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Pavement-Watering for Cooling the Built Environment: A Review

Martin HENDEL[1]

[1]Univ Paris Diderot, Sorbonne Paris Cité, LIED, UMR 8236, CNRS, F-75013, Paris, France

Abstract

Pavement-watering is being considered by decision-makers as a means of cooling the built environment and adapting cities to the extreme heat they face as a result of climate change.

Keywords: pavement-watering, climate change adaptation, built environment, urban climate, urban heat island.

Nomenclature

a.g.l.	above ground level
E	evaporation rate [g/s]
exp.	experimental
$G(z)$	downwards conductive heat flux at depth z [W/m²]
H	upwards sensible convective flux [W/m²]
HIP	Heat Island Potential [°C]
IR	infrared
l	vaporization latent heat of water: 2,260 J/kg
LW	longwave
MRT/T_{mrt}	Mean Radiant Temperature [°C]
NA	Not Available
NR	Not Relevant
num.	numerical
Φ	pavement-watering cooling flux (total) [W/m²]
Φ_a	advective flux [W/m²]
PT	Perceived Temperature [°C]
RH	Relative Humidity [-]
SW	shortwave
T_a	dry-bulb temperature [°C]
$T_{wet\text{-}bulb}$	wet-bulb temperature [°C]
T_g	globe temperature [°C]
T_z	pavement temperature at depth z
TEB	Town Energy Balance
UHI	Urban Heat Island
UHII	Urban Heat Island Intensity [°C]
UTCI	Universal Thermal Climate Index [°C]
v	windspeed [m/s]
V	downwards conductive heat flux at pavement surface [W/m²]
WBGT	Wet-Bulb Globe Temperature [°C]
$z_{a/p}$	height/depth [m]

Introduction

Pavement-watering has been practiced for centuries in Japan where it is known locally as "Uchimizu" (Japan Water Forum 2015). It consists of watering ground surfaces around one's home or shop with the goal of placating dust particles on the ground and relieving pedestrians from the summer heat. Similar practices can be observed across the globe in areas with hot summers, even when water is not readily available.

Today, cities across the globe have begun considering the method as a means of improving their built environment by reducing extreme urban heat, countering the urban heat island (UHI) effect and helping cities adapt to intensified heat-waves caused by climate change (Maillard et al. 2014; Paris City Council 2012). Indeed, extreme weather events are expected to increase in both frequency and intensity in the coming decades, including heat-waves (IPCC 2013). Given that such events are associated with strong UHIs (Li and Bou-Zeid 2013; Météo France and CSTB 2012) and very high health impacts in urban areas (Pascal et al. 2006; Robine et al. 2008), the stakes behind urban cooling are high.

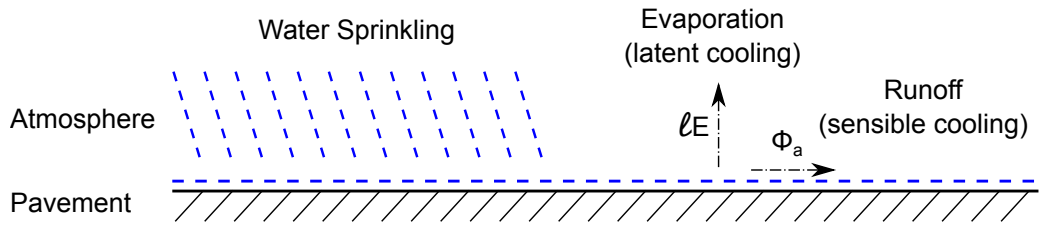


Figure 1: Cooling Mechanisms of Pavement-Watering: Evaporation and Advection

As illustrated in Figure 1, the sprinkled pavement is cooled by latent and sensible heat transfers through evaporation (ℓE) and – in the case where the water film runs off to the sewer system – advection (Φ_a). Cumulative cooling from these two contributions will hereafter be noted Φ. These fluxes cool the watered surfaces, which in turn contribute less to atmospheric warming, thus helping create a cooler environment for pedestrians. Several studies have taken an interest in the thermal and micro-climatic effects of pavement-watering in recent years. To obtain these cooling effects, pavement-watering obviously relies on the use of water. With many regions facing the risk of increased water scarcity due to climate change (IPCC 2013), accurate knowledge of the water intensity of pavement-watering is crucial for decision-makers in addition to its cooling effects.

This paper offers to review the existing literature on the topic of pavement-watering, with a focus on its reported cooling effects, implemented watering strategies, water consumption and proposed attempts to optimize them. The review aims to detect shared trends among articles as well as provide recommendations for future work.

We begin by describing our review methodology and briefly discussing the resulting literature selection. We will then present the methodology of the articles, including details on their watering strategy and analysis method. We then take a look at the cooling effects reported. Finally, we conclude these analyses with recommendations for future studies of pavement-watering.

A variety of tables will be used to summarize our analyses, dutifully noting when information is either not available (NA) or not relevant (NR).

Review Methodology

Articles published in English or French journals up to the 1st of July 2016 were selected for this review. These articles must present findings from experimental or numerical studies of pavement-watering, i.e. the intentional watering of ground surfaces with the aims of cooling urban areas. Studies of building surface watering are not included unless pavement-watering is part of the watering scheme.

With these criteria, 13 studies were found, published between 1997 and 2015, reporting results from studies conducted between 1993 and 2014.

Some of the reviewed articles merit comment. Namely, two articles are published in the French professional journal *Techniques, Sciences et Méthodes* (TSM) (Bouvier, Brunner, and Aimé 2013; Maillard et al. 2014). Although its peer-review process is not as rigorous as most of the scientific journals cited here, these articles provide recent examples of pavement-watering field trials.

In addition, a conference paper is included (Kinouchi and Kanda 1998) as well as a freely-available report by Météo-France and CSTB (Météo France and CSTB 2012). Neither of these was published in a scientific journal.

Finally, a PhD manuscript is also referenced (Hendel 2015). It focuses on a single field study whose major findings have been published in peer-reviewed journals (Hendel and Royon 2015; Hendel et al. 2014, 2015a, 2015b, 2016). Rather than cite the individual articles by presented results, only the manuscript will be referenced hereafter.

At this point in the review, it is already clear that the number of papers addressing pavement-watering is currently quite limited. The method therefore merits much more attention from the scientific community if the needs of decision-makers in urban areas are to be addressed.

Part 1: Study Methodologies

We begin by reviewing the methodological choices made in the reviewed articles.

Study approach and scale

Three major groups can be identified according to the adopted approach: A) numerical studies, B) experimental studies and C) studies combining approaches A and B. In addition, four different study scales were found: laboratory, street, district and city. Table 1 classifies the articles by scale and approach.

Table 1: Number of articles investigating pavement-watering effects at laboratory-, street-, district- or city-scale, by type.

Scale	Numerical (A)	Experimental (B)	Combined (C)
Lab	0	2 (Kinouchi and Kanda 1998; Li, Kayhanian, and Harvey 2013)	0
Street	0	5 (Bouvier et al. 2013; Hendel 2015; Kinouchi and Kanda 1997; Maillard et al. 2014; Yamagata et al. 2008)	1 (Kubo et al. 2006)
District	1 (Wei and He 2013)	1 (Takahashi et al. 2010)	0
City	2 (Météo France and CSTB 2012; Nakayama, Hashimoto, and Hamano 2012)	0	1 (Nakayama and Fujita 2010)
Total	3	8	2

At first glance, it appears that numerical and experimental studies focus on complementary scales. Indeed, numerical studies (type A) focus on the district- or city-scale, while experimental studies (type B) focus on lab- or street-scales except for Takahashi et al. (2010) who conduct an experimental study of district-scale effects. Both type C studies use lab-scale experimental data to calibrate street- or city-scale simulations of pavement-watering.

The correspondence between scale and approach seems to stem naturally from practical considerations. Indeed, it is significantly cheaper and simpler to conduct experimental studies at limited spatial scales (lab- or street-scale) than larger ones (district- or city-scale). Given this limitation, numerical studies offer much more added value at larger scales, where experimental data is harder to obtain. Nevertheless, numerical studies could be used to model the thermal transfers taking place within the materials being watered, though no such studies were found.

For experimental studies, the lab-scale is too small for meteorological effects to be observed. Similarly, the cumulative effects expected from large-scale watering cannot be observed at the street-scale. City-scale experimental watering is costly and difficult to orchestrate, but district-scale studies, similar in design to Takahashi et al. (2010) for example, may offer a reasonable compromise.

It therefore seems that future experimental studies should attempt to explore district-scale effects to better appreciate the cumulative effects of pavement-watering, while numerical models could be used to study lab-scale effects. Similarly, Kubo et al. (2006) and Nakayama and Fujita (2010)'s approach of using small scale observations as an input for higher scale simulations is also promising.

Watering Method

Pavement-watering implies the choice of a watering method. Before reviewing the different watering methods, we first define the parameters that fully them. Table 2 summarizes these parameters.

The first step involves the choice of a target area. In any given street, three different watering combinations are available: sidewalk only, pavement only and both sidewalk and pavement. The terms "sidewalk" and "pavement" are used here in their American English sense, i.e. "footpath" and "carriageway" in British English, respectively.

Once the watering area has been defined, every watering method can be characterized by three parameters: the watering period, the watering rate and the watering frequency. The first outlines the period(s) of each day during which pavement-watering is conducted in order to keep the pavement wet. The second is the average amount of water delivered per unit area and per unit time (expressed in mm/h, equivalent to L/m².h), averaged over the watering period. Finally, the last indicates the frequency of the watering cycles in the case of discontinuous watering.

Table 2: Pavement-Watering Parameters

Parameter	Description	Unit
Target area	Area where watering is conducted (sidewalk only, pavement only or both)	-
Period	Time interval during which watering is conducted.	-
Rate	Amount of water delivered per units area and time during the watering period	[L/m².h] or [mm/h]
Frequency	Frequency at which watering is conducted (only for discontinuous watering)	[Hz]

Once the watering rate and period are known, the method's total water consumption is fully determined when combined with the surface of the target area. We therefore recommend that these three parameters be reported in all pavement-watering studies.

Target Area and Watering Parameters

The different watering methods used in our literature selection are summarized graphically in Figure 2 according to the information provided by the authors in their articles. As can be seen, varying levels of detail are provided, with certain articles providing nearly no information and others providing very detailed descriptions of their watering method. Table 3 classifies studies conducted at the street-scale or higher according to the area targeted for pavement-watering.

Table 3: Pavement-Watering Target Area (for street-scale or higher only)

Target Area	Number of papers
Pavement only	7 (Kinouchi and Kanda 1997, 1998; Maillard et al. 2014; Nakayama and Fujita 2010; Nakayama et al. 2012; Takahashi et al. 2010; Yamagata et al. 2008)
Sidewalk only	1 (Wei and He 2013)
Pavement and sidewalk	3 (Bouvier et al. 2013; Hendel 2015; Météo France and CSTB 2012)

As can be seen, most articles consider pavement-only watering or pavement-and-sidewalk watering, with only one study of sidewalk-only watering. Given that the meteorological effects of pavement-watering can be expected to be commensurate to the area that is watered, watering both pavement and sidewalk should give the best results. In the case where the pavement is significantly wider than the sidewalk, pavement-only watering should also yield high results. Sidewalk surfaces, which are often smaller than pavement surfaces in wide streets, should provide the smallest cooling.

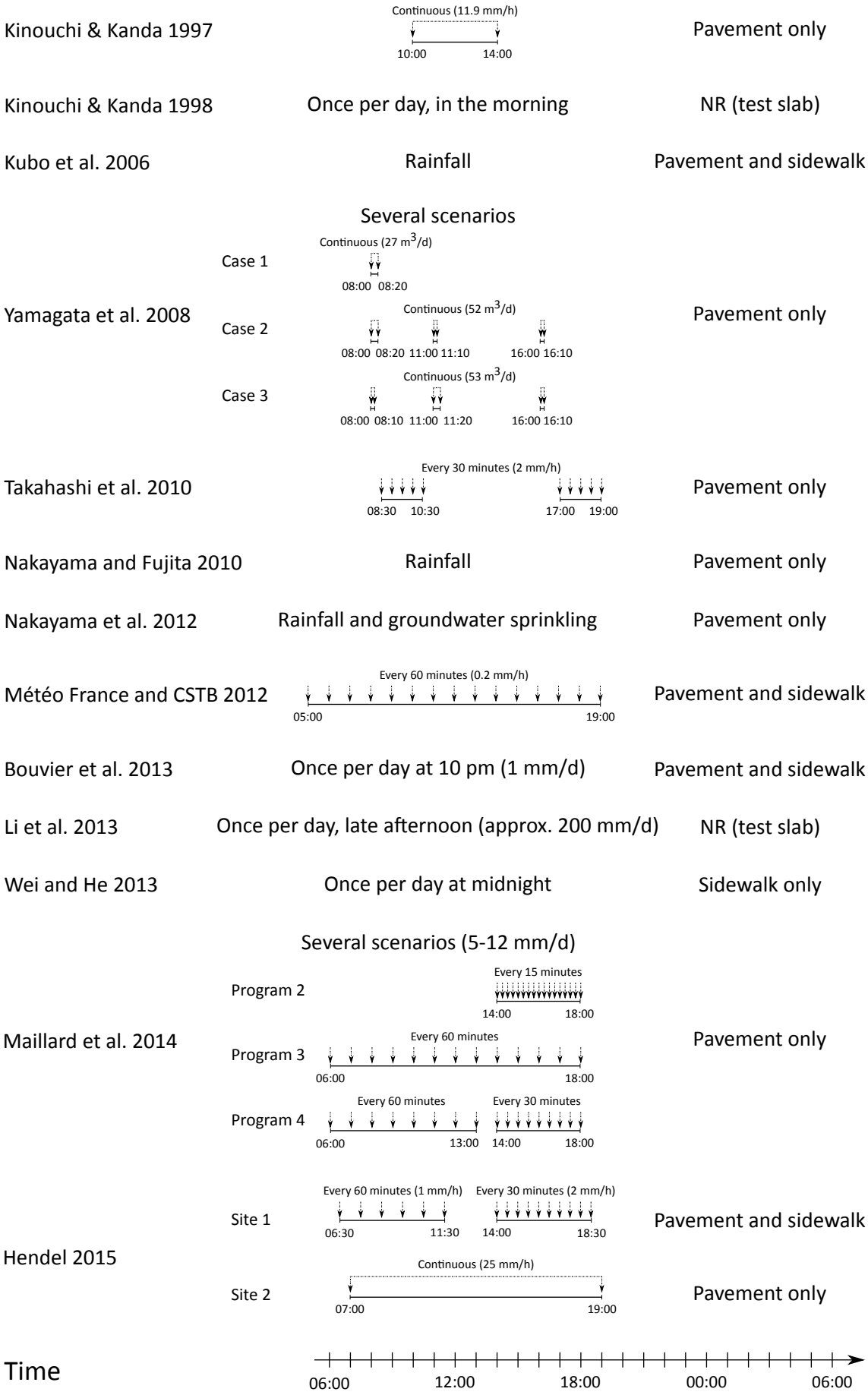


Figure 2: Diagram of watering methods used in the surveyed articles.

However, pedestrians are nearly exclusively present on the sidewalk and watering only the sidewalk may significantly reduce total water consumption. In addition, pavement-only watering does not expose pedestrians to reduced surface temperatures as much as sidewalk-only watering. Therefore, watering the sidewalk may still be preferable to watering the pavement if the obtained reduction in pedestrian radiant load is sufficient to compensate the reduced atmospheric cooling while providing significant water savings.

Further work should therefore be conducted on sidewalk-only watering to determine how effective it may be at improving pedestrian comfort. If found to be sufficiently effective, sidewalk-only watering could yield substantial water savings, especially if sidewalks are much smaller than pavement surfaces. This approach may be of particular interest in East-West oriented streets where the North side (South side for the Southern Hemisphere) receives much more solar energy than the other.

Watering Optimization

Among the reviewed papers, only Takahashi et al. (2010), Météo France & CSTB (2012) and Hendel (2015) describe attempts to optimize the watering method. Furthermore, only Hendel (2015) conducts a formal optimization process.

Takahashi et al. (2010) optimize both watering rate and frequency based on surface and 90 cm air temperature observations over a period of one hour after watering. On this basis, it was found that each watering cycle should deliver 1 mm. Their analysis then led them to conclude that watering during the day, between 11 am and 3 pm, was ineffective as no temperature difference could be detected. Finally, the watering frequency was designed to water the pavement as soon as it became completely dry. This resulted in watering roughly every 30 minutes.

Météo France & CSTB (2012) base their own optimization on findings from Takahashi et al. (2010) with the hypothesis of a pavement water-holding capacity of 1 mm. They optimize the watering rate based on 2 m a.g.l. air temperature simulations with a one-hour time step. Watering rates are deemed optimal if increasing them further only marginally increases cooling. It should be noted that these analyses are only briefly described in both papers and make no mention of explicit optimization targets or goals.

Hendel (2015) on the other hand explicitly defines the goals of the watering optimization process, i.e. 1. the maximization of cooling effects, 2. minimization of the watering frequency, 3. minimization of the watering rate, and 4. minimization of the watering period. With these goals, the watering method is optimized on the basis of heat flux measurements conducted 5 cm below the pavement surface (Hendel et al. 2015a) and of surface temperature measurements (Hendel et al. 2014). Subsurface pavement temperatures, measured 5 cm deep, were found to be unsuited to this task due to signal smoothing by the surface course material (Hendel and Royon 2015). As a result of this process, Hendel (2015) finds that watering should be conducted every 30 minutes during pavement insolation at a rate of 0.31-0.40 mm/h (i.e. 0.16-0.20 mm/cycle).

Given the current concerns for future water resource availability in many regions, we recommend that future studies of pavement-watering systematically include attempts to formally optimize the method's water consumption.

Analysis Method

We now describe the different methods used to determine the effects of pavement-watering in the selected literature.

Approach A: numerical studies

All of the numerical studies reviewed here determine the cooling effects of pavement-watering by comparing a single area in two states: with and without watering, all else being equal. As a result, the observed differences can be unquestionably attributed to pavement-watering. Assuming that the model has been properly calibrated for the study site, the method can be deemed robust and reliable.

Approach B: experimental studies

Laboratory-scale studies directly compare the same pavement area in dry and wet conditions. While varying solar irradiance from one day to the next is taken into account, none of these studies compare a control slab with a watered one simultaneously.

In all of the considered field trials conducted at the street-scale, simultaneous case and control measurements are compared. All but one study (Hendel 2015) determine the micro-climatic effects of pavement-watering by comparing these measurements directly. Indeed, Kinouchi & Kanda (1997), Yamagata et al. (2008), Bouvier et al. (2013) and Maillard et al. (2014) base their analyses on the differences observed between a watered station and an unwatered one. Takahashi et al. (2010), though they use average observations from several watered and unwatered weather stations, proceed in the same manner. In all of these cases, the observed difference between watered and control sites is interpreted as the effect of pavement-watering.

While Hendel (2015) uses the same method as that of the laboratory-scale studies for the analysis of thermal effects, a statistical analysis method is developed to determine the micro-climatic effects. Rather than directly studying the interstation difference obtained on days with watering to evaluate the micro-climatic effects of pavement-watering, the approach statistically compares the difference between the interstation difference on watered and on reference days. This method takes preexisting differences between sites into account and therefore factors them out when the effects of pavement-watering are quantified.

This approach can be compared to the Lowry approach designed as a guide when investigating the differences between urban and rural climates (Lowry 1977). Indeed, there is no theoretical basis for case and control site (microclimatic) differences to be attributable solely to the effect of pavement-watering, since preexisting differences between sites are not removed from the measurements. Given this severe methodological flaw, micro-climatic findings reported in type B studies that do not take preexisting differences between case and control sites into account should not be considered reliable, even though they are comparable to the micro-climatic effects reported by Hendel (2015) (see next Section).

Approach C: combined studies

In both type C articles, lab-scale experimental findings are used to calibrate their higher-scale simulations.

Kubo et al. (2006) use lab-scale experimental findings of surface temperature reductions as an input for their street-scale simulation of pavement-watering. Indeed, their model does not include heat and mass transfer from water evaporation, but only simulates a forced 10°C reduction in pavement and sidewalk surface temperatures. This results in an indirect simulation of the effects of pavement-watering on air temperature, but is unsuited to simulate the changes in air humidity. It can therefore not be used to study its impact on thermal comfort.

For their part, Nakayama and Fujita (2010) rely on their lab-scale study of the water mass transfer in permeable materials to calibrate their numerical model, which solves the water budget for the study area.

As with other numerical studies, these two articles determine the effects of watering by comparing a given study site with and without watering.

Part 2: Reported Cooling Effects

We now proceed to present the cooling effects reported in the selected literature. These are measured using a variety of indicators, which will be grouped into two categories: micro-climatic and thermal. The former describe the impact of pavement-watering on climatic variables relevant to pedestrians' thermal state, i.e. air temperature, humidity, wind speed and radiant load. The latter describe the effect of pavement-watering on the watered materials. These effects are behind the mechanisms responsible for the observed micro-climatic impacts of pavement-watering.

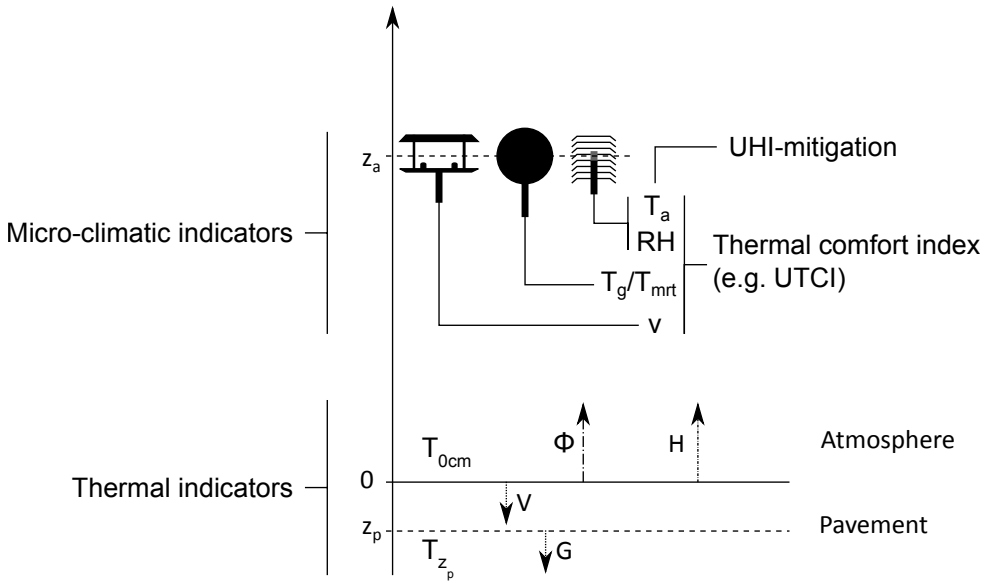


Figure 3: Illustration of the cooling indicators found.

Micro-Climatic Effects

The micro-climatic effects are quantified in the selected articles by changes in air temperature, relative humidity, globe temperature and mean radiant temperature (MRT). In addition, thermal comfort and UHI-mitigation are also evaluated. Air temperature is the used most often, while globe temperature and MRT are least represented, though they may be tacitly included in the calculation of thermal comfort indexes.

Meteorological parameters

As can be seen, reported maximum air temperature effects span a wide range from -0.4°C to -5°C, but good agreement is found for relative humidity (increase of a few percentage points) and the radiative environment. Unfortunately, measurement heights are rarely the same, making it difficult to compare findings.

Among these papers, only Bouvier et al. (2013) and Hendel (2015) indicate how long cooling lasts after watering (up to several hours) or describe average effects in addition to maximum effects. Only Kinouchi & Kanda (1997) and Hendel (2015) describe the instruments used and their properties, although the globe thermometer is not described by Kinouchi & Kanda (1997). When information is available (pictures, descriptions, …), air temperature and humidity measurements are sheltered.

Such shortfalls have been reported in other literature reviews in the field of urban climatology and are clearly valid for studies of pavement-watering (Johansson et al. 2014; Stewart 2011).

Air Temperature

Air temperature is frequently used in the articles we have selected. Table 4 provides a summary of the air temperature effects reported as well as the instrument type and measurement height used, when indicated.

Air Humidity

Air humidity is not as widely represented in the literature as air temperature. It is considered by Kinouchi & Kanda (1997), Bouvier et al. (2013), Hendel (2015) and Météo France & CSTB (2012) who investigate changes in RH. Their findings are presented in Table 5.

Radiative Environment

Apart from air temperature and humidity, indicators representative of the radiative environment have also been used to quantify the effects of pavement-watering, such as MRT and globe temperature. Only three studies include these parameters (Hendel et al. 2016; Kinouchi and Kanda 1997; Wei and He 2013). Their results are presented in Table 6.

Unlike the cases of air temperature and humidity measurements, Kinouchi & Kanda (1997) do not specify what kind of globe thermometer is used, unlike Hendel (2015).

Table 4: Reported air temperature effects.

Author	Instrument	Height	Max
(Kinouchi and Kanda 1997)	Pt Resistance	1 m	-1°C
(Yamagata et al. 2008)	NA	0.5 m	-2.5°C
(Takahashi et al. 2010)	NA	0.9 m	-4°C
(Bouvier et al. 2013)	NA	2 m	-0.4°C
(Hendel et al. 2016)	Pt-100 Resistance	1.5 m	-0.8°C
		4 m	-0.7°C
(Kubo et al. 2006)	numeric	0.5 m	-2.13°C
		1.5 m	-0.73°C
(Nakayama et al. 2012)	numeric	1.5 m	-5°C
(Météo France and CSTB 2012)	numeric	2 m	-2°C

Table 5: Reported air humidity effects.

Author	Instrument	Height	Max
(Kinouchi and Kanda 1997)	Capacitive hygrometer	1 m	+4%
(Bouvier et al. 2013)	NA	2 m	+4%
(Hendel et al. 2016)	Capacitive hygrometer	1.5 m	+4.6%
		4 m	+3.4%
(Météo France and CSTB 2012)	numeric	2 m	A few %

Table 6: Reported effects on the radiative environment.

Author	Parameter	Height	Max
(Kinouchi and Kanda 1997)	Globe temperature	1 m	-4°C
(Wei and He 2013)	MRT	1.5 m	-6°C
(Hendel et al. 2016)	MRT	1.5 m	-3.7°C

Other Micro-Climatic Indicators

On the basis of the previous meteorological measurements, authors evaluate the effect of watering on UHI-mitigation and on pedestrian thermal comfort. Since the indicators used are rarely the same, it is difficult to compare findings. Also, only few studies of pavement-watering estimate thermal comfort with indexes taking all meteorological parameters into account such as UTCI.

Indicators of UHI-Mitigation Effects

UHI-mitigation is investigated by Météo France & CSTB (2012), Wei & He (2013) and Hendel (2015). Météo France & CSTB (2012) define their UHI-mitigation index as the difference in the average air temperature measured 2 m and 30 m a.g.l. between 3 and 6 am (local daylight savings time: CEST, i.e. UTC+2). Hendel (2015) also uses this indicator.

Wei & He (2013) use an indicator called Heat Island Potential (HIP), which reflects the average temperature difference between urban surfaces and the atmosphere. As defined, a positive HIP indicates that urban surface temperatures are warmer on average than the ambient air temperature. Wei & He (2013) compare HIP with and without watering. Reported results are presented in Table 7.

Table 7: Reported UHI-mitigation effects.

Author	Parameter	Height	Max
(Météo France and CSTB 2012)	UHI-mitigation	2 m	-0.5°C
		30 m	NA
(Hendel et al. 2016)	UHI-mitigation	1.5 m	-0.14°C
		4 m	-0.22°C
(Wei and He 2013)	HIP	NR	-25°C

Results obtained by Météo France & CSTB (2012) and Hendel (2015) are similar if the difference in watering scale is taken into account (city- vs. street-scale). Unfortunately their findings cannot be compared with Wei & He (2013) given how different their UHI-mitigation indicators are.

Thermal Comfort Indicators

Several different thermal comfort indexes are used in the selected articles, including Wet Bulb Globe Temperature (WBGT) and the Universal Thermal Climate Index (UTCI). Kinouchi & Kanda (1997, 1998) use three different comfort indexes: the Discomfort Index, Thermal Load and Thermal Sensation. Few details are given on these indexes and their supporting papers are in Japanese, preventing us from obtaining further details. The reported thermal comfort effects of pavement-watering are summarized in Table 8.

Table 8: Reported thermal comfort effects.

Author	Parameter	Height	Max
(Kinouchi and Kanda 1997)	Discomfort Index	1 m	-
(Kinouchi and Kanda 1997)	Thermal Load	NR	-10 W/m²
(Kinouchi and Kanda 1998)	Thermal Sensation	NR	-3°C
(Yamagata et al. 2008)	WBGT	0.5 m	-2°C
(Maillard et al. 2014)	WBGT	1.5 m	-0.5°C
(Hendel et al. 2016)	UTCI	1.5 m	-1.5°C

Thermal Effects

The thermal effects of pavement-watering have been a recurrent focus point of the reviewed studies. These include pavement temperatures and heat flows. The latter include surface latent, convective and conductive flows, as well as conductive transfers at different depths.

Better agreement is found between studies for thermal effects than for micro-climatic ones.

Surface Temperature

Surface temperature is very often considered. If the differences in watering method are taken into account as well as site metadata, the reviewed articles are found to agree on an approximate 10°C surface temperature reduction during direct insolation. Nighttime reductions are reported by a few authors and range from -3°C to -6°C (Bouvier et al. 2013; Hendel 2015; Wei and He 2013; Yamagata et al. 2008). Table 9 summarizes the reported findings.

Table 9: Reported pavement surface temperature effects.

Author	Instrument	Height	Max
(Kinouchi and Kanda 1997)	IR thermometer	1 m	-10° to -30°C
(Kinouchi and Kanda 1998)	Net radiometer	65 cm	-14° to -18°C
(Kubo et al. 2006)	Thermocouple	0 cm	-16.4°C
(Yamagata et al. 2008)	IR camera	NA	-3° to -8°C
(Nakayama and Fujita 2010)	NA	0 cm	-5° to -20°C
(Bouvier et al. 2013)	IR camera	NA	-6° C
(Maillard et al. 2014)	NA	-1 cm	-5°C
(Hendel et al. 2014)	IR camera	20 m	-4° to -13°C
(Wei and He 2013)	numeric	NR	-5°C

Pavement Temperature

No papers focusing solely on the watering of impervious street surfaces were found that report pavement temperature observations, except for Hendel (2015). Among those studying pervious materials, Kinouchi & Kanda (1998) report temperature effects 5 cm below the pavement surface and H. Li et al. (2013) investigate effects 1.3 cm, 3.8 cm, 6.4 cm and 25.4 cm deep for two different permeable pavements compared to a standard impervious pavement. Table 10 summarizes these findings.

Table 10: Reported pavement temperature effects.

Author	Instrument	Depth	Max
(Kinouchi and Kanda 1998)	Thermocouple	5 cm	-7°C
(Li, Harvey, et al. 2013)	T-Type Thermocouple	1.3 cm	-7°C
		3.8 cm	-12°C
		6.4 cm	-14°C
		25.4 cm	-15°C
(Hendel and Royon 2015)	T-Type Thermocouple	5 cm	-8°C

Maximum effects described by Hendel (2015) and Kinouchi & Kanda (1998) are quite comparable. However, those reported by Li, Harvey, et al. (2013) are significantly higher at 6.4 cm and increase with greater depths. This may be caused by differences in measurement frequency or in initial water temperature, especially considering the amount of water delivered at once in this study (see Figure 2).

Latent Heat Flux

Five studies estimate or measure the latent heat flux created by pavement-watering (Hendel 2015; Kinouchi and Kanda 1997; Météo France and CSTB 2012; Nakayama et al. 2012; Yamagata et al. 2008). Their findings are summarized in Table 11. It should be noted that the latent flux is estimated both experimentally and numerically by Nakayama et al. (2012). The method used for the former estimation is not provided.

Kinouchi & Kanda (1997) use two methods to determine the latent flux on the basis of their measurements: from the energy balance and from the gradient method. The former uses measurements of the heat flow into the pavement at its surface. As they encountered difficulties with this measurement, their second estimation is deemed more reliable and agrees better with other authors. Indeed, the average latent heat flux determined by the gradient method is in the order of 200-300 W/m², with a localized peak of 400 W/m².

Table 11: Reported latent heat flows.

Author	Instrument	Max
(Kinouchi and Kanda 1997)	Energy balance	1,300 W/m²
	Gradient method	400 W/m²
(Kinouchi and Kanda 1998)	estimated	600 W/m²
(Yamagata et al. 2008)	Evaporation gauge	365 W/m²*
(Hendel et al. 2015a)	Energy balance	229 W/m²
(Nakayama et al. 2012)	NA	337 W/m²
	numeric	345 W/m²
(Météo France and CSTB 2012)	numeric	180 W/m²

*Average daytime value calculated from reported daily latent energy transfer.

Kinouchi & Kanda (1997), Yamagata et al. (2008), Nakayama et al. (2012), Météo France & CSTB (2012) and Hendel (2015) report similar results in the order of 300 W/m².

Pavement Heat Flux

Kinouchi & Kanda (1997, 1998) and Hendel (2015) are alone in reporting the pavement heat flux effects of pavement-watering. Kinouchi & Kanda (1997) attempt to measure the downwards heat flux at the surface with a heatflowmeter but encounter difficulties, while Kinouchi & Kanda (1998) and Hendel (2015) place their sensor 5 cm below the pavement surface, pervious for Kinouchi & Kanda (1998) and impervious for Hendel (2015). Their findings are summarized in Table 12.

Table 12: Reported pavement heat flux effects.

Author	Instrument	Depth	Max
(Kinouchi and Kanda 1997)	Heatflowmeter	0 cm	-1,300 W/m²
(Kinouchi and Kanda 1998)	Heatflowmeter	5 cm	-50 W/m²
(Hendel et al. 2015a)	Heatflowmeter	5 cm	-150 W/m²

Judging by their graph, Kinouchi & Kanda (1998) observe a reduction of the downwards heat flux 5 cm below the surface in the order of 50 W/m². For their part, Hendel (2015) report average reductions in the order of 100-150 W/m² during pavement insolation. Differences between these two studies are likely due to the difference in the thermal properties of the studied paving materials.

In addition, Kinouchi & Kanda (1998) analyze a linear relation found between pavement heat flux 5 cm deep and net radiation. Hendel (2015) conducts a similar analysis using solar irradiance rather than net radiation.

Conclusion

13 studies published from 1997 to 2015 were found studying the effects of pavement-watering. Table 13 summarizes their type (A, B or C), scale and the micro-climatic and thermal indicators they consider.

As can be seen, a wide variety of cooling indicators, representative of both micro-climatic and thermal effects, are used. In addition, several different watering methods are used, though they are described in varying detail. Unfortunately, only few efforts to optimize them and their water consumption were reported. Among the reviewed authors, only Bouvier et al. (2013), Maillard et al. (2014) and Hendel (2015) present pavement-watering as a tool for heat-wave adaptation for urban areas.

Overall, agreement found among authors allows us to identify clear trends only for surface temperature reductions and latent flow and RH increases. Indeed, the other reported effects are either not comparable, for example as a result of using different indexes, or too few studies have quantified them.

Table 13: Literature review summary.

Type	Author	Scale	Micro-climatic Indicators					Thermal Indicators			
			T_a	RH	MRT/T_g	UHI	Thermal Comfort	T_{surf}	$T_{pavement}$	*Æ*	*V*
A	(Nakayama et al. 2012)	City	X							X	
A	(Météo France and CSTB 2012)	City	X	X		X				X	
A	(Wei and He 2013)	District			X	X		X			
B	(Kinouchi and Kanda 1997)	Street	X	X	X		X		X	X	X
B	(Kinouchi and Kanda 1998)	Laboratory						X	X	X	X
B	(Yamagata et al. 2008)	Street	X				X	X		X	
B	(Takahashi et al. 2010)	District	X								
B	(Li, Harvey, et al. 2013)	Laboratory							X		
B	(Bouvier et al. 2013)	Street	X					X			
B	(Maillard et al. 2014)	Street						X			
B	(Hendel et al. 2014)	Street						X			
B	(Hendel et al. 2015a)	Street								X	X
B	(Hendel and Royon 2015)	Street							X		
B	(Hendel et al. 2016)	Street	X	X	X	X	X				
C	(Kubo et al. 2006)	Street	X								
C	(Nakayama and Fujita 2010)	Laboratory						X			

In addition, too few experimental studies provide sufficient metadata with regards to the instruments used, their properties, measurement heights, etc. This issue has been previously raised by Stewart (2011) for studies of the UHI effect and Johansson et al. (2014) for outdoor thermal comfort studies, but their recommendations appear valid for studies of pavement-watering as well.

Most preoccupying however is the dubious reliability of the analysis method used by most authors to determine micro-climatic effects in the field. Indeed, the analyses are based on the direct comparison of measurements from case and control areas. This approach tacitly assumes that inter-area differences are equal to zero in the absence of watering. Given the complexity of urban environments, this hypothesis is likely invalid. Hendel et al. (2016) identified that this hypothesis was not valid for their test sites nor other ones *a priori* and proposed an alternative statistical approach that accounts for pre-existing differences between sites and is applicable to other UHI-countermeasures as well.

This assumption calls into question the validity of many of the micro-climatic effects reported here, especially for air temperature, MRT and thermal comfort. It is essential that future work conducted in the field interested in the micro-climatic effects of pavement-watering and other urban cooling techniques take this into account, for example with Hendel et al. (2016)'s approach, when analyzing micro-climatic field measurements.

In addition, due in part to the small number of studies found, pavement-watering has only been studied at the street scale or higher for cities in France and Japan. The number of locations is therefore also quite limited and are representative of only two different climate types: Cfa (humid temperate with hot summers) and Cfb (maritime temperate climate). The same can be said of the Local Climate Zone (LCZ) classes where pavement-watering has been studied. Table 14 summarizes this information. The geographic distribution of the reviewed studies, placed against Peel et al.'s Köppen-Geiger climate type map of the World (2007), is illustrated in Figure 4.

Table 14: Number of papers by location, site LCZ class and Köppen-Geiger climate type configuration for studies conducted at street scale or higher.

Location	Number of studies	LCZ classifications	Authors	Köppen-Geiger Climate Type
Tokyo, Japan	3	LCZ 1 LCZ 2 LCZ 3	(Yamagata et al. 2008) (Kubo et al. 2006) (Wei and He 2013)	Cfa
Nagaoka City, Japan	2	LCZ 3	(Kinouchi and Kanda 1997; Takahashi et al. 2010)	Cfa
Kawasaki City, Japan	1	LCZ 3	(Nakayama and Fujita 2010; Nakayama et al. 2012)	Cfa
Paris, France	3	LCZ 2	(Bouvier et al. 2013; Hendel 2015; Météo France and CSTB 2012)	Cfb
Lyon, France	1	LCZ 2	(Maillard et al. 2014)	Cfb

Clearly, the potential benefits of pavement-watering should be considered under other regional climates, particularly those facing increasingly dangerous heat levels during summer as a result of climate change.

These limitations indicate that more work is needed to adequately and reliably characterize the effects of pavement-watering, both thermal and micro-climatic. More work on the influence of urban materials and urban canyon morphology on pavement-watering performance is also required.

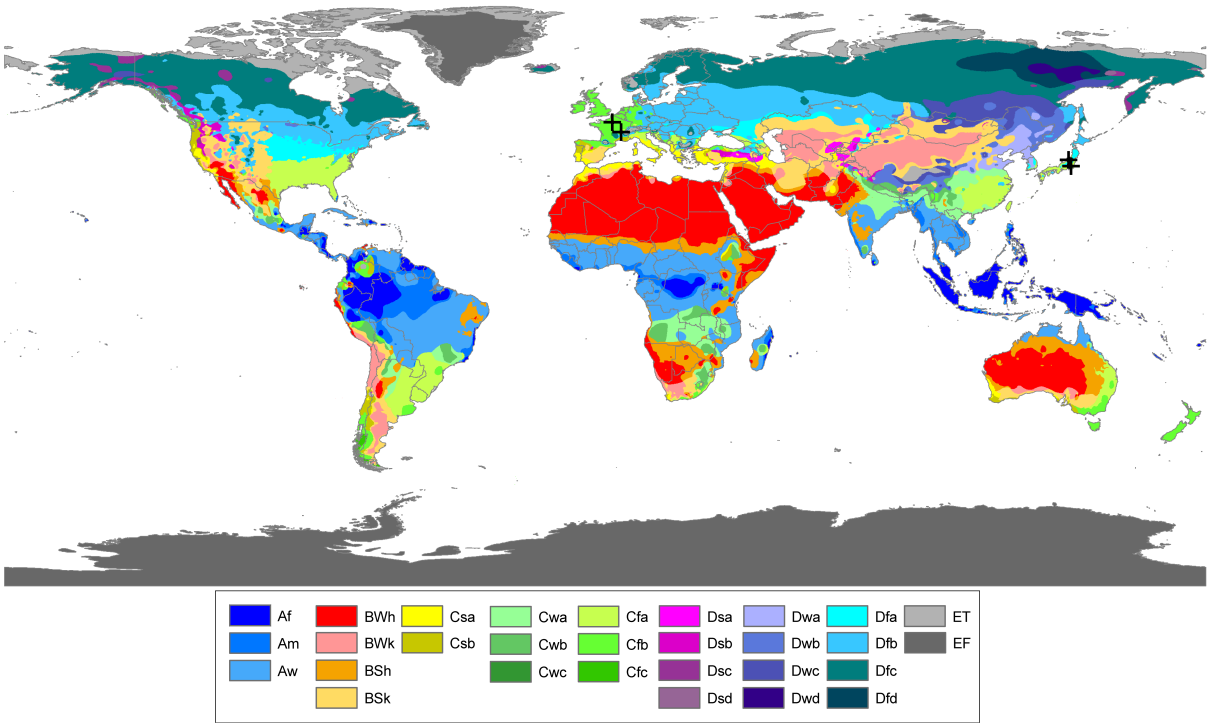


Figure 4: Geographic location (+) of the reviewed studies of pavement-watering conducted at the street-scale or higher against Peel et al. (2007)'s Köppen-Geiger climate type map of the World.

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