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Enhancing the Potential Cooling Benefits of Urban Water Bodies

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ABSTRACT

In Saitama, Japan, a series of experimental studies has been conducted inside an outdoor scale model canopy to find an effective design solution of water bodies for improving urban thermal environment and pedestrian comfort. Thus, the study result may help designers and planners to manage tradeoffs between the cooling effect demands, land-use limits and other design elements in urban environments. By modifying its physical properties, the present study shows a clear evidence of the mitigating capacity of urban water bodies. The result shows that generally, a bigger pond has greater cooling benefits. Nevertheless, by lowering the water temperature, the cooling benefit improved by 0.3 ˚C and 0.5 ˚C on average, as compared to natural pond and no-pond condition, respectively.

Keyword: *urban canyon, urban water body, cooling effect, field measurement, outdoor scale model*

INTRODUCTION

Water bodies in urban areas have an important role in regulating the urban microclimate. Mainly through evaporation, these water bodies improve surrounding thermal environments by maintaining cooler air temperatures (Oke, 1987). Theoretically, these evaporative cooling processes alter radiant energy portioning by increasing sensible heat absorption and latent heat transfer between the water and air (Pearlmutter et al, 2009). Together with large thermal capacities and unlimited water for evaporation, water bodies create an efficient heat sink. These unique characteristics generate opportunities to manipulate the water bodies' cooling effect to efficiently regulate an urban microclimate, particularly for the benefit of pedestrians.

Currently, although it still limited, research has been done by conducted studies on a water body's ability to ameliorate the urban microclimate. A study by Murakawa et al (1991) in Japan shows that air temperature near a river was found to be 3-5°C lower as compared to a nearby city.. Hatway and Sharples (2012) in UK, found that during ambient temperatures above 20°C, a small urban river was able to cool the air temperatures by nearly 1°C. The cooling effect however, was only prominent during the daytime. In China, Chen et al. (2006) documented a 1.3°C of air temperature difference between measurement points near to and away from an urban lake. A study in Singapore also found that air temperatures near water features, such as ponds and water walls, were found cooler by up to 1.8°C as compared to surrounding built areas during sunny, clear days (Jusuf et al, 2009). Furthermore, a study by Nishimura et al (1998) shows that air temperatures above an urban water pond was 1°C to 2°C lower as compared to the surrounding park during the daytime and with the introduction of water sprays, the reduction is increased.

Although, all of the research shows clear evidence of water bodies' cooling effect, there is still a need to have a a better understanding of the issues of thermal environments being influenced by the urban water bodies and its association with the microclimate. Therefore, effective use of urban water bodies could be established within limited spaces in urban areas.

The present study assesses the effect of water bodies to its immediate surrounding by utilizing an outdoor scale model. The study also looks at finding an effective design consideration within urban settings.

Located at Saitama Prefecture, Japan, the outdoor scale model (namely Comprehensive Outdoor Scale model - COSMO) consists of cubical array of 512 concrete cubes and built to represent 1/5 low rise urban setting (Kanda et al, 2006; Kanda, 2006; Kanda et all, 2007; Kawai & Kanda, 2010a; Kawai & Kanda 2010b). The outdoor scale model generic forms have the advantages of conducting various experimental studies while observing it under real urban climate conditions. Therefore, the present study aims to assess the potential benefits of urban water bodies and their influential factors affecting the cooling effect as well as to elaborate the possible effective water body's modification and alteration for better urban thermal environment. (Figure 1)

METHODOLOGY

Inside the scale model canopy, a series of experimental studies were conducted in the summers of 2015 (July-August) and 2016 (August -September). These studies employed a couple of cases with distinctive pond conditions. The details of each experimental study are as follows.

During the summer of 2015, two adjoining street canyons were exposed to two different water pond conditions, in addition to one no-pond canyon that acted as a reference (Figure 2). To have a better insight on the cooling effect and the effect of other influential factors (e.g. size, prevailing wind and solar radiation), one canyon was exposed to a 1.5m x 6m pond (Case 1) and the other one was exposed to 1.5m x 1.5m pond (Case 2). Both ponds have depth of 0.15m. Subsequently, in the summer of 2016, two additional experimental studies were installed to evaluate the effect of water thermal capacity modification (figure 3). In the 2016 studies, a smaller pond (sized at 1.5m x 0.5m, with depth of 0.15m) was used to have more focused experimental studies. The pond was arranged parallel relative to the prevailing South East winds and the water temperature was varied; one case was kept natural (Case 3), the other one was kept at 15°C by mechanically chilling the water (Case 4).

Similar to the 2015 study, an additional control reference point was also installed on a nearby canyon for comparison purposes. For each case, one measurement point was installed in the middle of

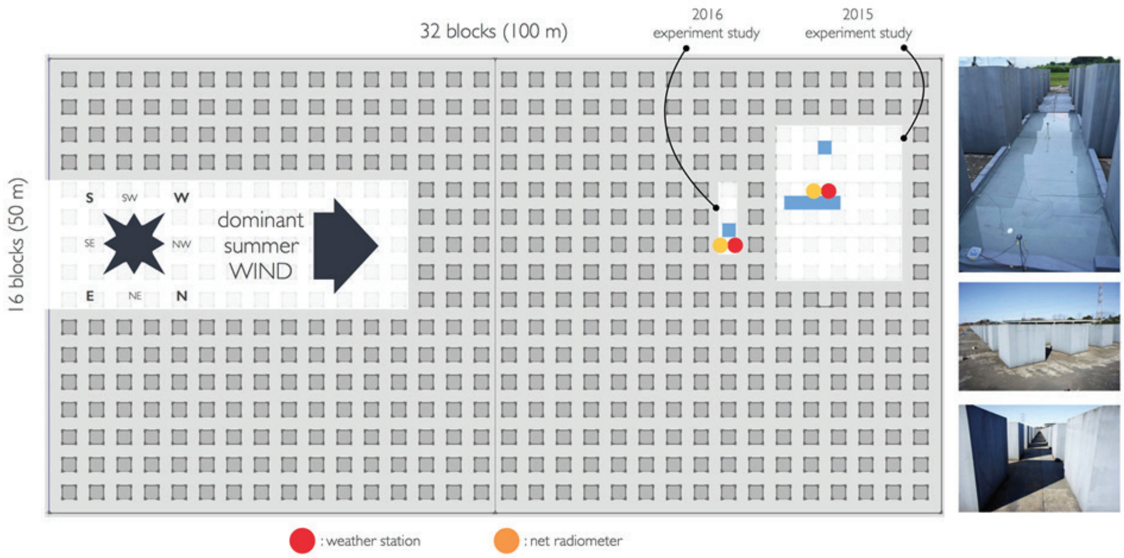


Figure 1:
COSMO and footage of the measurement

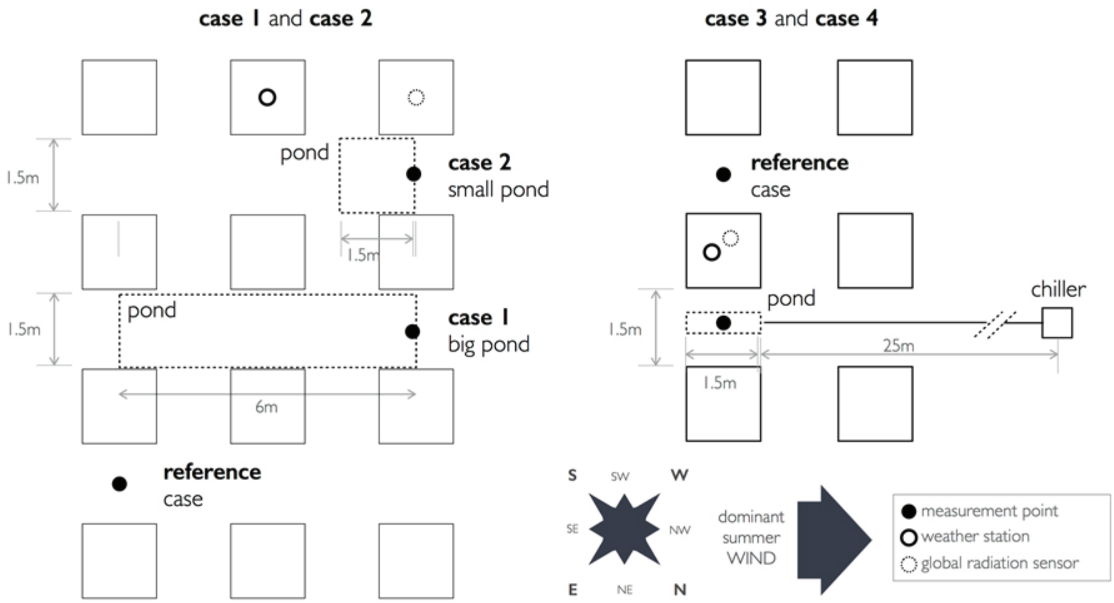


Figure 2:
Experimental study plan view

the canyon, representing the street canyon's average condition. The measurement point consisted of these elements: fine type-T bare thermocouples (TC) with a junction wire diameter of 0.01 inch (approx. 0.025 mm), a TC with 0.05 inch junction wire, a thermistor sensor and a grey-globe thermometer with TC sensor. These instruments recorded air temperature, water temperature, absolute humidity and radiant temperature measurement respectively. The grey-globe thermometer was made of a grey painted 40mm, table tennis ball and has been widely used in several other outdoor studies (Thorsson et al, 2007a; Thorsson et al, 2007b, Liang et al, 2014). As a good indicator of radiation changes, the grey globe temperature helps to estimate and evaluate the pedestrian thermal sensation. The air temperature and globe temperature sensors were placed at 30 cm from the ground, which represents the scaled down average human height and taken with a sampling frequency of 10 second. To measure the background climate, an additional weather station was placed at 2m above the COSMO and a global radiation sensor was installed just above the COSMO cubes. Details on all the measurement equipment are shown in Table 1.

Figure 3:
Footage of the field measurement at COSM

Table 1: Equipment detail

Measured parameter	Equipment detail (sensitivity range)	Accuracy
Air temperature	Thermocouple, T-type, copper – constant, Φ0.025mm	±0.1°C
Humidity	Thermistor type TDK RH sensor (5% - 95%)	± 3%
Water temperature	Thermocouple, T-type, copper – constant, Φ0.05mm	±0.1°C
Globe temperature	Thermocouple, T-type, copper – constant, *Φ* 0.05mm inside a grey painted 40mm celluloid globe	±0.1°C
Global solar radiation	Pyranometer - EKO ML-01 (50 μV/W/m²)	±2%
Background climate (air tempt, relative humidity, wind speed & direction)	Vaisala WXT520	±3°C, ±3%RH, ±3% at 10m/s
Wind profile below canopy (wind speed & direction)	Vaisala WXT520	±3% at 10m/s

ANALYSIS METHOD AND SELECTED DAY DATA

For the following analysis and discussion the measured data was presented in an hourly average and only data from hot days was used. All of the selected days' data and the analysis method are shown in Table 2.

Table 2: Selected day data and analysis method

Analysis	Selected days	Remarks
Experimental study 1	4 Aug and 5 Aug 2015	Case 1 (Big pond) and case 2 (small pond), simultaneously
Experimental study 2	4 Oct and 6 Oct 2016	Case 3 (Natural water) on 6 Oct and case 4 (chilled water) on 4 Oct

FINDINGS AND DISCUSSION

The experiments' studies were performed during the summer season in COSMO. The local weather is characterized by strong diurnal temperature fluctuations (average daily range of 25-36 °C), high global radiation (averages daily up to 800 kWh/m2) and prevailing winds consistently from the south-east (SE) direction with its strongest value recorded in the afternoon and evening (Figure 4 and Figure 5). Additionally, on a typical day around 10am – 12pm, when the sun was at the highest position, there was almost no shadow cast at the horizontal surface of COSMO canyon. During these hours, COSMO canyons experienced the most direct solar radiation, which might consider as the hottest time of the day (Figure 6).

The experimental study made in the summer of 2015, measured air temperatures, water temperatures and the grey-globe temperatures to examine the canyon's thermal environment influenced by two different water pond conditions (i.e. big pond and small pond), in addition to a no pond (dry) condition which acted as a reference. In the present paper, however, the discussion will focus more on the comparisons of the water bodies' alterations in regards to the surrounding thermal environment and to find likely influential factors affecting cooling benefits. Therefore, an effective design consideration could be identified for future urban development. By comparing the different alterations of the ponds, a comprehensive understanding of the effects of the physical modification was acquired.

Figure 7 shows the diurnal profile of the differences of the measured air temperatures on both ponds relative to the reference case (ΔTa). If the reference point is considered as the condition of no evaporation, the average difference of air temperature may refer to the evaporation cooling effect. The figure shows that the bigger pond (Case 1) tends to provide more cool air temperatures as compared to the smaller pond (Case 2), particularly at noon to late afternoon. As may be expected, more water surface means that there will be more surfaces for evaporative cooling.

The temperature difference, however, does not necessarily follow the increment ratio of pond size. The big pond has four times a larger surface area than the smaller pond, nevertheless the cooling benefit is merely 0.3˚C improvement on average. However, later in the night the bigger pond tends to warm the air more than the smaller pond. Due to its larger surface area and bigger thermal capacity, the big ponds tend to absorbs and store more heat during the day time. In which the extra heat will be converted into more heat being released, particularly during the night. Interestingly, during the early part of the day, both ponds show a nearly similar value. Due to relatively low wind speed and morning shadowing effect from the COSMO cubes, the size difference effect seems to be limited.

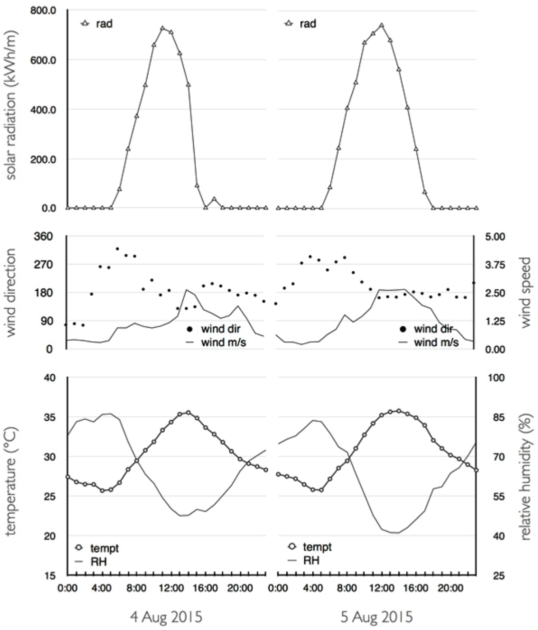


Figure 4:
The background microclimate condition (air temperature, wind profile, and solar radiation) of the 2015 experimental study

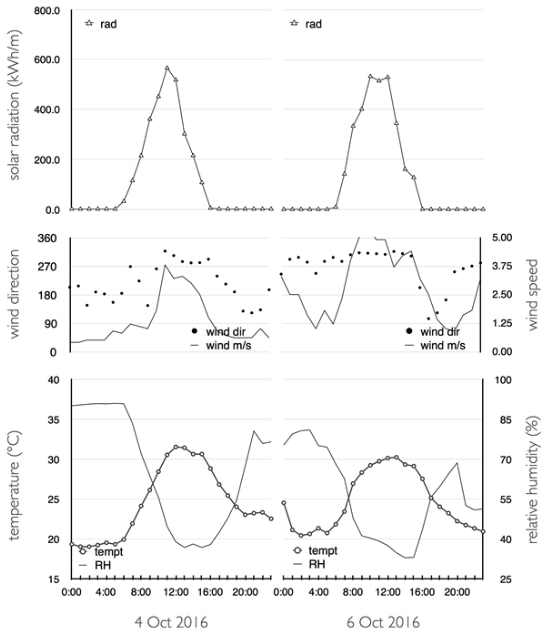


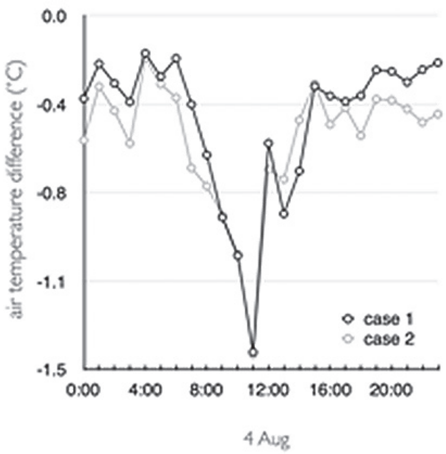
Figure 5:
The background microclimate condition (air temperature, wind profile, and solar radiation) of the 2016 experimental study

Figure 6:
The typical shadow condition inside the COSMO canyon

As found by others (Oke, 1987; Tang and Etzion, 2004), wind and solar radiation have an important role on the cooling process. Theoretically, the prevailing winds provide drier air for evaporation and at the same time it helps to enhance the convection process, while the solar radiation provides necessary energy for evaporation. Due to less availability of these factors, the benefit of having a bigger surface area and thermal capacity is not noticeable. Nevertheless, both ponds still show apparent cooling effect relative to the no-pond reference case. (Figure 7)

The daily cycles of these warming and cooling effects, related to heat absorption and release, are also reflected in the measured water temperature (*Tw*). As shown in figure eight the diurnal profile of the difference of *Tw* at the big pond relative to the small pond (Δ*Tw*) show negative value during the day but relatively positive during the night. Which translates into the larger pond having warmer water during the night, but colder water during the night. Despite the fact that bigger pond absorbs more heat, the diurnal Δ*Tw* profile suggests that the big pond seems to warm up relatively faster but cools slower as compared to the smaller pond. The warming rate of both ponds is distinguishable and seems to correlate to the thermal capacity of each pond. This particular finding opens the possibility of thermal capacity modification for better cooling benefits. (Figure 8)

Additionally, the measured radiant temperatures from the gray globe readings (*Tg*) shows similar trends yet supports the earlier findings. Figure nine, shows the diurnal profile of the globe temperature difference (Δ*Tg*) of both ponds relative to the reference. Generally, the diurnal profile of Δ*Tg* shows a negative value, which means that the present water body was clearly able to maintain lower radiant temperature inside the canyon. Case one with bigger pond has significantly lower Tg value during the daytime, but slightly higher *Tg* value during the night as compared to the Case two (small pond). With bigger thermal capacity and larger evaporation surface, the large pond tends to absorbed and convert more heat. These changes into latent heat through the evaporation surface yielding in the less sensible heat being transformed into warming the air during the day. On the other hand, during the night, this excess heat is released, resulting in slightly warmer conditions. Nevertheless, the Δ*Tg* profile seems to have positive correlation with the availability of solar radiation, with the bigger pond appearing to be more sensitive to the incident solar radiation. Interestingly, the radiant temperature around the small pond show warmer conditions during the day as compared to during the night-time. This distinguish trend may suggest the influence of other surface radiation, particularly during the day, which slightly overshadowed the cooling effect from pond. (Figure 9)



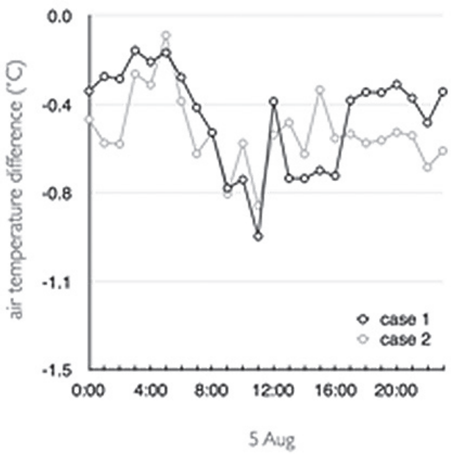


Figure 7:
Diurnal profile of air temperature difference (ΔTa) of Case 1 (big pond) and Case 2 (small pond) in the experimental study in the summer of 2015

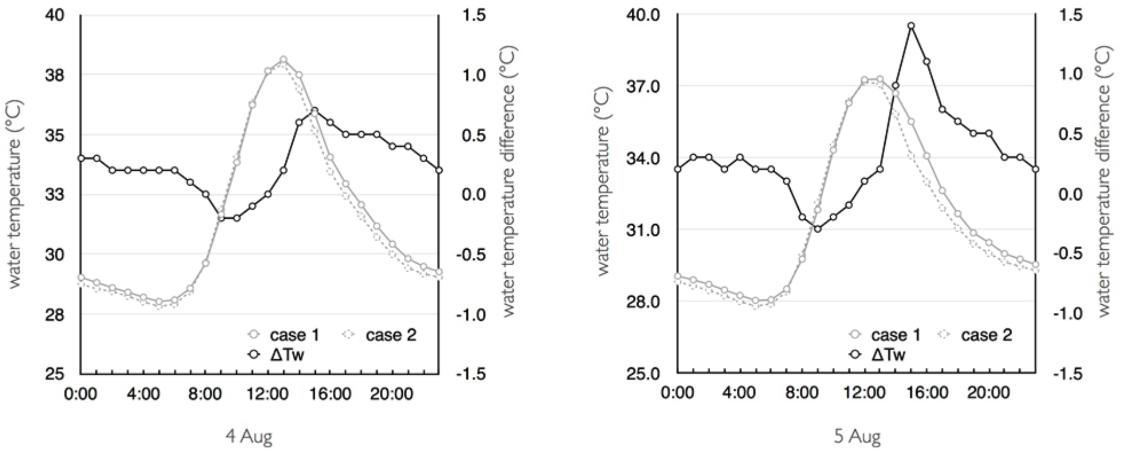


Figure 8:
Diurnal profile of water temperature (Tw) and water temperature difference (ΔTw) of Case 1 (big pond) and Case 2 (small pond) on the summer of 2015experiment study

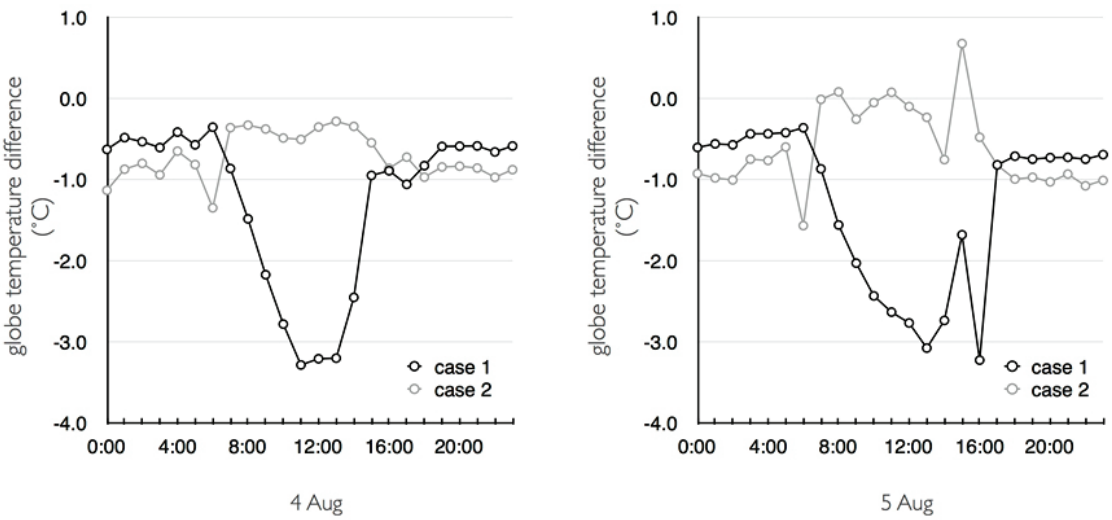


Figure 9:
Diurnal profile of globe temperature difference (ΔTg) of Case 1 (big pond) and Case 2 (small pond) on the experimental study of summer 2015

Furthermore, a secondary influence of water thermal capacity on the radiation properties inside the canyon may be detected by comparing the measured air temperature and water temperature. As shown in Figure 10, the diurnal profile of the differences in values of air temperature and water temperature (ΔTa-*w*) show an unusual but rather consistent trend. Generally, the ΔTa-*w* shows negative value during daytime and evening, while it shows positive values in the late night and early morning. The negative value indicates that the water temperature (*Tw*) is found higher than the air temperature (*Ta*). According to Fritschen and van Bavel (1963), if the air-water interface was considered as the reference plane, the negative value indicates that the sensible heat flows toward these reference planes (positive sensible heat). Consequently, positive sensible heat flux means that the energy was not used to heat the air. Due to these unique properties, air temperature near water bodies tends to be cooler *Tw* as compared to that of temperatures shown over land or pavement.

The diurnal profile, the ΔTa-*w* on both ponds shows interesting and relatively consistent fluctuation. The ΔTa-*w* pattern shows sudden decrease and sudden increase at a particular time. If water bodies tend to have small temperature fluctuation, the sudden increase and decrease pattern seems to be correlated with the incident solar radiation on the surface of the pond's water. On daily cycle, the COSMO canyon experiences less shadowing during a certain time. This period is where the canyon experiences more direct solar radiation (refer to figure 10, grey background). The increase of incident solar radiation on the surface of the water pond seems to change the pattern quite dramatically. The ΔTa-*w* start to increase in magnitude towards positive value when there was more energy entering the canyon, which might also increase the transformation of sensible flux. However, the trend was suppressed later in the day, when more evaporation of water starts to contribute to the transformation of more latent heat.

In addition, the diurnal profile also shows a different intensity of ΔTa-*w* between the large pond and the small pond, particularly during the last hour of the day. In the case of the small pond the ΔTa-*w* shows a greater difference as in comparison to the case of the big pond, although it is not significant. This greater ΔTa-*w* difference, however, seems not translated into cooler air. Further analysis shows that the tendencies appear to be related to the *Tw* diurnal profiles, which illustrate the different thermal capacity of different sizes of the water ponds. One possible reason is, during the evening, the smaller pond seems to release heat much faster. If the *Ta* difference between the large pond and small pond was not so great, these ΔTa-*w* progressive changes may be significantly influenced by the *Tw* changes. (Figure 10)

Therefore, in the summer of 2016, an additional experimental study was conducted to have a better understanding of the water body's thermal capacity on the air temperature and the gray globe temperature. Two distinguished cases with smaller ponds was installed inside the COSMO canyon. To limit the effect of different canyon surface properties, the two cases were assessed on different days in a subsequent manner, instead of doing it simultaneously. Furthermore, having smaller ponds has the advantage of ease of alteration and maintenance. The two experiments consist of a case study with no-chilled water, i.e water kept at air temperature (Case 3) and a case study with chilled water, i.e the water temperature was mechanically kept at 15˚C (Case 4). The diurnal profile of air temperature (*Ta*), globe temperature (*Tg*) and its difference values relative to the reference (Δ*Ta* and *ΔTg*) are shown on figure 11. Generally the Δ*Ta* and *ΔTg* shows negative values, which shows the pond's ability to maintain cooler air throughout the day, as found on earlier cases. The *Ta* and *Tg*

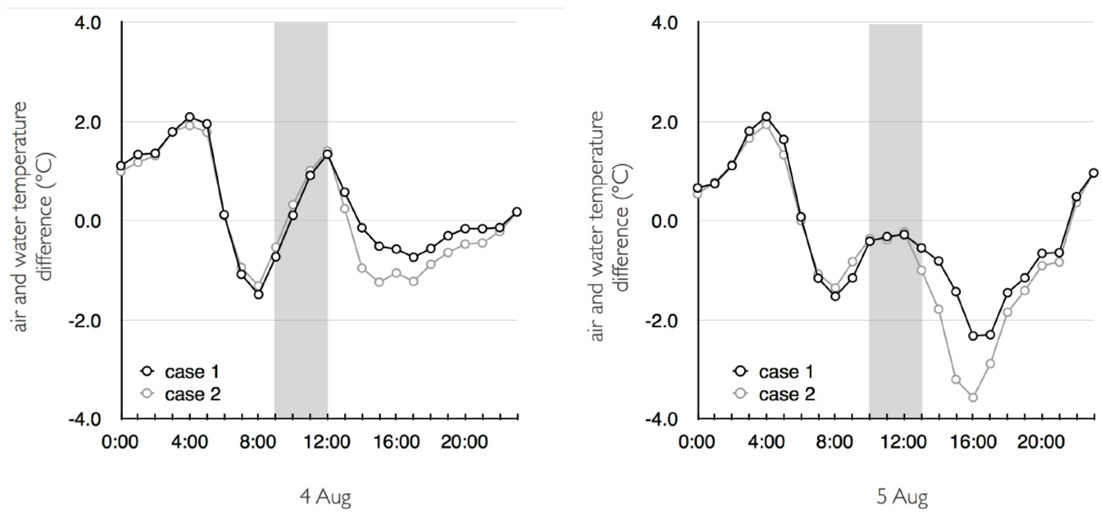


Figure 10:
Hourly average profile of difference of air temperature relative to water temperature difference (ΔTw-a) of Case 1 (big pond) and Case 2 (small pond) in the experimental study of summer 2015

of Case 4, however, seem to show better thermal conditions. The chilled water in Case 4 appears to be able to maintain lower *Ta* and *Tg*. The average improvements were recorded up to 0.3˚C and 0.5˚C for *Ta* and *Tg*, respectively. By mechanically removing the heat absorbed by the water, the heat released from the pond was also greatly reduced, resulting in lower *Ta* and *Tg* near the chilled water. Furthermore, the Δ*Ta* and Δ*Tg* diurnal trend shows an interesting pattern. Particularly in the Δ*Tg* diurnal trend, there is a sudden increase during the first hour of the morning. Although, part of the incident heat was absorbed by the pond or blocked by the COSMO blocks, low wind speed and limitation of the evaporation process seems to offset the cooling benefits. This suggests the dependence of each of these influential factors to the cooling potential of the water pond. Nevertheless, when the evaporation process started and more heat was being absorbed, the *Tg* was greatly reduced followed by the *Ta*. (Figure 11)

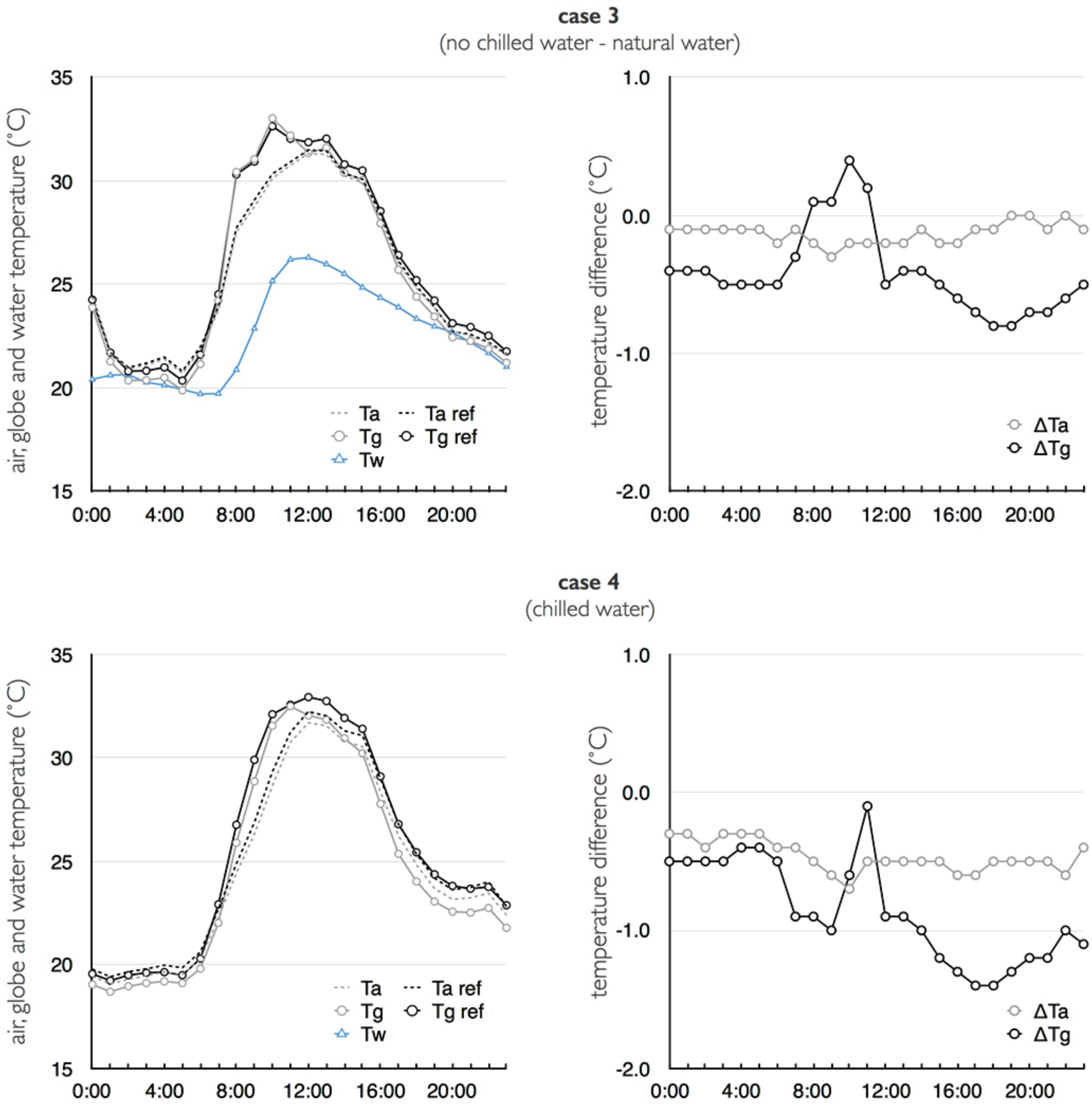


Figure 11:
Hourly average profile of air temperature (Ta) and globe temperature (Tg) of Case 3 (natural water condition) and Case 4 (chilled water condition), in addition with its difference relative to reference point on summer 2016 experiment study

CONCLUSION

The microclimate near the bodies of water is found to be different from that over the land. Owing to its transparency, larger thermal capacity and unlimited water for evaporation, bodies of water form an efficient heat sink and cool the immediate air temperature. In an urban context, water bodies have the potential to mitigate many urban problems related to thermal environment due to these beneficial characteristics. However, due to limited open spaces in urban areas, there is a need to find an effective design solution of water bodies for better urban thermal environment and pedestrian comfort.

In this present paper, a series of experimental studies with artificial water pond has been conducted inside an outdoor scale model canopy, in Saitama, Japan. The cooling benefits of these water ponds were assessed and evaluated, in terms of air temperature (*Ta*), radiant temperature (*Tg*) and water temperature (*Tw*). Generally, the results shows that the bigger pond provided a better thermal environment by reducing the value of *Ta* and *Tg*. The larger pond tends to absorb more radiant heat while also having a larger evaporation surface. Naturally, the heat is most likely dissipated by evaporation, rather than being converted into sensible heat. This shows the influential role of water bodys' thermal capacity and opens the possibility of controling these factors for better urban thermal environments. Therefore, a supplementary study was conducted in the summer of 2016 with alterations in water temperatures. As a good indicator of thermal capacity changes, the water temperature was manipulated by keeping it chilled (15 ˚C). The result shows that the thermal environment was improved with the introduction of chilled water. As compared to a non-chilled natural water condition, the average improvement was recorded at up to 0.3˚C and 0.5˚C for *Ta* and *Tg*, respectively. Nevertheless, the lower *Ta* and *Tg* values found in each cases compared to dry conditions, show the unique ability of water ponds to maintain lower air and radiant temperatures.

LIMITATION AND POSSIBLE AREAS FOR FUTURE RESEARCH

The outdoor scale models used for the present study may not perfectly represent the actual urban environment. However, it's simple and generic form may help to simplify the complexity of real urban environments while also isolating other unnecessary influential factors. Nevertheless, the present study shows the possibility of improving the cooling benefits of water ponds by introducing chilled water. Constantly cooling the water, however, may need additional energy. Therefore, in the perspective of sustainability, there is a need for further study to manage the tradeoff between these concerns.

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