6, Figure 7 & Figure 8. **La Fábrica del sol**



Source: own elaboration and own images.
Note: blue roof (#7) and green-blue roof (#8).

Again, surface temperatures were higher than Te on the wet day (the day after rain there were 3 cm of water; on the dry day the roof structure was just partially wet from the last rain and without water). This was explained in depth in the article "WSUDs thermal behavior" (Pérez Cambra M. & Roca Cladera, 2018) but the statistics in Fig. 13 were not shown.

Figure 9. **Blue and Green-Blue roof measurements on the dry day (just wet but without water) and the day after rain (3 cm of water)**

Figure 9.1. **Artificial stone surface (blue roof): a) wet day and b) dry day**

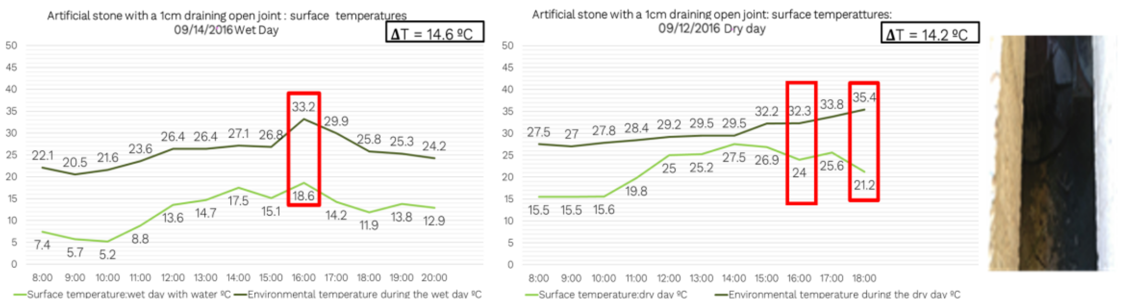
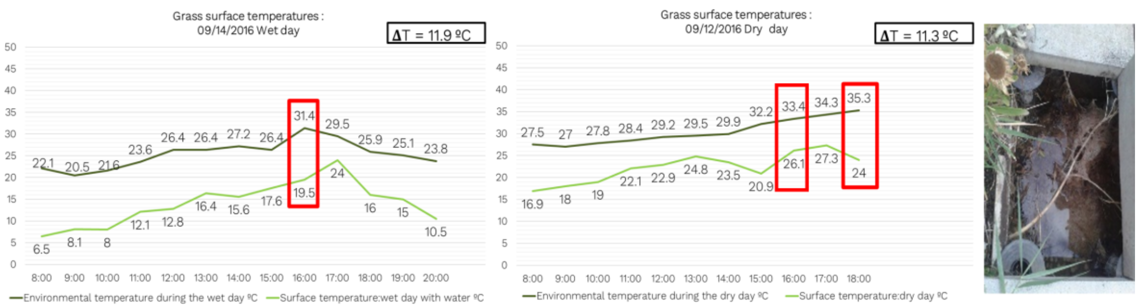


Figure 9.2. **Vegetation surface (blue roof): a) wet day and b) dry day**



Source: own elaboration.

There is a lower difference between surface temperature and Te when the structure is just wet and a higher difference when there is water (3 cm), in both cases at the same time (16:00 h). The temperature gradient when Te is the maximum in each case is also highlighted.

Therefore, water presence is the most effective at reducing surface temperatures on a roof, even if it is not in direct contact, whether it is underneath a material, without any vegetation or retained in a vegetated surface to reduce temperatures.

As water had such a strong effect, a prototype of a blue roof was built at the Architecture School of Barcelona to verify the strong water impact on surface temperatures. It was built with the same stone and layers as La Fábrica del Sol's blue roof. As it was analyzed deeply in "WSUDs thermal behavior"

(Pérez Cambra M. & Roca Cladera, 2018) for the CTV'18 Congress, here we will only describe briefly the measurements of the surface temperatures of the blue roof without water and with 1 cm of water. As it could not be built earlier, the prototype was measured in summer and early autumn and the performance of surface temperatures followed the same trend. On the dry day (without rain, 24 hours before the measurements and without water in this case), the surface temperature was above the Te in the hours with most radiance, and the surface temperature was below the Te when there was 1 cm of water on the blue roof during the wet day (it had rained in the previous 24 h).

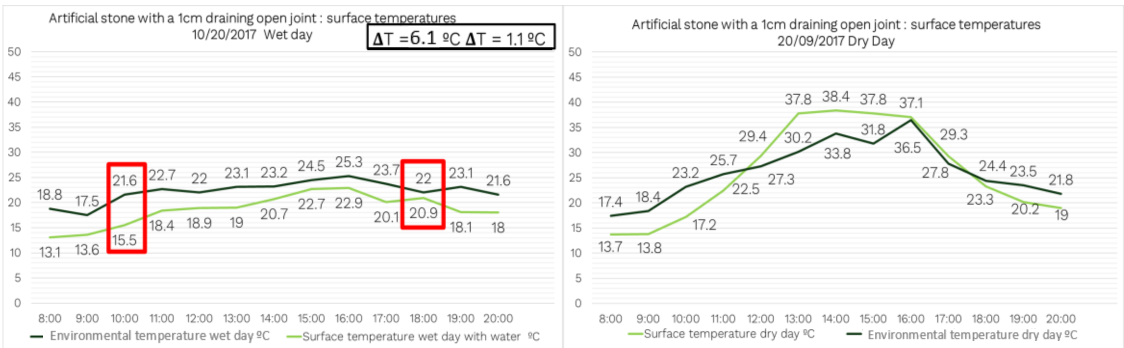
Figure 10. **Blue roof prototype**

Source: own construction and elaboration.

Note: a) prototype section, & b) prototype on the ETSAB terrace (6 cm of water).

During the dry day, the blue roof had no water in the ventilated chamber of the prototype. Thus, surface temperatures were above the environmental temperatures at the hottest times of the day (Fig. 11b), from 11:30 to 17:30 h). However, the day after rain, when water was only present in the prototype's ventilated chamber (6 cm), the temperature of the stone decreased below the environmental temperature by between 6.1ºC and 1.1ºC (Figure 11a).

Figure 11. **Blue roof prototype measurement: a) wet day and b) dry day**



Source: own elaboration.

Hence, the environmental temperatures were not the same on both days (wet day and dry day). (Pérez Cambra M. & Roca Cladera, 2018) also showed measurements close to summer 2017 on 20 September (dry day) and 20 October (wet day), and on 18 June (dry day) and 31 May (wet day). The last two dates are not included in this article. An approximation with a numerical calculation for the four dates showed Ts of the artificial stone as if the wet and the hot day had the same environmental temperature. In both cases (September-October 2017 and May-June 2017), the Ts would have been lower on the wet day than on the dry day.

The trend shown on the four dates is that Ts was always lower for the same material on the wet day, with more water on the blue roof, than on the dry day. Other studies and situations have been reported on infiltrating surfaces. In the study "Progettare il comfort degli spazi pubblici", dry grass was reported to be at 42.2ºC (Dessì, Valentina, 2015) while green vegetation was at 28.0ºC and air temperature at 36.9ºC (21 July 2015). This research was carried out in Milan. They have hot summers but a rainier climate (Cfa; in 2015 pluviometry was 639, 85 mm but it is usually higher than in Barcelona). The study follows the trend reported in this article.

However, it introduces the question about what happens to Ts when it is not rainy and the vegetation is dead.

In summer 2023, meteorological drought was declared in Barcelona. On 25 July, new measurements were recorded at 15:00 h (when Ts is usually the highest in most of the graphics), to check the surface temperatures of vegetation. Zoysia japonica was yellow (41.434075, 2.152357, point 2 in Table 4) and dead. Zoysia Ts (53.0ºC) was above the draining concrete temperature (50.0ºC) but below that of gravel (60.3ºC). However, the same Zoysia, in the shade in the same infiltration basin was green and its Ts was 36.5ºC, while Te was 34.2ºC. Thus, vegetation in the shade could live. Yellow Zoysia was dead and become a fire charge. At that time, the city parks and gardens maintenance service had not irrigated for at least three weeks due to the drought. In the same area (41.435277, 2.153176), Muehlenbeckia was also measured and provided better results than Zoysia (Ts 38.9ºC while Te was 35.5ºC with no shade).

During the drought, yellow Zoysia recordings followed the same trend as those included in the research carried out in the same summer (Moyasevich Tristan, Nevenka, 2023) in Barcelona. The three days of data recording were: 25 July, 28 July and 2 August. The average Te was 32.4ºC and grass was 54.8ºC under the sun. In areas with rainy summers and high relative humidity, non-vegetated construction systems can be used to retain water. This is the case of Osaka or Tokyo. To benefit from water retention surface temperature effects, the city of Osaka implemented water-retentive pavements in 1998. They reported a decrease of 10.0ºC with their technology with retentive asphalt (Osaka City Public Bureau, 2024).

In Tokyo, reclaimed wastewater has been recycled widely for non-potable urban applications like sprinkling retentive pavements to mitigate heat islands in urban areas. These methods decreased the road surface temperature by 8.0ºC during the daytime and 3.0ºC at night; temperatures equal to those in planted zones.

In our research and climate, non-organic retentive pavements showed zero electrical conductivity 24 h after rain, and relative humidity and pluviometry are lower than in Cfa climates such as that of Tokyo and Osaka. How can we protect infiltrating surfaces that cannot retain water? Is it possible to protect vegetated systems during droughts to provide them with living conditions and keep on retaining water? One of the most effective methods is covering them with shade.

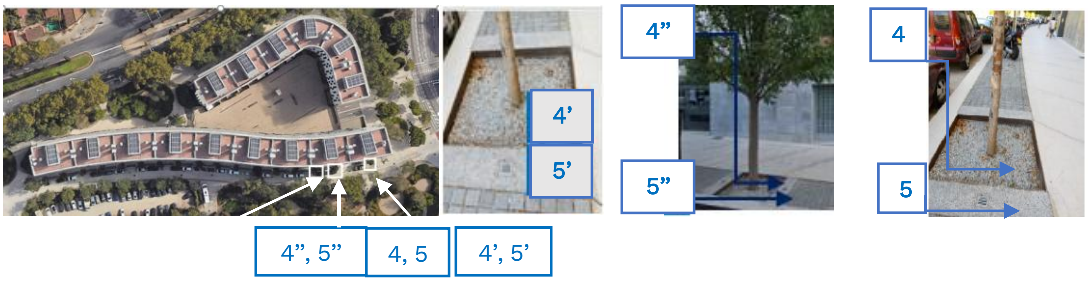
3.2 *Systems that do not retain water: Can Cortada and Cristóbal de Moura*

The first step was measuring the building and tree shade effect on WSUDs. There are three examples: the structural soil pit trees, the gravel of the infiltration of Can Cortada and the sand infiltration basin of Cristóbal de Moura. They were measured during summer 2016 (on a dry day and a wet day). The Ts gradient of the structural soil pit tree that changed, in the same day, from a sunny situation to a shaded situation was so significant (Figure 12d & Figures 13a & 13b) that new measurements were made to verify this behavior in the second phase of the research in 2021 (Figures 14 & 15).

3.2.1. Building shade effect

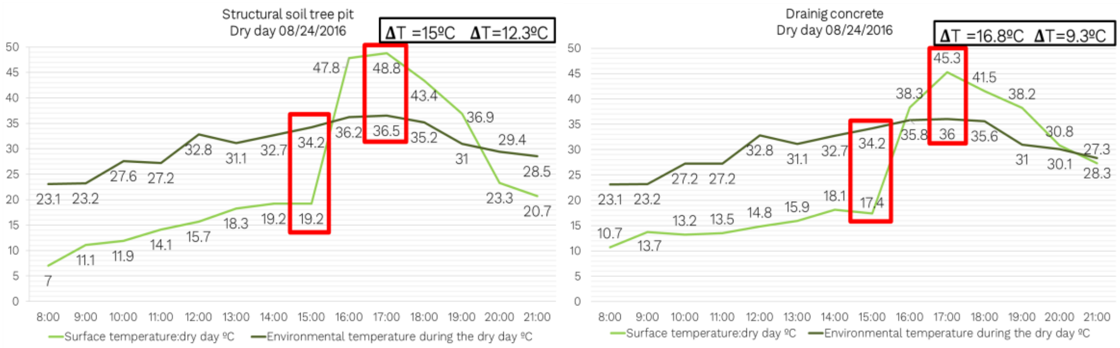
Can Cortada structural soil pit tree was built with a continuous layer of structural soil composed of gravel and vegetative soil (80% and 20% respectively). This layer goes under the root balls of the entire street. Above this layer, on the sidewalk part which connects the soil pit trees, there is a layer of geocells and, above it, draining concrete. Above the root ball is a layer of granite gravel. Although structural soil pit trees contain large gravel, surface materials like draining concrete on the structural soil pit tree do not show different thermal behavior from the draining concrete of the infiltration basin (Figures 13a & 13b from Figures 5.1 & 5.3).

Figure 12. **Building shade**



Source: own elaboration.
Note: a), b), c) Can Cortada structural soil pit trees (4, 4’, 4”) and a) b) c) d) gravel (5, 5’, 5”): a), b) sunny (4’, 5’); c) shaded (4”, 5”); d) sunny and shaded during the day (4, 5).

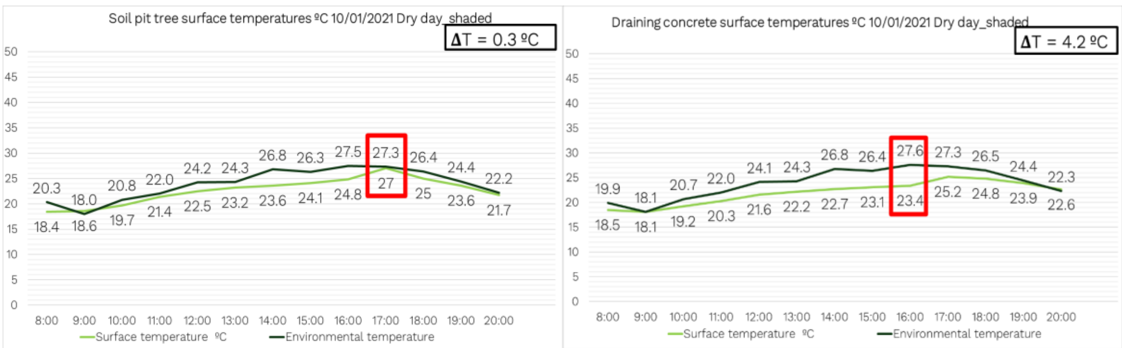
Figure 13. **a) structural soil pit tree and b) draining concrete sunny and shaded on the same day**



Source: own elaboration.

During the first phase of the research, the structural soil pit tree was recorded. The surface was shaded before 15:00 h. Its Te-Ts gradient was 15.0ºC and 16.8ºC for the draining concrete around it (#5 Fig 12d), both on the dry day. When it was sunny, after 15:00 h (and Te was the maximum), the Ts-Te maximum gradient (while Ts the highest) was 12.3ºC for the structural soil pit tree and 9.3ºC for the draining concrete, on the wet day.

Figure 14: **Building shaded**



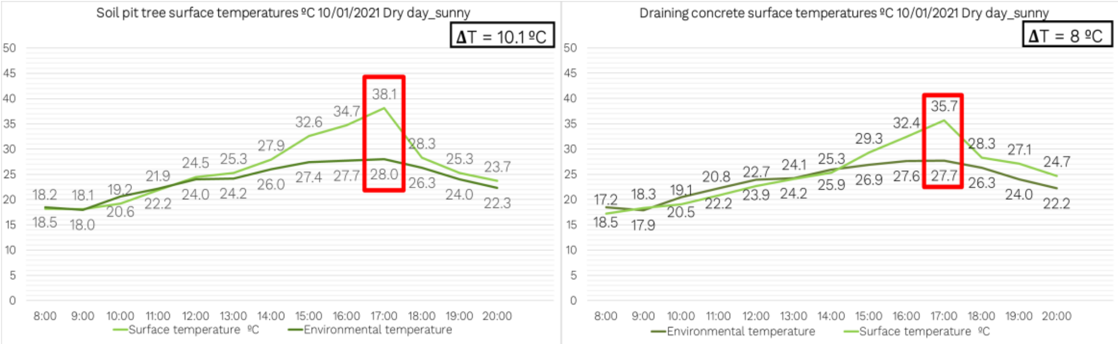
Source: own elaboration.
Note: a) structural soil pit tree and b) draining concrete measurements #4” & #5”, Figure 12c pictures (Can Cortada).

In the second phase of the research, there was a second measurement of building shade for verification. This time, measurements were made in a shaded structural soil pit tree and in the shaded draining concrete around it during the entire day, and in the sunny structural soil pit tree and surrounding concrete on the same day (it was a dry day).

The date was 1 October, just ten days after finishing summer. The performance of the construction system under a building’s shade or without shade confirmed the trend of the first recorded thermal performance. Under the shade, the Ts of the draining concrete and the soil pit tree were lower than the Te in the hours with the highest Te during the day.

However, both the sunny draining concrete and the sunny structural soil pit tree Ts were again above the Te, even by almost 10.1ºC in early autumn (although the maximum temperature gradients were not as high as in summer).

Figure 15. **a) sunny soil pit tree and b) draining concrete measurements #4' and #5' of Fig. 12b pictures (Can Cortada)**



Source: own elaboration.

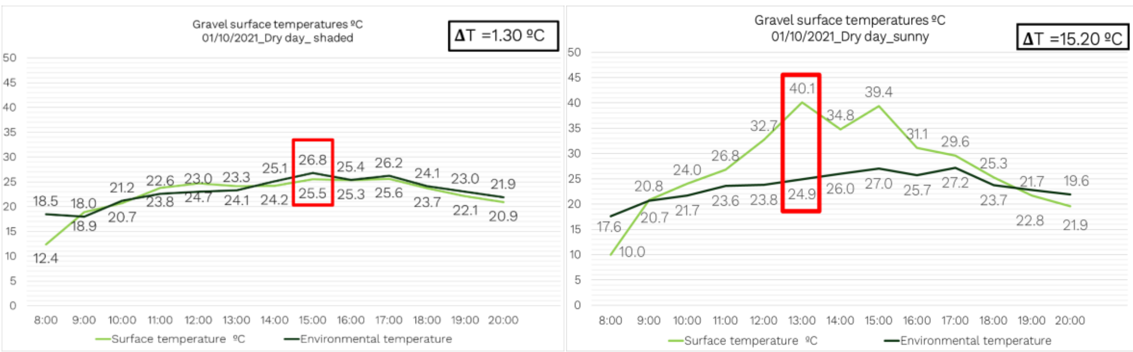
3.2.2. *Green shade*

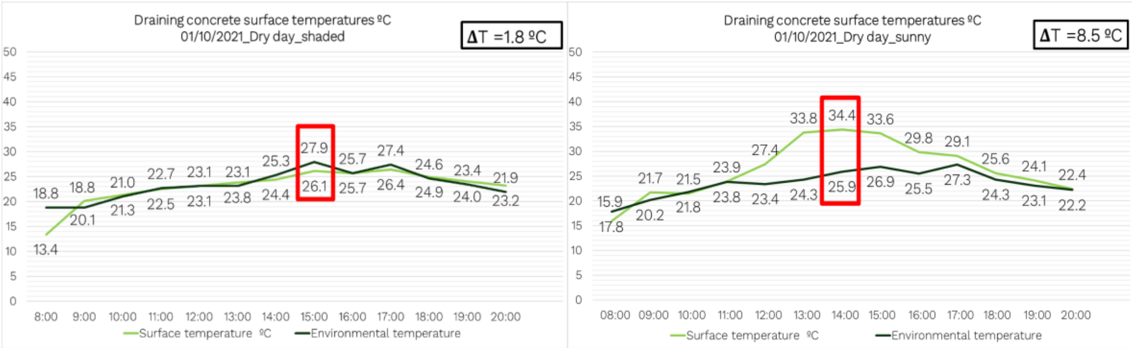
On the same day (1 October, a dry day), measurements were made in two infiltration basins: in a green shaded one (under the trees) and in a sunny one. The maximum temperature gradients were not as high due to the month of the recordings. However, this confirms that Ts peaks are reduced even from 40.1ºC to nearly Te or a bit lower.

Figure 16. **Infiltration basin**

Source: own elaboration.
Note: a) gravel area under green shaded area (#9) and area without shade (#10) and b) draining concrete shaded (#9') and without shade (#10').

Figure 17. **Infiltration basin measurements of the a) gravel area under green shade and b) without shade and c) draining concrete under the shade and d) without shade**





Source: own elaboration.

Under the shade, the surface temperature of the gravel in the infiltration basin is similar to Te. However, gravel in the sunny infiltration basin can reach even 15.20ºC above the Te temperature.

The maximum gradient Te-Ts is Te maximum (Figures. 17a & 17c) and the maximum gradient Ts-Te reached is Ts maximum (Figures 17b & Fig. 17d).

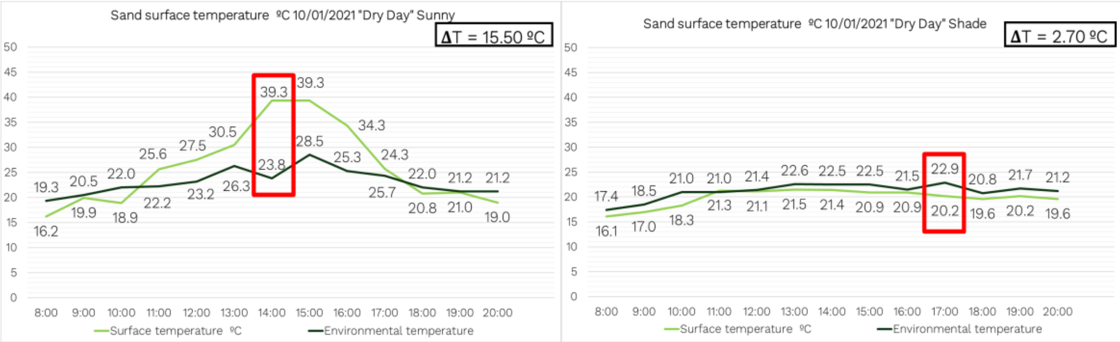
Figure 18. **a) Cristóbal de Moura Nbs green axis, sunny and shaded, b) gravel and c) sand infiltration areas**

Source: own elaboration.

Fine sands (#11 and #14) have a lower range of infiltration speed than gravels. “Albero” or fine sands are in the range of 5.80 x 10 - 3 and 4.43 x 10 - 5 cm/s and gravels of the same granulometry as in Cristóbal de Moura have an infiltration speed of 3.80 x 10 - 1 cm/seg., according to “Hydraulic and physical property characterizations of materials for the design of sustainable urban drainage systems” (Alhama, Iván, et al., 2023).

However, the same gradient between surface temperatures and environmental temperatures is maintained in small gravel in Can Cortada (15.20ºC in Figure 17b) and in the sand infiltration areas of Cristóbal de Moura on sunny days (15.50ºC in Figure 19a). Both materials behave in a similar way under the shade, with very slight differences between Ts and Te (Figure 17b & Figure 19a). This is because factors other than granulometry and hydraulic conductivity determine surface temperatures.

Figure 19. **Cristóbal de Moura Nbs green axis**



Source: own elaboration.
Note: a) sunny and b) shaded sand infiltration areas' statistics.

Tree shade is one of the heat island mitigation strategies of the Environmental Protection Agency (EPA; Climate Protection Partnership Division in the U.S. Environmental Protection Agency's Office of Atmospheric Programs, 2017). Other studies examine surface temperature recordings depending on the type of tree and the material surface. Results range from 8.8ºC of a surface temperature gradient to 17.8ºC (Van Doan Cao, Pavel Kic, 2019).

According to the PhD thesis *"La vegetación como instrumento para el confort climático"* (Ochoa de la Torre, 1999), the shade effect of a pergola covered by wisteria was recorded. During the summer there was a difference of up to 20.0ºC between the sunny pavement and the air temperature at the hottest time of the day. The shaded pavement was up to 2.0ºC below air temperature. This is a similar range to the results obtained in the shaded structural soil pit tree and the shaded draining concrete in summer (Figures. 13a & 13b); 15ºC and 16.8ºC respectively). In addition, EPA indicates a surface reduction of 11–25°C lower than the peak temperatures of unshaded materials ("Using Trees and Vegetation to Reduce Heat Islands", 2016).

A Barcelona study was undertaken on surface temperatures with two trees: Celtis australis and Platanus hispanica on two streets and summer days (25 June and 16 July 2015). The results obtained showed a temperature gradient between surface temperatures outside the shade and under the tree between 11.9ºC and 27.12ºC for Celtis australis and 14.52ºC and 23.2ºC for Platanus hispanica (Rojas, et al., 2016). The same author wrote a PhD thesis with more examples explaining the radiant temperature of shaded surfaces under some species of Barcelona trees and outside of the shade (Rojas, 2016).

3.2.3. Granulometry, albedo and thermal inertia

During the second phase of the research, the last part was focused on finding parameters that could help to reduce Ts in materials that are frequently used to build WSUDs that cannot retain water and usually have higher hydraulic conductivity.

Measurements were made on 21 July 2022 at the Architecture School of Barcelona, during a dry day. This was due to the fact that, according to all previous results, rainwater would not change the thermal trend performance.

The materials analyzed were sedimentary, volcanic and metamorphic gravel of different granulometries and colors (two colors for each group), grey draining concrete (one sample), structural soil (one sample), rubbers of three colors and two kind of substrates (with slightly different compositions).

Why were different colors analyzed? Without shade and during the hours and season of highest radiance, one of the parameters that mainly determines the radiation absorbed or reflected and the subsequent accumulation due to thermal inertia is albedo.

Albedo derives from the Latin “albus” which means white (Lambert, Johan Heinrich, 1760). It was introduced by Johann Heinrich Lambert in his book Photometria. He explains, in Theroema XXXV, that albedo is determined by the relation of the brightness of the surface when it receives light and the brightness of this incident light. Thus, it is the relation between the radiance reflected and received by a surface. It depends on the whiteness of the surface (albedo).

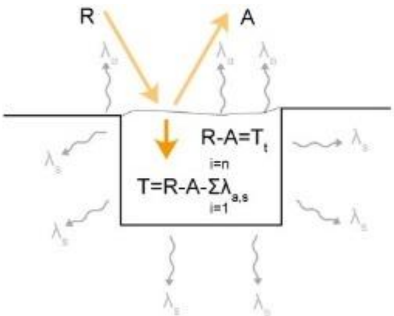
Why was thermal inertia examined?

After this reflection, the part of the radiance that was absorbed by the material will heat it. Depending on the material thermal inertia, the material temperature will be higher or lower. Thermal inertia has been defined as the ability of a material to resist a temperature change when a periodic forcing function is applied (Veto & Christensen, 2015). It is defined as the square root of the thermal conductivity, specific heat and density with the units of joules per square meter per kelvin per root second:

$$I = \sqrt{k\delta c} \quad \left[\mathrm{J} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1} \cdot \mathrm{S}^{-\frac{1}{2}} \right]$$

During this research, in summer wind speed was usually zero or nearly zero during the daytime. Thus, during the daytime, incident radiance (“R” Fig. 20) minus reflected radiance albedo (“A” Fig. 20) is the heat transmitted (“Tt” Fig. 20) to the material. The more radiance is absorbed, depending on the albedo, the more heat can be stored due to the specific thermal inertia of each material.

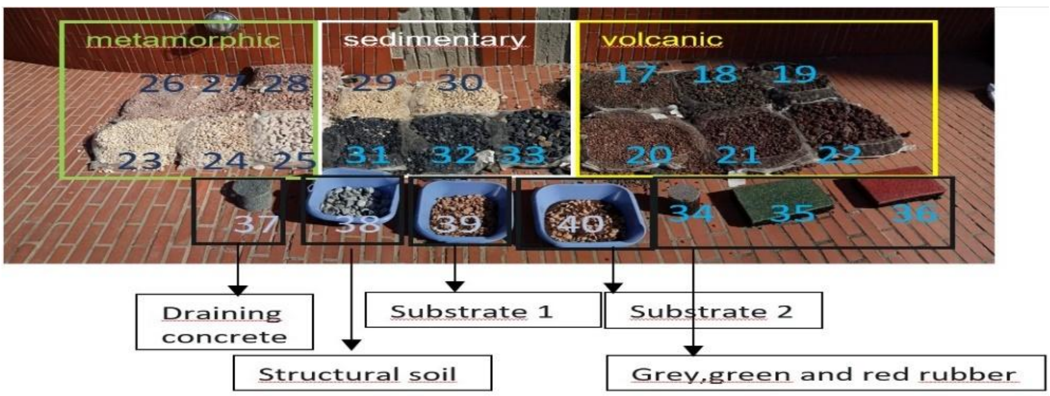
Figure 20. **Heating process**



Source: own elaboration.

Why is granulometry important? Thermal inertia variables depend on the material but the kinematics of heat depends on its shape. For the same material with the same thermal inertia, the bigger the granulometry, the higher the hydraulic conductivity that is reached (Berry, Peter L. & Reid David, 1993; González de Vallejo, Luis I. et al., 2002; *Permeabilidad Del Suelo, Fao*, n.d.) and the lower Ts that is achieved during a hot dry summer.

Figure 21. **ETSAB terrace measurements: materials that do not retain water**



Source: own elaboration.

E-ISSN 1886-4805

- *Volcanic stones (Figure 21, #17 to #22)*

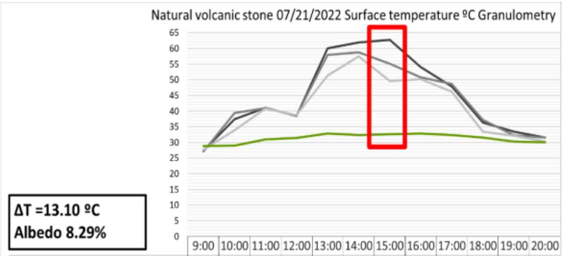
Some WSUDs are built with gravel to allow fast water percolation, for example, French drains, infiltration and detention basins, among others (Woods-Ballard et al., 2007).

To determine how much granulometry can affect the range of gravel Ts, a comparison between the same type of stones (volcanic, metamorphic and sedimentary stones) was recorded and studied. This last study was recorded in summer.

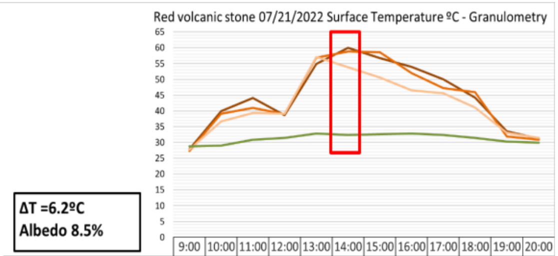
The first group analyzed is comprised of two volcanic stones: natural volcanic stones (black) and red volcanic stones (dark red). In this case, each group has three granulometries (5-10 mm, 10-25 mm, 25-50 mm) and similar albedo. Measured in summer on 21 July 2022, the red volcanic stone albedo average was 8.96% and natural volcanic stone albedo average was 8.29% (similar). Then, volcanic stones, with similar characteristics, should behave the same way thermally.

Below is an analysis of how granulometry changes surfaces temperatures.

Figure 22. **Natural and volcanic stone granulometries and surface temperatures (Fig. 21 #17 to #22): a) natural volcanic stone and b) red volcanic stone**



	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Natural volcanic stone 5-10mm	27.30	37.40	41.00	38.50	60.10	61.90	62.70	54.10	47.90	36.30	33.40	31.60
Natural volcanic stone 10-25mm	27.10	39.40	40.90	38.60	57.90	58.70	55.10	50.80	48.70	37.20	32.20	31.60
Natural volcanic stone 25-50mm	27.70	33.90	40.80	38.70	51.40	57.50	49.60	50.20	46.20	33.40	32.10	30.20
Environmental temperatures 1	28.80	29.00	30.90	31.40	32.80	32.40	32.60	32.80	32.40	31.50	30.27	30.00



	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Red volcanic stone 5-10mm	27.80	39.90	44.10	38.70	54.90	60.00	56.70	54.00	50.00	44.20	33.50	31.20
Red volcanic stone 10-25mm	27.30	39.10	41.00	39.00	56.90	58.80	58.60	52.00	47.20	46.00	31.90	30.90
Red volcanic stone 25-50mm	27.70	36.70	39.30	39.10	57.10	53.80	50.60	46.50	45.60	41.10	33.10	31.40
Environmental temperatures 3	28.80	29.00	30.90	31.40	32.80	32.40	32.60	32.80	32.40	31.50	30.27	30.00

Source: own elaboration.

Surface temperatures can reach a maximum thermal gradient of 13.10ºC for 5-10 mm and 25-50 mm natural stone gravels. This maximum thermal gradient reaches 6.2ºC for gravels of the maximum and minimum granulometry shown in the charts for red volcanic stones. In this case, intermediate granulometry gravels (10-25 mm) are similar to 5-10 mm gravels.

The same trends occurred when they were measured in the preliminary measurements of 19 November 2021, but with a minor thermal gradient. It is remarkable to see how for these stones, Ts doubles Te (62.70ºC and 60.0ºC versus 32.60ºC and 32.40ºC) one or two hours after the time of maximum radiance (99700 luxes at 13:00 h).

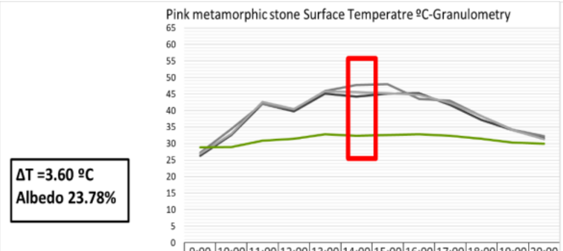
- *Metamorphic stones (Figure 21 #23 to #28)*

This second case examines two metamorphic stones with different albedos. They both have the same thermal inertia but the albedo is 6.37% higher in pink metamorphic stones than in red marble ones. This higher albedo means that pink metamorphic stone absorbs less radiation. As a consequence, red volcanic stones reach higher temperatures than pink metamorphic stones (57.80ºC versus 48.0ºC as a maximum, which is a 15.4% less).

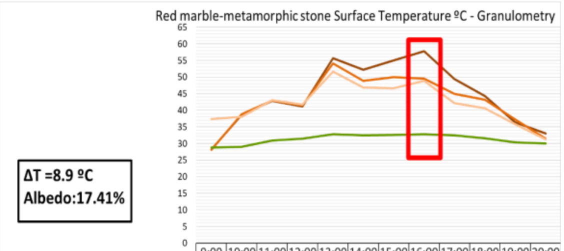
If we analyze the granulometry, when the radiation absorbed is lower, differences between granulometries are also lower and start to get mixed. This also happens in yellow sedimentary stone (Figure 24) and in the preliminary measurements made in November, when radiance was lower in absolute values. In the case of red marble stones (Figure 23), the albedo is 5.3% higher than for pink metamorphic stone. The maximum Ts differences between granulometries were higher (8.9ºC amongst the highest Ts maximum of the same material versus 3.6ºC) for the red marble stone than for the pink stone.

Figure 23. **a) Pink metamorphic stone and b) red marble metamorphic stone granulometries and surface temperatures (Fig. 21 #23 to #28)**

Thermal Inertia: 1927.22 $\left[J \cdot m^{-2} \cdot K^{-1} \cdot S^{-\frac{1}{2}} \right]$



	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Pink metam. stone 6-12mm	26.30	32.60	42.10	39.80	45.10	44.20	45.10	45.20	41.70	37.10	34.10	31.60
Pink metam. stone 12-24mm	27.20	34.40	42.10	40.30	45.90	47.80	48.00	43.50	43.00	38.30	34.20	32.20
Pink metam. stone 24-40mm	26.90	32.90	42.60	40.40	45.80	45.60	45.20	44.80	42.30	38.30	34.10	31.30
Environmental temperatures 12	28.80	29.00	30.90	31.40	32.80	32.40	32.60	32.80	32.40	31.50	30.27	30.00



	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Red marble gravel 10-20mm	28.20	38.60	42.80	41.20	55.70	52.20	55.00	57.80	49.40	44.30	36.30	33.00
Red marble gravel 20-30mm	28.10	38.80	42.90	41.50	54.10	48.90	50.00	49.50	44.90	43.20	37.20	31.40
Red marble gravel 24-40mm	37.40	38.00	43.10	41.70	51.70	46.90	46.60	48.90	42.20	40.60	35.80	31.20
Environmental temperatures 15	28.80	29.00	30.90	31.40	32.80	32.40	32.60	32.80	32.40	31.50	30.27	30.00

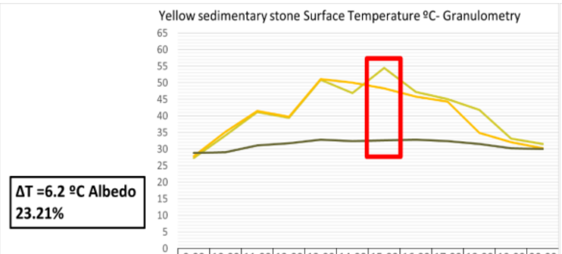
Source: own elaboration.

- Sedimentary stones (Fig. 21 #29 to #33)

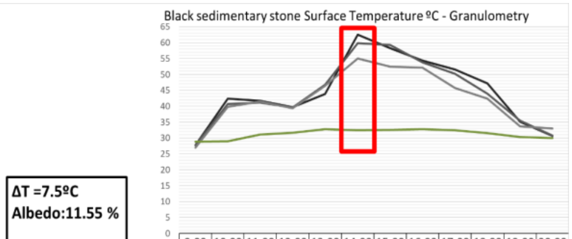
In this case, the trend is repeated. Yellow sedimentary stone has an albedo that almost doubles that of black sedimentary stone (23.21% versus 11.55%) and maximum temperatures for yellow sedimentary stones were only 12.8% lower than for black sedimentary stones.

Figure 24. **a) Yellow sedimentary stone and b) black sedimentary stone granulometries and surface temperatures (Figures 21 #29 to #33)**

Thermal Inertia: 1628.80 $\left[J \cdot m^{-2} \cdot K^{-1} \cdot S^{-\frac{1}{2}} \right]$



	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Yellow sedim. stone 6-12mm	27.30	34.10	41.10	39.40	50.90	46.90	54.50	47.20	45.00	41.80	33.10	31.50
Yellow sedim. stone 12-18mm	27.80	35.20	41.50	39.70	51.10	50.00	48.30	45.80	44.30	34.90	32.10	30.20
Environmental temperatures 7	28.80	29.00	31.10	31.70	32.80	32.40	32.60	32.80	32.40	31.50	30.27	30.00



	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Black sedim. stone 6-12mm	27.70	42.40	41.70	39.70	43.80	62.50	58.30	54.30	51.60	47.20	35.10	30.60
Black sedim. stone 12-24mm	27.70	40.70	41.20	39.60	46.80	59.80	59.30	53.80	50.20	44.00	35.50	30.80
Black sedim. stone 24-40mm	27.00	39.80	41.50	39.40	46.40	55.00	52.40	52.10	45.70	42.40	33.70	33.00
Environmental temperatures 9	28.80	29.00	31.10	31.70	32.80	32.40	32.60	32.80	32.40	31.50	30.27	30.00

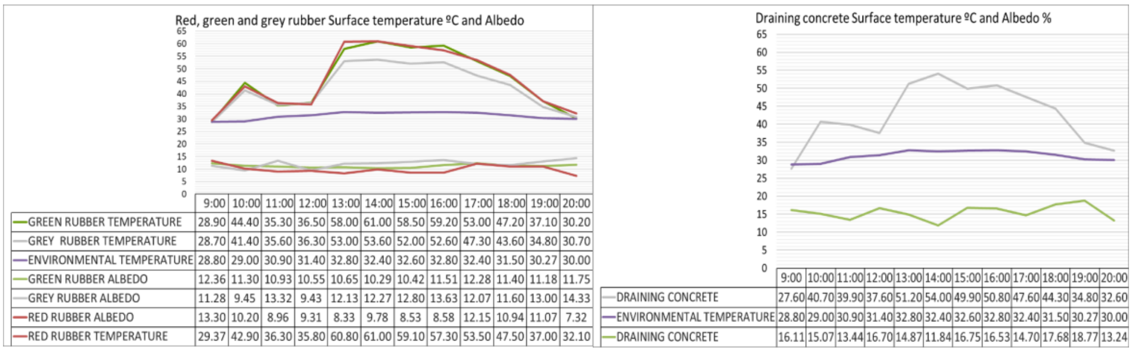
Source: own elaboration.

- Rubbers and grey draining concrete (Fig. 21 #34 to #37)

Rubber and other materials were measured and the relation between a higher albedo and a lower surface temperature, and vice versa, was repeated (Figures 25 & 28). Grey rubber and grey draining concrete behave similarly (Figures 25a & 25b). If they are used as infiltration surfaces to reduce Ts, building or green shades would be necessary to reduce heating by sun radiation.

As mentioned before, gravel is used for many WSUDs on their surface. Thermal behavior conclusions for these WSUD materials are briefly shown in Figure 26, showing maximum temperatures on 21 July 2022 and 19 November 2021 (Figure 26a) and minimum temperatures for both dates (Figure 26b). Note that when radiation is nearly zero or zero, on 19 November 2021 (in graphic 26b, the lowest values), the thermal trend is inverted for minimum temperatures. This means that the bigger the granulometry, the higher the Ts (gradients from 0.9ºC to 2.3ºC in Fig. 26b) and conversely for Ts under summer radiance. However, on 21 July (Figure 26a) the higher the granulometry, the lower the Ts, with a maximum gradient of 7.5ºC in the same material.

Figure 25. **a) Red, green and grey rubber and b) grey draining concrete Ts and albedos (Figure 21 #34 to #37)**

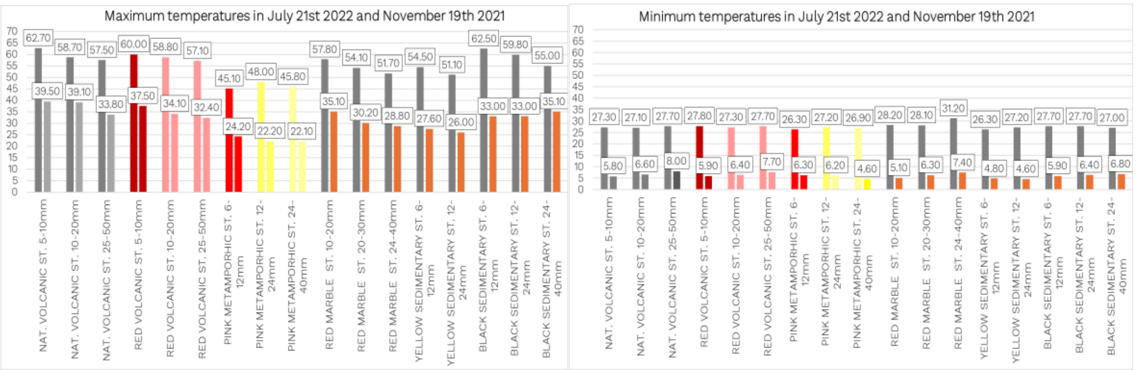


	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
GREEN RUBBER TEMPERATURE	28.90	44.40	35.30	36.50	58.00	61.00	58.50	59.20	53.00	47.20	37.10	30.20
GREY RUBBER TEMPERATURE	28.70	41.40	35.60	36.30	53.00	53.60	52.00	52.60	47.30	43.60	34.80	30.70
ENVIRONMENTAL TEMPERATURE	28.80	29.00	30.90	31.40	32.80	32.40	32.60	32.80	32.40	31.50	30.27	30.00
GREEN RUBBER ALBEDO	12.36	11.30	10.93	10.55	10.65	10.29	10.42	11.51	12.28	11.40	11.18	11.75
GREY RUBBER ALBEDO	11.28	9.45	13.32	9.43	12.13	12.27	12.80	13.63	12.07	11.60	13.00	14.33
RED RUBBER ALBEDO	13.30	10.20	8.96	9.31	8.33	9.78	8.53	8.58	12.15	10.94	11.07	7.32
RED RUBBER TEMPERATURE	29.37	42.90	36.30	35.80	60.80	61.00	59.10	57.30	53.50	47.50	37.00	32.10

	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
DRAINING CONCRETE	27.60	40.70	39.90	37.60	51.20	54.00	49.90	50.80	47.60	44.30	34.80	32.60
ENVIRONMENTAL TEMPERATURE	28.80	29.00	30.90	31.40	32.80	32.40	32.60	32.80	32.40	31.50	30.27	30.00
DRAINING CONCRETE	16.11	15.07	13.44	16.70	14.87	11.84	16.75	16.53	14.70	17.68	18.77	13.24

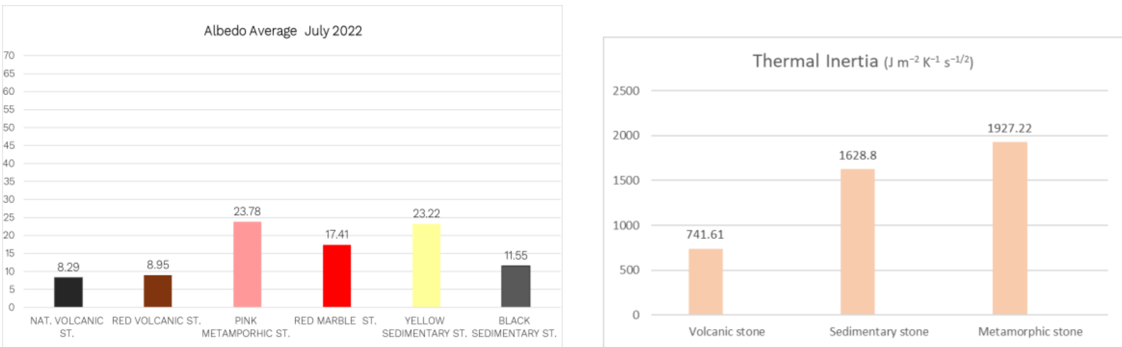
Source: own elaboration.

Figure 26. **Gravel a) maximum and b) minimum Ts on 21 July 2022 and 19 November 2021**



Source: own elaboration.

Figure 27. **a) Gravel albedo and b) thermal Inertia, 21 July 2022 and 19 November 2021**



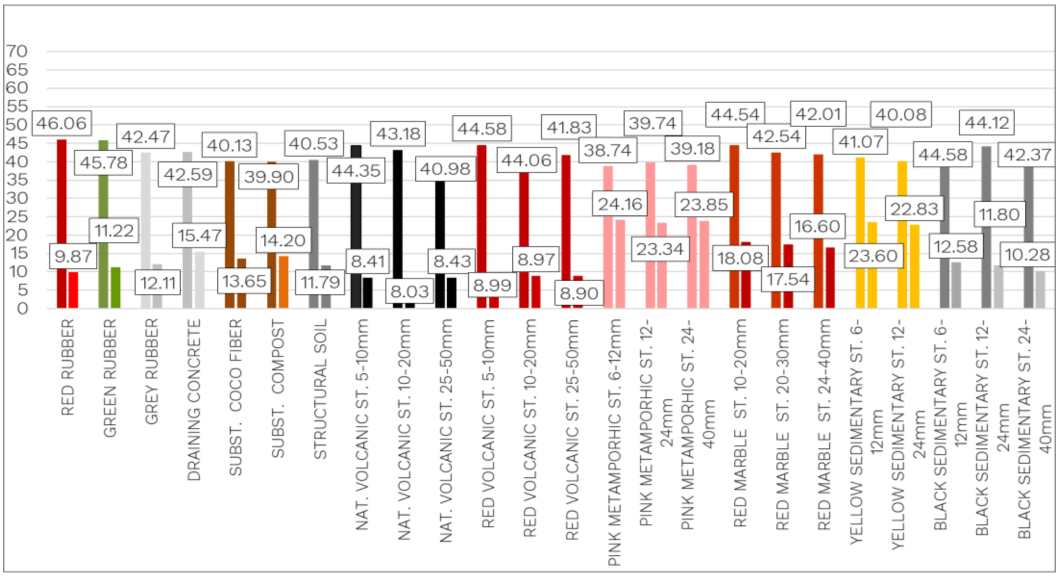
Source: own elaboration.

It is also remarkable that materials with higher albedo have the lowest surface temperatures and vice versa, not only in gravels but also with other materials such as rubbers with different albedos (Fig. 25, Figures 27a & Fig. 28). This is not the case with thermal inertia. It is a factor that helps to keep the heat, but not with the same strength as albedo (or radiation received). It also comes after radiance absorption, after reflection due to the brightness of surfaces (in summer during the daytime).

Thermal inertia allows storage of the radiance received due to the low albedo. Volcanic porous stones have low thermal inertia, but Ts are the highest and albedo are lower than for the other stones. Metamorphic stones have the highest albedos (Ts are the lowest) but the thermal inertia is the highest (it balances the high albedo to increase Ts).

Briefly, there is a clear relationship between albedos and surface temperature averages of the materials recorded, as shown in the next graphic (Fig. 28).

Figure 28. **Albedos and Ts materials average 21 July 2022**



Source: own elaboration.

Other studies have reported the same relation between high albedos and low surface temperatures and vice versa. For instance, with the same material, differences of about 15.0ºC have been found between a black and a white concrete (Dessi, 2008). An extreme example of reflective pavements, under desert weather conditions, shows a reduction of a 22% (from 60.0ºC to 47.0ºC) when the pavement is covered by a white surface and increases its albedo 192% (from 24% to 70%) in a total area of 0.8Ha (Ghenai et al., 2023).

4. Conclusions

We can establish two groups of WSUD construction systems and materials. The first group includes WSUDs that can retain and store water, due to their specific heat (that is, vegetated construction systems and blue roofs with or without vegetation but with water). The recorded reduction in temperature gradient (Te-Ts) reached 14.6ºC (Figure 9.1). The Ts reached at the end of the day is similar to that at sunset and almost no energy can be dissipated during the night.

Thermal behavior showed a different performance between WSUDs that could retain water and those that could not retain water.

The second group is WSUDs that showed no electrical conductivity (0) 24 h after rain. In this group, Ts above Te reached 14.8ºC for the gravel infiltration basin and 15.0ºC for draining concrete (Figure 5.3. & Figure 5.1 respectively). Summarized values are shown in Table 5. In these cases, the sunrise Ts is higher than the sunset Ts. This extra heat is released during the night, which increases the urban heat island (UHI) effect.

During the drought (summer 2023), there was scarce rain and no irrigation (with phreatic water) for weeks in the measured areas. Thus, there was no possibility of retaining water. During those summer days, the Ts of vegetated surfaces was as high as the Ts of inorganic material. Therefore, it became "fire charge".

The most effective method to reduce Ts to below Te in systems that cannot retain water was shading them. Shade also provided living conditions for vegetated systems especially during the drought (Ts recorded in the shade were below Te and plants were alive).

Table 5. **Scheme of WSUD construction systems' recorded thermal behavior**

WSUDs	Material	Date	Max ΔT Ts<Te	Ts<Te cause	Sunny Shaded	Max ΔT Ts>Te	Ts max	Te max	Albedo average	Granulo metry	Photo
1.Infitration basin (Fig. 4 and 5.3-Dry day)	gravel	08/24/2016	-	-		14.8ºC	52.7ºC	37.9ºC	16.0	6-12mm	
2.Infitration basin (Fig. 4 and 5.2.-Dry Day)	grass	08/24/2016	5.3ºC	water retention and vegetation		-	34.1ºC	39.4ºC	13.0	-	
3.Infiltration basin (Fig. 4 and 5.3.-Dry Day)	draining concrete (grey)	08/24/2016	-	-		11.9 ºC	49.1ºC	37.2ºC	17.0	-	
4. Blue-green roof (Fig.6-7-8-9.2. Wet Day)	green area	09/14/2016	11.9ºC	water storage evaporation and		-	24ºC	31.4ºC	11.4		
5. Blue roof (Fig.6-7-8-9.1. Wet Day)	artificial stone	09/14/2016	14.6ºC	water storage evaporation (3cm		-	18.6ºC	33.2ºC	14.9	-	
6. Blue roof 2- prototype (Fig.10 and Fig.11-Wet Day)	artificial stone	10/20/2017	6.1ºC	water storage evaporation (1cm		-	22.9ºC	25.3ºC	14.9	-	
7. Structural soil pit tree (Fig.13- Dry day)	structural soil pit tree shaded	08/24/2016	15.0ºC	Building shade		-	19.2ºC	34.2ºC	18.0	-	
8. Structural soil pit tree (Fig.13-Dry day)	concrete (grey) shaded	08/24/2016	16.8ºC	Building shade		-	17.4ºC	34.2ºC	21.0	-	
7. Structural soil pit tree (Fig.13-Dry day)	structural soil pit tree- sunny	08/24/2016	-	-		12.3ºC	36.5ºC	48.8ºC	18.0	-	
8. Structural soil pit tree (Fig.13-Dry day)	draining concrete(grey	08/24/2016	-	-		9.3ºC	36.0ºC	45.3ºC	21.0	-	
9. Infiltration basin (Fig.17 Dry day)	gravel-shaded	10/01/2021	1.3ºC	Green shade		-	25.5ºC	26.8ºC	16.0	6-12mm	
9'.Infiltration basin (Fig.14 Dry Day)	concrete (grey)shaded	10/01/2021	4.2ºC	Green shade		-	23.4ºC	27.6ºC	17.0	-	
10.Infiltration basin (Fig.16.Fig.17 Dry day)	gravel-sunny	10/01/2021	-	-		15.2ºC	40.1ºC	24.9ºC	16.0	6-12mm	
10'.Infiltration basin (Fig.15 Dry day)	draining concrete (grey)sunny	10/01/2021	-	-		8.0ºC	35.7ºC	27.7ºC	17.0		
11.Infiltration basin (Figs.19 Dry day)	sand-shaded	10/01/2021	2.7 ºC	Green shade		-	20.2ºC	22.9ºC	20.0	<6mm	
12 Infiltration basin (Fig.18 Dry day*)	draining concrete (light	10/01/2021	1.6 ºC	Green shade		-	23.3ºC	21.7ºC	19.0	-	
13Infiltration area Nbs (Fig. 18 Dry day*)	substrate- shade	10/01/2021	1.2ºC	Green shade.water retention and		-	21.3ºC	22.5ºC	10.0	<6mm	
14.Infiltration area Nbs (Fig. 19Dry day))	sand-sunny	10/01/2021	-	-		15.5ºC	23.8ºC	39.3ºC	20.0	<6mm	
15. Infiltration surface (Fig. 18 Dry day*)	draining concrete (light brown)-sunny	10/01/2021	-	-		9.7ºC	38.4ºC	28.7ºC	19.0	-	
16.Infiltration surface (Fig. 18 Dry day*)	substrate-sunny	10/01/2021	4.2ºC	and vegetation		-	23.5ºC	27.7ºC	10.0	<6mm	

Source: own elaboration (*data recorded during the research, not included in the manuscript statistics).
Note: This is a synthesis. The original table contains more data.

During periods without drought, building shade reduced Ts in non-vegetated areas up to 16.8ºC (Fig. 13b). This temperature gradient was similar to that achieved in La Fábrica del Sol blue roof's Ts reduction when there was 3 cm of water (14.6ºC, Figure 9.1, with no green above it). In addition, green shade records showed WSUD Ts below Te (Figures. 14a & 14b, Figures 17a & 17c, & Figure 19b) in early autumn).

In early autumn, green shade could reduce by up to 2.7ºC (Figure 19b & Table 5) the temperature of non-retentive materials (Cristobal de Moura infiltration area).

The more water is harvested, the greater the temperature gradient achieved (Figures. 9.1 & 9.2, & Figure 11 with the prototype). Evaporation of water produces a Ts decrease on the artificial stone surface. Recordings have demonstrated that plants are not required with this blue roof type to achieve a Ts below the Te (Pérez Cambra & Roca Cladera, 2018), as long as there is water present. Systems that do not retain water always reach Ts higher than Te during the hottest hours of the day in hot dry summers. Temperatures can reach over 60.0ºC (Figure 26), especially gravels. The most effective measure to mitigate this are building and green shades. They can decrease Ts even by up to 16.8ºC below Te (Figure 13b).

The most effective other parameters to improve Ts are shown in Figures. 22 to 26, with respect to granulometry. The Ts maximum gradient range is between 3.6 ºC and 13.1ºC with the same stones and different granulometries (Figure 21 & Figure 24). Granulometry must be taken into consideration along with hydraulic conductivity to build an effective WSUD construction system for thermal and hydraulic behavior (plus chemical behavior).

Thermal inertia is the parameter that has least influence on the Ts. As explained before, gravels are the materials with which thermal inertia has been compared. Comparing gravels with similar albedos and granulometries but different origin (red volcanic and black sedimentary stones), black sedimentary stone reaches a Ts maximum that is only 2.5ºC higher than the red volcanic one (62.5ºC and 60ºC) when volcanic stone thermal inertia is 45% of the sedimentary one (Figure 22, Figure 24, & Figure 27).

Finally, recordings of WSUD Ts explain thermal behavior. They show different strategies to decrease Ts. These strategies have also been implemented in other cited countries. This study includes data to implement them in a Csa climate.

Acknowledgements

We thank Cementos Molins, Crous Expert, Bruc Jardí and RNC Murcia for donating part of the material that enabled us to carry out the research.

Suthorship’s contribution

The first author: Writing – review and editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. The second and third author: review the text.

We are grateful to the X-ClimPlan project, *“Extreme spatial and urban planning tool for episodes of heat waves and flash floods. Building resilience for cities and regions”.* Ref. PID2019-105976RB-I00 (MINCIU – AEI).

Author statement: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

AENOR. (2014). Norma Española UNE-EN ISO 22282-5. Investigación y ensayos geotécnicos. Génova,6 28004 MADRID, España: AENOR.

Alhama, I., Jiménez-Valera, J.A., & Del Mar Pérez Cambra, M. (2024). Hydraulic and physical property characterizations of materials for the design of sustainable urban drainage systems. *Urban Climate, 53*, 101779. https://doi.org/10.1016/j.uclim.2023.101779

Andrés-Doménech, I., Anta, J., Perales-Momparler, S., & Rodriguez-Hernandez, J. (2021). Sustainable Urban Drainage Systems in Spain: A Diagnosis. *Sustainability, 13*(5), 2791. https://doi.org/10.3390/su13052791

Ankenbauer, K. J., & Loheide, S.P. (2017). The effects of soil organic matter on soil water retention and plant water use in a meadow of the Sierra Nevada, CA: Soil organic matter affects plant water use. *Hydrological Processes, 31*(4), 891–901. https://doi.org/10.1002/hyp.11070

Arellano Ramos, B., & Roca Cladera, J. (2021). Urban-CLIMPLAN: La Isla de Calor Urbana en la Región Metropolitana de Barcelona: estudio de la intensidad de la UHI diurna y nocturna a partir de diversos sensores. *ACE: Architecture, City and Environment, 15*(45), 10381. https://doi.org/10.5821/ace.15.45.10381

Arellano Ramos, B., Roca Cladera, J., Serra De Larrocha, C., Martínez Santafé, M. D., Biere Arenas, R. M., & Lana Pons, F. J. (2022). Olas de Calor en la ciudad de Barcelona: 1971-2020. *ACE: Architecture, City and Environment, 17*(50), 11684. https://doi.org/10.5821/ace.17.50.11684

ASCE, USEPA, et al. (2024). The International Stormwater BMP Database.

Balian, E., Eggermont, H. & Le Roux, X., Eggermont, H., & Le Roux, X. (2014). BiodivERsA Strategic Foresight workshop, Naturebased solutions in a BiodivERsA context. [online]. Retrieved from http://www.biodiversa.org/687/download

Barcelona Cicle de l’Aigua. (2023). El consum d’aigua a Barcelona. L’aprofitament i els usos dels recuros hídrics.

E-ISSN 1886-4805

Bellwald, U. (2007). The Hydraulic Infrastructure of Petra: A Model for Water Strategies in Arid Land. Department of Antiquities of Jordan Studies in the History and Archaeology of Jordan 09. https://publication.doa.gov.jo/Publications/ViewPublic/24

Berry, P.L., & Reid, D. (1993). Mecánica de suelos (McGraw-Hill).

Casas Castillo, M. del C., Rodríguez Solá, R., Lana Pons, F.J., Serra de Larrocha, C., Martínez Santafé, M.D., Biere Arenas, R.M., ... Roca Cladera, J. (2019). Consecuencias hidrológicas del cambio climático en entornos urbanos. XIII CTV 2019 Proceedings: XIII International Conference on Virtual City and Territory: "Challenges and paradigms of the contemporary city": UPC, Barcelona, October 2-4, 2019, 8291. CPSV / UPC. https://doi.org/10.5821/ctv.8291

Charlesworth, S.M., Harkerand, E., & Rickard, S. (2003). A Review of Sustainable Drainage Systems (SuDS): A Soft Option for Hard Drainage Questions? *Geography,* 88(2), 99–107. https://doi.org/10.1080/20436564.2003.12219866

City of Melbourne. (2014). Total Watermark—City as a Catchment (update 2014).

Cooper, N., & Cooke, S. (2015). Assessment and management of unexploded ordnance (UXO) risk in the marine environment. London, UK: CIRIA.

De Salort Giménez, C., Corral García, B., Astiz, C.L., Pons Machado, J., Rodríguez Florit, A., & Robledo Ardila, P. (2020). Water collection systems in the prehistory of Menorca: The Circle 6 cistern at Torre d'en Galmés. *Boletín Geológico y Minero, 131*(1), 147–164. https://doi.org/10.21701/bolgeomin.131.1.009

Dessi, V. (2008). Progettari il comfort urbano. Sistemi Editorialli.SE.

Dessì, V. (2017, September). PROGETTARE IL COMFORT DEGLI SPAZI PUBBLICI. *REBUS: REnovation of public Buildings and Urban Spaces,* (8), 1–32.

European Environment Agency. (2021, October). Water stress is a major and growing concern in Europe - EEA [News]. https://www.eea.europa.eu/highlights/water-stress-is-a-major

Ghenai, C., Rejeb, O., Sinclair, T., Almarzouqi, N., Alhanaee, N., & Rossi, F. (2023). Evaluation and thermal performance of cool pavement under desert weather conditions: Surface albedo enhancement and carbon emissions offset. *Case Studies in Construction Materials, 18,* e01940. https://doi.org/10.1016/j.cscm.2023.e01940

Gimenez-Maranges, M., Breuste, J., & Hof, A. (2020). Sustainable Drainage Systems for transitioning to sustainable urban flood management in the European Union: A review. *Journal of Cleaner Production, 255,* 120191. https://doi.org/10.1016/j.jclepro.2020.120191

Gómez Valentin, M. (2008). Curso de Hidrología Urbana (1st.Edition.). Barcelona: Distribuidora Alfambra de Papelería, S.L.

González de Vallejo, Luis I., L., Ferrer, Mercedes, Ortuño, Luis, & Oteo, Carlos. (2002). Ingeniería Geológica (Pearson, Prentince HAll).

Instituto de Ciencias de la Construcción Eduardo Torroja, ICCL, & Instituto de la Construcción Eduardo Torroja. (2007). CTE WEB. http://cte-web.iccl.es/materiales.php?a=14

Introduction to WSUD | Melbourne Water. (2017, September). https://www.melbournewater.com.au/building-and-works/stormwater-manage/intro-wsud

Iranian Government. (2009). Shushtar Hydraulic System (Iran) No1315. ICOMOS.

Izembart Helene, L.B.B. (2003). Waterscapes: El tratamiento de aguas residuales mediante sistemas vegetales (SIN COLECCION) —Tapa blanda. GG, S.L.

Kabisch et al. (2017). Nature -based Solutions to Climate Change Adaptation in Urban Areas. https://library.oapen.org/bitstream/handle/20.500.12657/27761/1002244.pdf?sequence=1#page=128

Kappou, S., Souliotis, M., Papaefthimiou, S., Panaras, G., Paravantis, J. A., Michalena, E., ... Mihalakakou, G. (2022). Cool Pavements: State of the Art and New Technologies. *Sustainability, 14*(9), 5159. https://doi.org/10.3390/su14095159

Lambert, J.H. (1760). Photometria. Bibliotheca Regia. Monacensis. Bayerische Staatsbibliothek Munchen.

E-ISSN 1886-4805

Masson-Delmotte, e, Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, & O. Yelekçi, R. Yu and B. Zhou (eds.)]. (2021). IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.

Melbourne City Council. (2009). Total watermark: City as a catchment.

Meteo IllesBalears. (2015, January). Clasificación de Köppen en territorio español. Caracterización y cambios recientes. Retrieved March 23, 2023, from http://www.meteoillesbalears.com/?p=272

Moyasevich Tristan, Nevenka. (2023). Influencina de pavimentos en el confort térmico urbano: Análisis de temperaturas radiantes en plazs de Barcelona durante el verano.

Ochoa de la Torre, J.M. (2011). Ciudad, vegetación e impacto climático El confort en los espacios urbanos. ETSAB, UPC, Barcelona.

Ochoa de la Torre, J.M. (1999). La vegetación como instrumento para el control microclimático (Universitat Politècnica de Catalunya). Barcelona. http://hdl.handle.net/2117/93436

Osaka City Public Bureau. (2024). Water-retentive pavement. Public works Bureau. Retrieved from Osaka City website: https://www.city.osaka.lg.jp/contents/wdu020/kensetsu/english/project/project3.html

Pérez Cambra, M. del M., Martínez Santafé, M.D., & Roca Cladera, J. (2022, November 22). Water Sensitive Urban Design Systems Thermal Behavior II: Thermal Analysis of WUD's Which Do Not Retain Water. 50–55. Santiago de Chile: Bustamante, W. et. al. https://upcommons.upc.edu/handle/2117/386921

Pérez Cambra M.M., & Roca Cladera, J. (2018). *WSUDs (Water Sensitive Urban Design Systems) Thermal Behavior.* Libro de Proceedings, CTV 2018: XII Congreso Internacional Ciudad y Territorio Virtual: "Ciudades y Territorios Inteligentes": UNCuyo, Mendoza, 5-7 septiembre 2018, 401–416. CPSV / UPC. https://doi.org/10.5821/ctv.825

Pérez Cambra, M.M., Roca, J., & Martínez Santafé, D. (2019). *Rainwater harvesting and reuse and rainwater runoff management in Barcelona thanks to the WSUD (Water Sensitive Urban Desing) construction systems: The Sant Martí Case.* CTV2019: XIII Congreso Internacional Ciudad y Territorio Virtual: Retos y Paradigmas de La Ciudad Contemporánea: Barcelona: 2-4 octubre 2019: Actas = CTV2019: XIII CTV, International Conference Virtual City and Territory: Challenges and Paradigms of the Contemporary City: Barcelona: October 2-4, 2019: Proceedings Book. Presented at the International Conference Virtual City and Territory - 13o Congreso Internacional Ciudad y Territorio Virtual, Barcelona, 2-4 octubre 2019 [107], Barcelona. Barcelona. https://doi.org/10.5821/ctv.8500

Permeabilidad del suelo (Fao). (2024, Update). https://www.fao.org/fishery/static/FAO_Training/FAO_Training/General/x6706s/x6706s09.htm

PIU | Portal de Información Urbanística | Ajuntament de Barcelona. (2024, Update). https://ajuntament.barcelona.cat/informaciourbanistica/cerca/es/

R20 Regions of Climate Action. (2012). A Practical Guide to Cool Roofs and Cool Pavements. https://www.coolrooftoolkit.org/wp-content/pdfs/CoolRoofToolkit_Full.pdf

Roca J., & Arellano, B. (2020, May). *Measuring night-time urban heat island*. Still a pending issue, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-19577, https://meetingorganizer.copernicus.org/EGU2020/EGU2020-19577.html

Rojas Cortorreal, G.M. (2016). Cuantificación de la mejora de las condiciones ambientales producida por el arbolado urbano: Caso de estudio Barcelona, España y Santo Domingo, República Dominicana (Universitat Politècnica de Catalunya. Departament de Tecnologia de l'Arquitectura). Universitat Politècnica de Catalunya. Departament de Tecnologia de l'Arquitectura, Barcelona. http://doi.org/10.5821/dissertation-2117-107044

Rojas-Cortorreal, G., Roset Calzada, J., Navés Viñas, F., López-Ordoñez, C., & Crespo Cabillo, I. (2016). El efecto del confort térmico producido por la especie arbórea almez en el espacio público. *ACE: Architecture, City and Environment, 11*(32), 187–202. https://doi.org/10.5821/ace.11.32.4839

E-ISSN 1886-4805

Rojas-Cotorreal, G., Roset, J., Navés, F., & López-Ordóñez,C. (2016, March). Evaluation of Vegetation in Urban Space: Barcelona Base Model and Proposed Model for Dominican Republic. A: International Sustainable Built Environment. 295–306. La Valetta,Malta: Ruben Paul Borg, Paul Gauci, Cyril Spirteri Staines.

SEPA Scottland Environment Protection Office. (2000). Sustainable Urban Drainage: An Introduction. SEPA.Scottland Environment Protection Agency.

Soriano Soto, María Desamparados. (2020). Efectos de la materia orgánica sobre el suelo. 5.

United Nations, DESA, Population Division. (2018). Popular Division. World Urbanization Prospects 2018. https://population.un.org/wup/Maps/

Urban Water. City of Melbourn. (n.d.). Urban Water. City of Melbourne [Water senstive urban desing]. https://urbanwater.melbourne.vic.gov.au/melbournes-water-story/water-sensitive-urban-design-wsud/

U.S. Environmental Protection Agency. (2012). Reducing urban heat islands: Compendium of strategies. Retrieved from https://www.epa.gov/heatislands/heat-island-compendium

U.S. Environmental Protection Agency. 2008. (2017). "Urban Heat Island Basics." In: Reducing Urban Heat Islands: Compendium of Strategies. US EPA. https://www.epa.gov/heat-islands/heat-island-compendium

Using Trees and Vegetation to Reduce Heat Islands. (2016, August). Using Trees and Vegetation to Reduce Heat Islands website: https://19january2017snapshot.epa.gov/heat-islands/using-trees-and-vegetation-reduce-heat-islands_.html

Valero Sancho, Agostín Loís. (1999). Capacidad de Retención de Agua Disponible (CRAD) para las plantas en suelos del Alto y Medio Aragón. EEAD.

Van Doan, C., & Kic, P. (2019). Effect of shading with trees to improve local temperature conditions. *Engineering for Rural Development, 7.* https://doi.org/10.22616/ERDev2019.18.N152

Veto, M. S., & Christensen, P. R. (2015). Mathematical Theory of Thermal Inertia Revisited 1: Improving Our Understanding of Martian Thermophysical Properties Through Analogous Examples of Periodic Diffusive Inertias. Presented at the 46th Lunar and Planetary Science Conference.

Victorian Stormwater Committee. (2006). Urban Stormwater: Best-Practice Environmental Management Guidelines. CSIRO Publishing. https://doi.org/10.1071/9780643100596

Vitruvio Polión, M. (1787). Los diez libros de archítectura. En Madrid de la Imprenta Real.

What are Nature-based solutions (NBS)? Setting core ideas for concept clarification | Elsevier Enhanced Reader. (n.d.). https://doi.org/10.1016/j.nbsj.2022.100009

What is a Sustainable Built Environment? (n.d.). Retrieved April 26, 2023, from World Green Building Council website: https://worldgbc.org/what-is-a-sustainable-built-environment/

WHO: Water,Sanitation, Hygiene and Health Unit. (2020, February). Rainwater collection and storage. Retrieved from https://cdn.who.int/media/docs/default-source/wash-documents/sanitary-inspection-packages/2-tfs-rainwater-collection-storage-d.pdf?sfvrsn=8dfb1bf8_6

Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., & Shaffer, P. (2007). The SUDS manual (C697). London, UK.

World Maps of Köppen-Geiger climate classification. (2013). https://koeppen-geiger.vu-wien.ac.at/applications.htm

Yamagata, et. a. (2008, April). Heat island mitigation using water retentive pavement sprinkled with reclaimed wastewater. 57, 763–771.