Urban Climate 32 (2020) 100607

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Are urban water bodies really cooling?

Cor Jacobs[a,b,*], Lisette Klok[a], Michael Bruse[c], João Cortesão[d], Sanda Lenzholzer[d], Jeroen Kluck[a,e]

[a] University of Applied Sciences Amsterdam, Urban Technology, Weesperzijde 190, 1097 DZ, Amsterdam, the Netherlands
[b] Wageningen University & Research, Wageningen Environmental Research, Droevendaalsesteeg 3, P.O. Box 47, 6700 AA, Wageningen, the Netherlands
[c] Johannes Gutenberg-Universität Mainz, Institute of Geography, Johann-Joachim-Becher-Weg 21, 55099 Mainz, Germany
[d] Wageningen University, Landscape Architecture Group, Droevendaalsesteeg 3, 6708 PB, Wageningen, the Netherlands
[e] Tauw bv, Handelskade 37, P.O. Box 133, 7400 AC, Deventer, the Netherlands

ABSTRACT

Small urban water bodies, like ponds or canals, are often assumed to cool their surroundings during hot periods, when water bodies remain cooler than air during daytime. However, during the night they may be warmer. Sufficient fetch is required for thermal effects to reach a height of 1–2 m, relevant for humans. In the 'Really cooling water bodies in cities' (REALCOOL) project thermal effects of typical Dutch urban water bodies were explored, using ENVI-met 4.1.3. This model version enables users to specify intensity of turbulent mixing and light absorption of the water, offering improved water temperature simulations. Local thermal effects near individual water bodies were assessed as differences in air temperature and Physiological Equivalent Temperature (PET). The simulations suggest that local thermal effects of small water bodies can be considered negligible in design practice. Afternoon air temperatures in surrounding spaces were reduced by typically 0.2 °C and the maximum cooling effect was 0.6 °C. Typical PET reduction was 0.6 °C, with a maximum of 1.9 °C. Night-time warming effects are even smaller. However, the immediate surroundings of small water bodies can become cooler by means of shading from trees, fountains or water mists, and natural ventilation. Such interventions induce favorable changes in daytime PET.

1. Introduction

Small urban water bodies, like ponds or canals, are often assumed to provide effective cooling during hot periods and to improve thermal sensation in the neighboring spaces and over the water. This is why urban designers often include them in the design of the urban environment.

In hot-weather periods, water bodies are often cooler than the overlying air, especially during the hottest hours of the day (e.g., Broadbent et al., 2017; Gross, 2017). Accordingly, their surface temperatures are often lower than the surface temperatures of surrounding urban structures (e.g., Sun and Chen, 2012; Méndez-Lázaro et al., 2018). For water bodies with a depth of at least half a meter, these temperature differences are expected because of the large heat capacity of water in combination with the ability of water to transport heat away from its surface by turbulent mixing (Oke, 1987). However, the latter mechanism also implies that water takes longer to cool down, which may result in water bodies being warmer than the air during the night (Steeneveld et al., 2014). Consequently, water bodies may enhance night-time urban heat islands, in particular in later summer season (Hathway and Sharples, 2012; Steeneveld et al., 2014; Van Hove et al., 2015).

So, the question arose if typical urban water bodies would actually have a significant effect on thermal sensation. And in case this effect does not occur, how the environments of urban water bodies could still offer cooling conditions during hot summer days by

* Corresponding author at: Wageningen University & Research, Wageningen Environmental Research, Droevendaalsesteeg 3, P.O. Box 47, 6700 AA, Wageningen, the Netherlands.
E-mail address: cor.jacobs@wur.nl (C. Jacobs).

https://doi.org/10.1016/j.uclim.2020.100607
Received 22 March 2019; Received in revised form 24 January 2020; Accepted 8 February 2020

implementation of shading, evaporation and ventilation interventions and how such interventions can be optimally combined in designs to reduce exposure to urban heat effectively, at least locally.

Therefore, the 'Really cooling water bodies in cities' (REALCOOL) project explored possible local cooling effects of combinations of shading, evaporation and ventilation interventions for relatively small urban water bodies. Sixteen representative virtual urban water body settings have been investigated and redesigned (combining shading, evaporation and ventilation interventions). These REALCOOL designs considered the water environment as a whole: the waterbody as well as the adjacent spatial features such as vegetation, ground cover, water mist or fountains. For more general information on the REALCOOL project the reader is referred to Cortesão et al., 2017 and http://climatelier.net/projects/research/realcool-really-cooling-water-bodies-in-cities/.

Given the comparatively limited evidence on cooling or warming effects by urban water, the first goal of the research presented in this paper was to assess the thermal effects of selected small urban water bodies types on their environment. The outcome of this assessment influenced the generating of new REALCOOL designs to optimize cooling based on shading, ventilation, and evaporation (Cortesão et al., 2019). The second goal was to assess the thermal effects of the resulting REALCOOL designs. The evaluation of thermal effects at larger or smaller scales was beyond the scope of the present study.

Thermal effects of the water body environments were computed using the micrometeorological model ENVI-met 4.1.3 (http://www.envi-met.com/). This ENVI-met version now enables the user to choose the intensity of turbulent mixing of the water. Furthermore, the light absorption characteristics can be specified by the user. Utilizing the new option by adjustment of these properties resulted in more realistic water temperature simulations than in the previous versions. Thermal effects were computed as differences in air temperature and PET, respectively, between the situation with and without water (first goal) and the REALCOOL design (second goal).

2. Background

2.1. Theoretical considerations

Surface-air temperature gradients drive heat exchange between the surface and the atmosphere. As such, their development is a precondition for water bodies to influence the air temperature (T_a). Obviously, if the water surface remains cooler than the air, the sensible heat flux is directed towards the water, which cools the air. Vice versa, if the water surface is warmer than the air, the sensible heat flux is directed towards the air, which warms the air.

Whereas the cooling effect of water bodies is often attributed to evaporation, the effect of evaporation is small on short timescales in reality. Compared to radiative gains and losses and on a daily scale, evaporation is a small component of the energy budget. In shallow water bodies with strongly rising surface temperatures during the day, radiative exchanges are expected to dominate the energy budget, in particular during the summer and in low wind speed conditions (Paaijmans et al., 2008) such as often encountered in urban settings (Van Hove et al., 2015). Nevertheless, on an annual basis, evaporation may be considered an important energy exchange mechanism for larger water bodies (Gunawardena et al., 2017), and large fractions of water environments may therefore help to reduce the urban heat island intensity by its impact on the urban energy budget (Oke, 1987).

The effect of evaporation is also indirect. Evaporation cools the water by extracting energy from the water body. This reduces water temperature, also at the surface, and so affects sensible heat fluxes depending on the water-air temperature gradient and turbulence in both media. Because sensible heat fluxes influence air temperature, even evaporating water bodies continue to warm the overlying air as long as the water surface temperature exceeds the air temperature and the sensible heat flux remains positive. Clearly, water surface temperature is not only controlled by evaporation, but by all of the aforementioned energy exchanges via the surface. Furthermore, the surface temperature will depend on mixing due to density differences, the impact of wind and the motion of the water (Jacobs et al., 1997).

Development of a surface-air temperature gradient is not a sufficient condition to significantly influence the atmosphere surrounding a water body. The cooler or warmer air near the water surface also needs to be transported to the urban surroundings in order to noticeably affect air temperature at a height where humans actually sense it. This also implies that a noticeable cooling effect for humans near water bodies requires the fetch over the water to be sufficiently large (Foken, 2008).

Cooling effects also need to be considered in meaningful quantities, since in most cases, attempts to cool the environment are targeted at improving human thermal sensation and comfort. For standing humans near water bodies, thermal effects are generally only relevant if they are perceived at a height of 1–2 m. In addition, wind (ventilation), humidity and radiation contribute to the heat load of humans. Therefore, possible cooling or heating effects need to be considered in terms of physiologically meaningful quantities, such as the Physiological Equivalent Temperature (PET) (Höppe, 1999; Walther and Goestchel, 2018).

2.2. Evidence from the scientific literature

The results presented in a recent review of 18 observational studies (Völker et al., 2013) demonstrate that the cooling effect of small urban water bodies is small, which is consistent with the considerations given above. In this review, the effect of water was evaluated as the median of the measured differences in air or surface temperature between the water and its surroundings. Unfortunately, thermal sensation was not considered. The height of the temperature measurements ranged between the surface and 2 m and was not explicitly accounted for. The differences in distance between the location over or near the water body and the urban reference site also varied between the studies. The resulting median cooling effects reported by Völker et al. (2013) range between 0.4 and 5.6 °C. The median of these effects is 2.5 °C. However, the median value appears to be larger when considering surface temperature effects based on remote sensing (3.3 °C) instead of on-site observations of air temperature (1.9 °C). The larger temperature differences found by remote sensing studies can be explained because these studies are based on surface temperatures, often obtained during daytime, when the water body is comparatively cool. The median cooling effect also declines from larger water bodies like big water reservoirs and rivers (3.3 °C), via intermediate size water bodies like inland lakes (2.1 °C) to smaller water bodies like small ponds (1.6 °C), consistent with fetch considerations. However, only four water bodies were included in the latter sample, one of which containing a fountain showing the largest effect within that group (4.7 °C).

Results from later papers (as of 2013) based on observational evidence or modelling studies, but excluding papers reporting surface temperature only, generally confirm the small cooling effect of water bodies on air temperature (see Supplementary Information I for references to these papers). From results reported in 20 papers for urban water bodies without fountains, the median thermal effect on air temperature was estimated to be about 0.5 °C. In total, 14 out of the 20 papers (70%) reported a thermal effect on air temperature of 1 °C or less. Only seven papers reported effects as a difference in PET. The maximum PET effects range between an observed warming of 5.3 °C, measured in Amsterdam near a river in the afternoon (Klok et al., 2019), to a cooling of up to 5.0 °C near a pond with a small fountain in Valencia on a clear summer day (Gomez et al., 2013), the average and median being near zero.

3. Method

3.1. Definition of the reference situation: Selection of recurring small urban water bodies

In REALCOOL, the thermal effects of the reference situations, i.e. the selected sixteen urban water body settings, and of the produced designs were evaluated for abstracted spatial layouts. The reference situations were defined through an inventory of recurring small urban water bodies in The Netherlands (Cortesão et al., 2017). This inventory was carried out in nine Dutch cities on clay or peat soils and with significant urban heat island intensities (http://www.klimaateffectatlas.nl/en/). The water body types were identified in dense, heat-prone urban environments within each city, based on their total length. In situ spatial analyses based on observations, measurements, photos, and mapping were conducted to further characterize the selected water bodies (e.g. spatial dimensions, paving materials, trees or buildings).

The relevance of each type for design practice was determined based on the spatial analyses and on expert judgement. The most relevant types of water bodies were clustered in four main categories: “canal”, “singel” (the Dutch word is retained because no appropriate English translation was found), “ditch” and “pond”. Fig. 1 provides examples of each category. For some categories,

Fig. 1. Examples of the four categories of typical Dutch water bodies considered in REALCOOL. The number between parentheses indicates the number of subcategories (see Table 1).

subcategories were distinguished. Eventually eight representative water bodies were selected and for each of them, North-South (NS) and East-West (EW) orientations were considered. This resulted in 16 virtual reference situations. Table 1 lists all water bodies considered in REALCOOL and their main characteristics.

3.2. ENVI-met simulations

The sixteen reference situations were represented as a three-dimensional environment in the micrometeorological model ENVI-met (http://www.envi-met.com/) which was used to assess the thermal effects of the reference situations and of the REALCOOL designs. ENVI-met is a widely used prognostic, three-dimensional model to simulate surface-vegetation-atmosphere interactions and resulting microclimate and pollutant dispersion in urban settings (Tsoka et al., 2018). For a full model description and quality assessment, the reader is referred to Bruse and Fleer (1998), Huttner (2012) and numerous papers using ENVI-met for similar purposes (see Tsoka et al., 2018 for a review). Since the water temperature determines the thermal effects and a proper calculation of this quantity is crucial in the present context, the treatment of the water temperature in ENVI-met and its improvements are described below, giving the essentials of the water energy budget. For additional details the reader is referred to Supplementary Information II.

In ENVI-met, water is treated as a special soil type that is partly transparent to shortwave radiation. Some special conditions apply which are highlighted in the supplementary information. Like for any other material in ENVI-met, the energy balance of the uppermost water layer is solved to estimate the water surface temperature at the air-water interface.

Whereas most terms of the energy budget follow the standard calculation procedures, the estimation of the absorbed shortwave radiation is more complex for a water body. Albedo is estimated for the direct and diffuse component of the incoming shortwave radiation and then averaged with weights given by the fraction of diffuse and direct sunlight (Oke, 1987). It is assumed that the near infra-red fraction of the of the absorbed solar radiation is absorbed in the uppermost water layer. Following Jacobs et al. (2007), this fraction was set to 45% of the energy contained in the downwelling shortwave radiation. The remainder of the energy, mainly visible radiation, is absorbed in the water layer according to Lambert-Beer's law:

$$Q_{sw}^{*}(z) = Q_{sw,trans}^{*}(0)e^{-\xi(z)} \tag{1}$$

where $Q_{sw}{}^{*}(z)$[W m^{-2}] is the amount of shortwave radiation reaching the top of layer z and $Q_{sw,\ trans}{}^{*}(0)$ is the amount of shortwave radiation transmitted through the very upper water layer and which contains the remaining 55% of the absorbed shortwave radiation. Furthermore, ξ [m^{-1}] is the extinction coefficient. The heating rate at depth z [m] due to absorption of shortwave radiation, $Q_w(z)$ [K s^{-1}], is then given by:

$$Q_w(z) = -\frac{1}{\rho C_w}\frac{\partial Q_{sw}(z)}{\partial z} \tag{2}$$

where $C_w = 4.2{\cdot}10^3$ [J kg^{-1} K^{-1}] is the heat capacity of water, $\rho = 1000$ [kg m^{-3}] is the density of water and $\partial Q_{sw}(z)$ is the solar radiation (W m^{-2}) absorbed in the layer located at z.

The extinction coefficient ξ in (1) is a crucial parameter for the thermal behavior of a water body. This coefficient reflects the turbidity of the water and had a fixed default value of 0.5–0.6 m^{-1} in older ENVI-met versions. Because the turbidity differs considerably among water bodies, a modified version of ENVI-met has been developed in which the value of ξ can be adjusted by the user to accommodate specific light absorption characteristics.

De Lange (2000) examined light absorption properties of 19 water bodies in The Netherlands, including urban water bodies, and found ξ to range between 0.8 and 6.4 m^{-1}, with an average of 2.8 m^{-1} and the median being 1.7 m^{-1}. Jacobs et al. (2009) carried out observations and simulations of water temperature and solar radiation of an open-air aquaculture pond in The Netherlands and found $\xi \approx 2.1$ m^{-1} on average. Based on these findings, $\xi \approx 2.5$ m^{-1} was used in the REALCOOL simulations.

The distribution of the water temperature (T_w [°C]) in time and space is computed using the three-dimensional heat transfer equation in a Cartesian co-ordinate system (x,y,z):

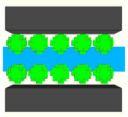
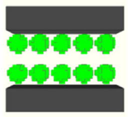
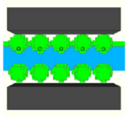
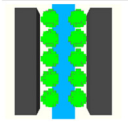
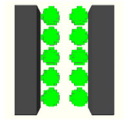
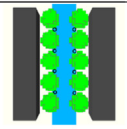
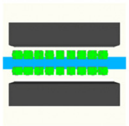
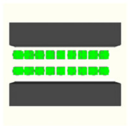
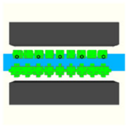
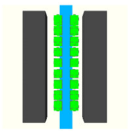
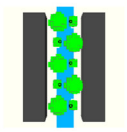
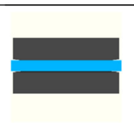
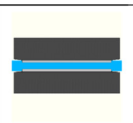
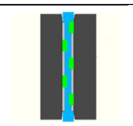
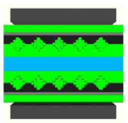
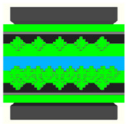
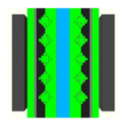
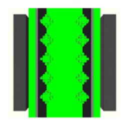
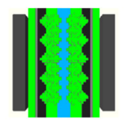
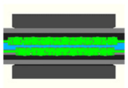
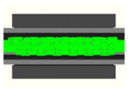
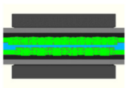
$$\frac{\partial T_w}{\partial t} = D_w\frac{\partial^2 T_w}{\partial x^2} + D_w\frac{\partial^2 T_w}{\partial y^2} + D_w\frac{\partial^2 T_w}{\partial z^2} + Q_w(z) \tag{3}$$

where t [s] is time and D_w [m^2 s^{-1}] is the heat exchange or heat transport coefficient within the water.

In previous versions of ENVI-met, the value of D_w was taken equal to the molecular diffusion coefficient. However, since water allows turbulent motion, this led to unrealistically large temperature gradients underneath the air-water interface. This would generally result in an overestimation of the surface temperature during daytime and an underestimation during night-time. Because the surface temperature strongly affects air-water energy exchange via its impact on the sensible heat flux, evaporation, longwave radiation and mixing, this may lead to unrealistic cooling or warming effects. Therefore, the effect of turbulent mixing can be introduced implicitly as of ENVI-met Version 4.1.3 by modifying the exchange coefficient D_w. In this study $D_w = 0.001$ m^2 s^{-1} was chosen, which assures well-mixed conditions in the water column and is twice the minimum value suggested by Losordo and Piedrahita (1991).

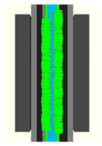
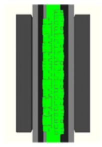
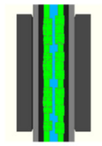
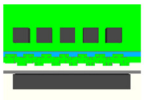
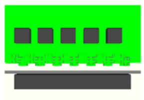
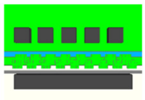
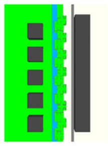
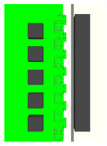
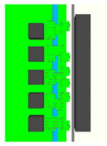
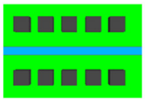
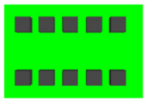
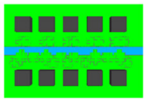
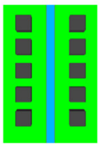
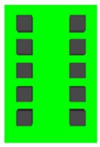
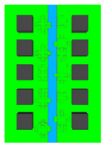
Test simulations of water temperature were carried out using the aforementioned new values for ξ and D_w. The results were compared with simulations using the previous settings in ENVI-met and with observations performed in the Netherlands, within and around a pond with a depth of approximately 4 m. Here, only the main result is shown in Fig. 2. Information on the site from which the temperature data were obtained can be found on www.climatexchange.nl/sites/ijzendoorn.

Table 1
Overview of the water bodies considered in REALCOOL, their width and depth and the initial water temperature ($T_{w,i}$) at 6 CET used in the ENVI-met simulations. Design interventions and tree species used in reference situation and design are listed. Color code and symbols: blue = water, grey = buildings, green = trees, grass, or pergola, white = bricks, light grey = wooden decks, black = asphalt, triangle = fountain, octagon = water mists.

Water body	Reference (REF)	No water (NO)	Design (DES)	Design interventions	Tree species in reference and in ***design***
Canal 1 EW *width = 20 m* *depth = 2 m* *$T_{w,i}$ = 24.1°C*				Water mist, green slope, stairs	Field elm A *Field elm A*
Canal 1 NS *width = 20 m* *depth = 2 m* *$T_{w,i}$ = 24.1°C*				Water mist, stairs	Field elm A *Field elm A*
Canal 2 EW *width = 9 m* *depth = 2 m* *$T_{w,i}$ = 24.1°C*				Different trees, water mist, non-linear quays	Field elm C *Field elm C at north and F at south side*
Canal 2 NS *width = 9 m* *depth = 2 m* *$T_{w,i}$ = 24.1°C*				Different trees, water mist, non-linear quays	Field elm C *Field elm A and C at both sides alternating*
Canal 3 EW *width = 10 m* *depth = 2 m* *$T_{w,i}$ = 20.8°C*				Decks	None
Canal 3 NS *width = 10 m* *depth = 2 m* *$T_{w,i}$ = 20.8°C*				Pergolas, decks	None
Singel 1 EW *width = 12 m* *depth = 1 m* *$T_{w,i}$ = 23.3°C*				Different trees, green slope	Field elm B *Field elm B at north side and B and F at south side*
Singel 1 NS *width = 12 m* *depth = 1 m* *$T_{w,i}$ = 23.3°C*				Different trees, green slope	Field elm B *Field elm B and F at both sides*
Singel 2 EW *width = 5 m* *depth = 1 m* *$T_{w,i}$ = 23.3°C*				Different trees, green slope, stairs	Field elm C, Black poplar *Field elm C and Black poplar*

(continued on next page)

Table 1 (*continued*)

Singel 2 NS *width = 5 m* *depth = 1 m* $T_{w,i}$ *= 23.3°C*				Different trees, green slope, stairs	Field elm C and Black poplar *Field elm C and Black poplar*
Ditch 1 EW *width = 3 m* *depth = 1 m* $T_{w,i}$ *= 23.3°C*				Different trees, green slope, stairs	Field elm C, Black poplar *Field elm C, Black poplar*
Ditch 1 NS *width = 3 m* *depth = 1 m* $T_{w,i}$ *= 23.3°C*				Different trees, green slope, stairs	Field elm C, Black poplar *Field elm C, Black poplar*
Ditch 2 EW *width = 5 m* *depth = 1 m* $T_{w,i}$ *= 23.3°C*				Trees, terraced gardens	None *Field elm B, C and Black poplar*
Ditch 2 NS *width = 5 m* *depth = 1 m* $T_{w,i}$ *= 23.3°C*				Trees, terraced gardens	None *Field elm B, C, and Black poplar*
Pond EW *width = 30 m* *length = 40 m* *depth = 0.5 m* $T_{w,i}$ *= 21.8°C*				Trees, decks, water mist and fountains	None *Field elm B and C*
Pond NS *width = 30 m* *length = 40 m* *depth = 0.5 m* $T_{w,i}$ *= 21.8°C*				Trees, decks, water mist and fountains	None *Field elm B and C*

It can be seen that the new version of ENVI-met, with the settings discussed above, produces a more realistic course of the near-surface water temperature during daytime. The new settings imply stronger mixing, which is considered more realistic than the almost complete absence of mixing implied in older ENVI-met versions. In the Netherlands, the assumption of well-mixed conditions is a reasonable one for shallow water bodies (up to 2-3 m) most of the time (Jacobs et al., 2009). Comparatively low solar elevation angles and frequent occurrences of (partly) cloudy conditions imply limited warming of the top layer in the water. The windy conditions that often occur in The Netherlands can then overcome stable stratification of the water by wave action, including microwave breaking, and shear stress. However, fair-weather daytime summer conditions with very low wind speed may lead to near-surface temperature gradients and hence higher surface temperatures. In such a situation, the modelled water surface temperature may be underestimated, which would then lead to an overestimation of the cooling effect. During night-time, cooling of the water by sensible and latent heat exchange and radiative cooling nearly always create well-mixed conditions in shallow water bodies like most urban ones.

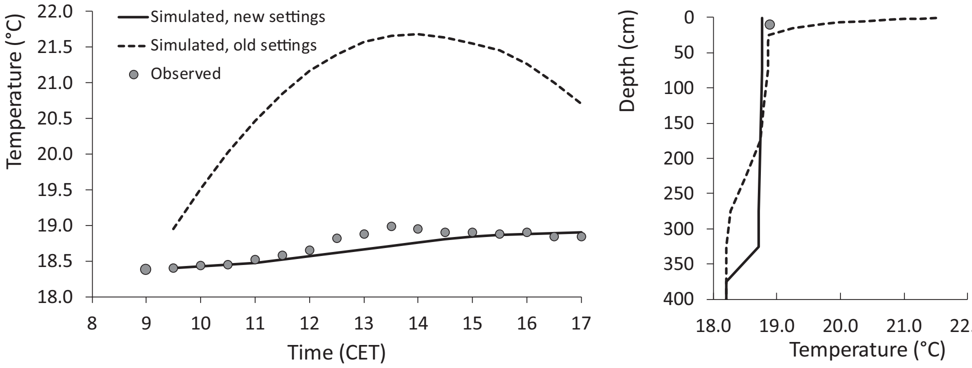


Fig. 2. Test of the water temperature simulations with ENVI-met: comparison of runs with new settings with results of runs with old settings and observations. Left: temporal evolution of near-surface water temperature during daytime; Right: vertical temperature profiles at 15 CET.

3.3. Boundary conditions and initial water temperature

All simulations were performed for meteorological conditions representing a typical heatwave day in the Netherlands. Using data from the main meteorological station in the center of the Netherlands (De Bilt, 52.101°N, 5.177°E), the mean diurnal variation of temperature and humidity of all so-called tropical days in the climatological period 1981–2010 (maximum temperature ≥ 30 °C, n = 95) was determined and used to drive the simulations. The mean diurnal variations are shown in Fig. 3. Whereas on larger, urban to regional scales surface-atmosphere feedbacks affecting the conditions at the reference level and inducing mesoscale circulations may have to be taken into account (Gunawardena et al., 2017), such feedbacks may be ignored at the scales considered here.

Mean cloud cover was determined for the same tropical days and was found to be 2.5 oktas.' The clouds were assumed to be middle clouds. Incoming solar radiation was computed in ENVI-met for 52.2°N and 4.5°E and on 23–24 June. For these conditions and at this location, the maximum global radiation estimated by ENVI-met is 981 Wm^{-2}, of which 287 Wm^{-2} (29%) is diffuse radiation. The corresponding incoming longwave radiation estimated by ENVI-met at the upper model level is 423 Wm^{-2}.

For the 95 tropical days examined, the mean wind speed was 2.8 ms^{-1} at a height of 10 m. This value was used in the model runs. An analysis of the wind direction revealed that the dominant direction on tropical days in The Netherlands is around East. Therefore, it was decided to fix the wind direction at 90°. Since each of the eight water bodies is given a NS or EW orientation, respectively (see Section 3.1), the sets of simulations include eight crosswind situations and eight situations with a canyon and water body orientation parallel to the wind.

All simulations start at 6 CET on June 23rd and end at 6 CET on June 24th. Normally, a spin-up time is needed to allow equilibration of T_a and T_w. Since this is not feasible in ENVI-met 4.1.3, the simulations required the initial water temperature to be chosen with care. To estimate a reasonable initial temperature, simulations were performed with the Cool Water Tool (CWT). The

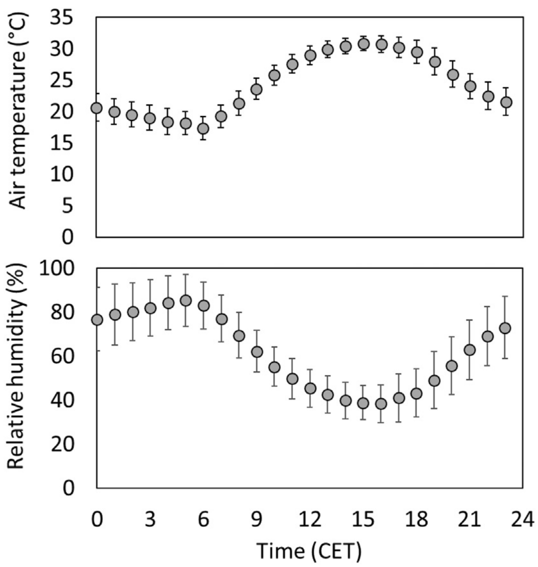


Fig. 3. Average diurnal variation of air temperature (upper) and relative humidity (lower) for 95 tropical days in the period 1981–2010 in The Netherlands.

Table 2
Overview of the tree species considered in the reference situations and the REALCOOL designs.

Species	Height (m)	Diameter (m)	Trunk height (m)	Crown height (m)	Crown shape	Foliage albedo
Field elm A	15	12	5	10	Rectangular	0.18
Field elm B	10	8	4	7	Rectangular	0.18
Field elm C	10	5	3	7	Rectangular	0.18
Black poplar	5	4	1	4	Circular	0.40

CWT is a 1D bulk model designed to assess water temperatures based on the energy budget of the water column as influenced by the weather conditions. The reader is referred to Jacobs et al., 2009, 2014 for a detailed description of the CWT.

Runs were performed with the CWT for a water depth of 2 m, 1 m and 0.5 m, respectively. These depths correspond to the depths of the REALCOOL water bodies (Table 1). For each water depth two CWT runs were performed, with an initial temperature of 28 °C (warm run) and 22 °C (cool run), respectively, and using the daily course of the atmospheric and radiation conditions estimated by ENVI-met, including shading effects. The three sets of simulations with the CWT all covered a period of 10 days, using these conditions repetitively. A separate run was performed for the water body indicated with "Canal 3" since, this water body is shaded during most of the day, unlike the other water bodies. Within 10 simulation days and for all water body depths, results from the cool and the warm run converged towards the same simulated water temperature and its diurnal variation. Therefore, the simulated temperature for the 10th day of the simulation corresponding to the starting time in the ENVI-met simulations, 6 CET, was used as the initial temperature (Table 1).

3.4. Evaluation of the thermal effects

The thermal effects of each water body on its environment and the thermal effects of each REALCOOL design were assessed from three sets of simulations. These simulation sets were named:

1) Reference (REF): simulation of the representative water body and its environment as derived from the inventory of the most frequent Dutch urban water bodies, characterized by the shape and dimensions of the water body and the type of urban environment. The main characteristics of the water bodies are given in Table 1. Tree species used in REF are further specified in Table 2
2) No water (NO): a simulation of the water body environment, in which the area occupied by the water body is replaced by the surface type flanking the water body, which is either grass or red brick (see Table 1);
3) REALCOOL design (DES): a simulation of the design produced for each water body and its environment based on the combination of shading, evaporation, and ventilation (see Table 1 for the design interventions) but also considering typical landscape design parameters (see Section 1).

Differences in T_a and PET between the simulations NO and REF were used to assess the thermal effect of the water bodies on its environment, whereas the differences between DES and REF were used to assess the thermal effects of the REALCOOL designs. T_a is model output that can be used directly. PET was computed from the ENVI-met output using the Biomet utility of the model suite. The PET calculations used in this utility are extensively discussed in Walther and Goestchel (2018). Since only differences are evaluated, both in T_a and in PET, possible bias issues are avoided.

All effects were evaluated at a height of 1.5 m. They were calculated as the average difference in the simulated T_a and PET, respectively, over the water surface and over areas such as quays and sidewalks in between the water body and the buildings, directly bordering the water, hereafter denoted as "street". When selecting these areas, the boundaries of the model domain were avoided, as well as model grid points directly bordering the buildings in the domain or next to the soil-water interface. Apart from comparing averages over somewhat larger domains, spatial patterns of the T_a and PET differences were also examined.

Thermal effects were evaluated at 15 CET on June 23rd and 5 CET on June 24th, because they normally represent the warmest hour during daytime and the coolest hour during night-time in the summer period in The Netherlands, respectively (see Fig. 3). At 15 CET, the incoming solar radiation in The Netherlands for the conditions simulated here is still about 95% of the maximum solar radiation, while the incoming longwave radiation typically reaches its maximum by then.

4. Results

4.1. Thermal conditions of the reference situations

The results of the different simulation runs are presented in tables to provide an optimal overview for the reader. The left parts of Tables 3 and 4 present the average thermal conditions over water and street of the reference water bodies on June 23rd 15 CET and June 24th 5 CET, respectively. T_a in the afternoon varies between 30 and 31 °C and does not vary much between the different water bodies and between water and street. The very small difference between T_a over the water and T_a in the street would be hardly noticeable in practice.

Table 3
Daytime situation T_a and PET from REF over water and street, June 23rd 15 CET, and the temperature differences between NO and REF (NO-REF). When differences are positive, the situation with water is cooler.

Water body	T_a (REF)		PET (REF)		T_a (NO - REF)		PET (NO - REF)	
	Water	Street	Water	Street	Water	Street	Water	Street
Canal 1 EW	30.0	30.3	39.7	36.9	0.8	0.3	2.0	1.4
Canal 1 NS	30.2	30.5	46.7	42.8	0.8	0.6	1.7	1.9
Canal 2 EW	30.3	30.4	40.4	39.3	0.5	0.3	1.1	0.8
Canal 2 NS	30.7	30.9	45.5	45.4	0.6	0.5	1.2	1.2
Canal 3 EW	29.7		36.6		0.4		0.9	
Canal 3 NS	29.7		41.1		0.3		0.8	
Singel 1 EW	30.0	30.4	43.7	41.8	0.5	0.2	0.6	0.5
Singel 1 NS	30.1	30.2	46.8	44.6	0.3	0.2	−0.1	0.5
Singel 2 EW	30.3	30.6	40.8	42.2	0.1	0.1	−0.5	0.2
Singel 2 NS	30.5	30.7	41.6	46.1	0.1	0.1	−0.8	0.1
Ditch 1 EW	30.2	30.4	39.6	43.6	0.1	0.0	−0.4	0.1
Ditch 1 NS	30.3	30.4	48.4	45.3	0.2	0.1	−0.1	0.2
Ditch 2 EW	30.2	30.3	43.7	43.3	0.3	0.1	0.2	0.3
Ditch 2 NS	30.3	30.4	47.0	46.2	0.2	0.1	−0.3	0.3
Pond 1 EW	29.8	30.1	45.5	45.4	0.5	0.2	1.0	0.7
Pond 1 NS	29.7	29.9	46.7	48.0	0.4	0.2	0.6	0.7
Average:(without Canal 3:)	30.1(30.2)	30.4(30.4)	43.4(44.0)	43.6(43.6)	0.4(0.4)	0.2(0.2)	0.5(0.4)	0.6(0.6)

Table 4
Night-time situation T_a and PET (°C) from REF over water and street, June 24, 5 CET, and the temperature differences between NO and REF (NO-REF). When differences are positive, the situation with water is cooler.

Water body	T_a (REF)		PET (REF)		T_a (NO - REF)		PET (NO - REF)	
	Water	Street	Water	Street	Water	Street	Water	Street
Canal 1 EW	19.4	19.4	13.9	14.4	0.0	0.0	−0.1	−0.1
Canal 1 NS	20.1	20.1	16.5	17.2	0.1	0.0	0.0	0.0
Canal 2 EW	19.3	19.3	14.3	14.3	0.0	0.0	0.0	0.0
Canal 2 NS	19.9	19.9	16.6	17.0	0.1	0.0	0.0	0.0
Canal 3 EW	19.2		13.2		0.1		0.2	
Canal 3 NS	19.9		16.4		0.2		0.1	
Singel 1 EW	19.2	19.1	13.1	13.5	−0.3	−0.1	−0.1	−0.1
Singel 1 NS	19.6	19.6	14.5	14.8	−0.1	−0.1	−0.1	−0.2
Singel 2 EW	19.3	19.3	15.6	14.6	−0.2	−0.1	0.0	−0.1
Singel 2 NS	19.4	19.4	16.3	16.1	−0.1	−0.1	−0.1	−0.1
Ditch 1 EW	19.0	19.1	13.9	14.1	−0.1	−0.1	0.0	−0.1
Ditch 1 NS	19.2	19.3	15.1	15.6	−0.1	0.0	−0.1	−0.1
Ditch 2 EW	19.0	18.9	12.7	12.9	−0.2	−0.1	−0.1	−0.1
Ditch 2 NS	18.9	18.9	13.4	13.7	−0.1	−0.1	−0.1	−0.1
Pond 1 EW	19.9	19.8	14.3	14.1	0.0	0.0	0.0	0.0
Pond 1 NS	20.1	20.1	14.8	15.0	0.0	0.0	−0.1	0.1
Average:(without Canal 3:)	19.5 (19.5)	19.4 (19.4)	14.7 (14.6)	14.8 (14.8)	−0.1 (−0.1)	0.0 (0.0)	0.0 (0.0)	−0.1 (−0.1)

The average PET varies between 37 and 48 °C. Its value strongly depends on the area shaded by trees or buildings. The shading pattern also determines if the area over water has a lower PET than the street. For most simulations, PET is somewhat higher over the water area, generally because there are less tree shadows in this part of the domain. The PET values imply that the thermal stress conditions range from very high (35–41 °C) to extreme heat stress (> 41 °C; Matzarakis et al., 1999). During the night, around 5 CET (Table 4), T_a drops by about 10 °C to values between 19 and 20 °C. At the same time, PET drops by nearly 30 °C on average, to values between 13 and 17 °C. These values now indicate the possibility of slight cold stress conditions for people staying outdoors. Local variations in PET decrease because sunshine and shading effects do not occur anymore.

4.2. Thermal effects of the water bodies (NO-REF)

The right parts of Tables 3 and 4 show the average difference in T_a and PET between NO and REF, along with the mean values of these quantities in the averaging domain for REF, at 15 CET on June 23rd and at 5 CET on June 24th, respectively. When differences are positive, the reference situation with the water is cooler. Negative numbers thus indicate a warming effect of the water.

Tables 3 and 4 show that the computed T_a differences due to the presence of a water body are all within 1 °C, both during day and night and both directly over the water and in the streets. During the day, all T_a differences are positive and suggest a cooling effect of the water. During the night, there are more water bodies creating a warming effect than a cooling effect. T_a differences are slightly

Table 5
Thermal effect (°C) of the REALCOOL design: T_a and PET differences between DES and REF (DES-REF) from averages over water and street compared for daytime conditions (15 CET; unshaded columns) and night-time conditions (5 CET; shaded columns). Local maximum PET differences for daytime conditions are also given (Column "Max"). Reference conditions can be found in Tables 3 and 4, respectively.

Water body	Daytime					Night-time			
	T_a (DES - REF)		PET (DES - REF)			T_a (DES - REF)		PET (DES - REF)	
	Water	Street	Water	Street	Max	Water	Street	Water	Street
Canal 1 EW	-0.1	-0.2	-0.3	-0.4	0	-0.1	-0.1	-0.1	-0.1
Canal 1 NS	-0.4	-0.5	-0.1	-0.2	0	-0.5	-0.6	-0.3	-0.3
Canal 2 EW	-0.3	-0.2	-2.7	-0.8	-9	-0.1	-0.1	-0.1	-0.1
Canal 2 NS	-0.6	-0.5	1.7	-0.8	-8	-0.7	-0.7	-0.5	-0.5
Canal 3 EW	0.0		-0.1			0.0		0.0	
Canal 3 NS	0.2		-0.2			-0.1		0.3	
Singel 1 EW	-0.1	0.0	-4.9	0.6	-8	0.1	0.0	0.4	0.5
Singel 1 NS	0.0	0.0	-7.3	-4.9	-9	0.0	0.0	0.7	0.8
Singel 2 EW	-0.1	-0.1	-0.2	-0.5	0	-0.1	-0.1	-0.2	-0.1
Singel 2 NS	0.0	-0.1	2.4	-0.9	-1	0.0	-0.1	-0.5	-0.3
Ditch 1 EW	-0.1	-0.1	-1.4	-1.1	-8	0.0	0.0	-0.2	0.1
Ditch 1 NS	-0.1	0.0	-6.6	-1.4	-9	0.0	0.0	0.4	0.3
Ditch 2 EW	-0.1	-0.1	-5.2	-3.0	-8	0.0	0.0	1.1	1.4
Ditch 2 NS	0.0	0.0	-4.6	-4.1	-10	0.0	0.0	0.7	0.7
Pond 1 EW	-0.3	0.0	-2.5	-2.6	-8	-0.4	-0.1	0.5	0.6
Pond 1 NS	-0.2	-0.1	-2.1	-2.7	-9	-0.4	-0.3	0.9	0.5
Average: (without Canal 3:)	**-0.1 (-0.2)**	**-0.1 (-0.1)**	**-2.1 (-2.4)**	**-1.6 (-1.6)**	**-5 (-6)**	**-0.2 (-0.2)**	**-0.2 (-0.2)**	**0.2 (0.2)**	**0.3 (0.3)**

larger over the water area. However, all T_a differences are quite small, in particular during the night.

According to the temperature differences between simulations without water (NO) and the corresponding reference simulation (REF), the water bodies examined here lead to an average reduction in the afternoon T_a of at most 0.8 °C directly over the water body and 0.6 °C in the streets. The presence of water bodies reduces PET by at most 2.0 °C and 1.9 °C in these areas (Tables 3 and 4). During night-time, a very slight warming effect occurs for most water bodies. The simulations indicate a maximum warming effect of 0.3 °C in T_a.

For the afternoon conditions, average PET differences are somewhat larger than T_a differences, owing to the influence of solar radiation during daytime. The largest cooling at 15 CET is simulated for Canal 1, with average differences in PET of up to 2.0 °C. Whereas the positive T_a differences between NO and REF indicate cooling for all daytime situations, slight warming effects of the water are simulated in terms of PET in 6 out of 16 cases over the water. These six situations refer to comparatively shallow water bodies in the REF situation that have been replaced by grass. During daytime, the strongly transpiring grass surface leads to a slightly lower surface temperature than in the case of the water bodies, resulting in a lower longwave radiation load. This effect obviously does not occur over the street and here, all PET differences indicate a very small cooling effect of the water. At 5 CET most of the PET differences are virtually zero, although there is an extremely slight tendency to warming by the water body.

4.3. Thermal effect of the REALCOOL designs (DES-REF)

Table 5 shows the average difference in T_a and PET between DES and REF, for 15 CET on June 23rd (unshaded left part) and 5 CET on June 24th (shaded right part). Negative numbers indicate a lower temperature in the REALCOOL designs. Because local effects on PET can be much larger than the average effect, especially during daytime, and since the purpose of the designs is also to create local cool spots, typical maximum local PET differences are listed in the column "Max". These maximum values are also communicated in the 3D animations of the designs (http://climatelier.net/projects/research/realcool-really-cooling-water-bodies-in-cities/).

The average differences in T_a due to the thermal effects of the REALCOOL designs are all less than 1 °C. Most of the computed differences are even less than 0.1 °C, both over water and in the street, and at 15 CET as well as at 5 CET. Such air temperature effects will be hardly noticeable by humans. Concerning PET, some of the designs (e.g. Singel 1 NS and Ditch 1 NS) result in average PET differences at 15 CET that are approaching or even exceeding 6 °C. This PET difference is as large as the PET range covering one heat stress class and implies that the thermal effect of the design can change the thermal sensation category by one class. Larger cooling

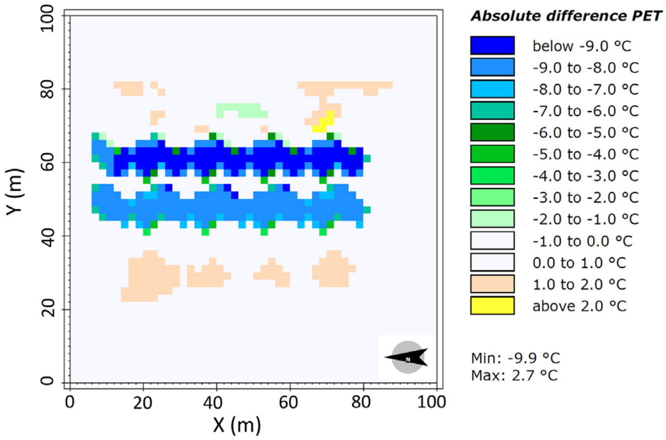


Fig. 4. Computed PET difference for Singel 1, 15 CET: REALCOOL Design (DES) – Reference (REF).

effects tend to occur over the water, in particular when trees are placed close to the water. In the street area, the differences are smaller, but in some situations, they are still over two-thirds of the PET range of the heat stress class (i.e. 4 °C). At 5 CET, the effects are generally small.

For some water bodies (for example, Canal 1, Canal 3 or Singel 2), hardly any difference in PET was obtained, neither during daytime nor during night-time. These water bodies and their environments can be considered as optimal for cooling already. For example, Canal 3 is shaded during most of the day. Adding more shading elements did not further decrease PET substantially. On the contrary, adding elements was found to block the wind. Reduced ventilation will then lead to an increased PET.

The large average PET differences during daytime are interesting as they suggest that water environments as a whole can actually become cooler, although not due to water itself (see Section 3.2). Primarily shading and, to a lesser extent, differences in natural ventilation explain the average differences in PET. Since such effects are often local, the average PET differences are a result of specific spots that have become significantly cooler in the REALCOOL designs. This is confirmed by maximum local PET differences of up to 10 °C.

This is further illustrated in Fig. 4 showing a map of the PET differences between the reference water body and the REALCOOL design for Singel 1. In some spots, PET has been reduced by 9 °C or more, owing to extra trees included in the design. This design provides significant relief from heat at such spots, making the water environment more attractive during heat stress conditions. In 10 out of the 16 designs there are considerable local cooling effects (Table 5), although most of them without a large average effect. The larger local effects are consistently due to shading by trees. For some water bodies, the importance of ventilation could be noticed. Water mist and fountains were not always applied and usually have small, rather local effects on T_a as well as on PET, in the order of 1 °C or less at a height of 1.5 m.

5. Discussion

5.1. Thermal effects of small water bodies and their relevance

The simulations with ENVI-met suggest that small water bodies have a rather small local cooling effect on T_a and *PET* during daytime and an even smaller warming effect during the night. Cooling effects during daytime and warming effects during the night, respectively, are to be expected because of the large thermal inertia of water: water tends to remain cooler than air in periods of warming and the reverse (Gunawardena et al., 2017).

During daytime, the effects on air temperature found here (0.1–0.8 °C over the water, 0.0–0.6 °C at street level) are somewhat smaller than the values extracted from measurements by Völker et al. (2013) for small ponds without a fountain (0.4–1.7 °C), although the ranges overlap. They are in accordance with the cooling effects of small water bodies found in later reports for which, in this study, a median cooling effect of 0.5 °C was derived, with 70% of the water bodies generating cooling effects below 1 °C (see Supplementary Information I for references). The thermal effect on PET found here is well within the range of values reported in the scientific literature for water bodies of similar types and sizes, between a 5.3 °C warming (Klok et al., 2019) and a 5.0 °C cooling (Gomez et al., 2013).

Are the cooling effects of the magnitudes found in this study relevant for designing cooling urban water environments? For daytime, most of the thermal effects are in the order of 0.5 °C PET, in particular in the street area, and are all less than 2 °C. Within the PET evaluation framework one heat stress class extends over 6 °C (Matzarakis et al., 1999). The simulated PET effects cover 1/3 of a PET heat stress class at most. This renders the local cooling resulting from the presence of water irrelevant. It is consequently concluded that the daytime cooling effect of small urban water bodies like the ones considered here may be neglected in practice. Further support to this conclusion can be found in Klok et al. (2019). These authors conducted PET measurements and simultaneous interviews at sites near water and at more urbanized locations, and obtained small differences in T_a and PET. Their results on PET are similar to the ones found in the present study. Moreover, the corresponding thermal perception of respondents interviewed near water bodies did not significantly differ from the thermal perception of respondents at more urbanized spots.

During night-time, the PET differences suggest a slight warming owing to the water body. However, the magnitude of the differences is even smaller than during daytime. A maximum warming of 0.2 °C was found over the water of Singel 1, NS. Nevertheless, one could argue that, during night-time, T_a is a more relevant parameter because most people stay indoors and T_a determines the potential to cool down urban objects including dwellings. In this study, T_a differences are found to be 0.3 °C or less and are considered too small to significantly lead to cooling effects and, thus, not *relevant* in the present context.

To summarize, it is concluded that daytime and night-time thermal effects of water on air temperature and thermal sensation in small urban water bodies may be neglected in climate-responsive design practice. Nevertheless, this also means that implementing small water bodies in urban environments need not be avoided because of night-time warming effects.

5.2. Explaining the small thermal effects of water

To explain the lack of relevant cooling or warming effects by means of water, the theoretical considerations presented in the introduction are taken into account (Section 1). Likewise, other existing frameworks of micrometeorological theory, notably atmospheric boundary layer theory (Stull, 1988; Monteith and Unsworth, 1990; Garratt, 1992; Foken, 2008), should be acknowledged.

First, a significant cooling or warming effect requires a surface-air temperature gradient to exist, along with atmospheric turbulence, so that a noticeable sensible heat flux will develop. In the REALCOOL simulations, the water-air temperature difference during daytime at 15 CET ranges between −5.4 and −8.8 °C, with considerable corresponding negative sensible heat fluxes over the water. During night-time at 5 CET, temperature differences between 1.3 and 5.5 °C develop with corresponding positive sensible heat fluxes. Therefore, the lack of relevant cooling effects at 1–2 m above the surface cannot be explained by the absence of water-air temperature differences and a corresponding sensible heat flux.

Second, the cooling or warming effect needs to reach the relevant height of 1–2 m in relevant areas, often the streets, but sometimes also the zone over the water surface. According to a first-order estimate, the height up to which the effects of surface changes are felt, is typically about 1% of the upwind distance to a surface change (fetch), such as the border between water and land (Garratt, 1992). Even for the largest water body width considered here, 30 or 40 m in the case of the pond (see Table 1), this rule-of-thumb would indicate that the cooling or warming signal is felt only below a height of half a meter in crosswind situations. This height is hardly relevant for human thermal sensation. For situations in which the wind direction is parallel to the water body, the effect will depend on lateral dispersion of the cooling effect, which is in general much less than the advection in the crosswind situation. The intrinsically small cooling effect of the water bodies also explains why there is hardly any difference in cooling effects for the different orientations (NS versus EW).

It is concluded that the urban water bodies considered in this study are too small to result in a relevant cooling effect of water on its surroundings. Only for water bodies that are sufficiently large, cooling effects may become noticeable. According to the aforementioned rule-of-thumb, one would expect water bodies allowing a fetch of ~200 m or more to induce noticeable thermal effects near their borders, as long as air-water temperature gradients are sufficiently large.

It is conceivable that many small water bodies contribute to some large-scale thermal effect (Gunawardena et al., 2017), notably at the scale of large neighborhoods, the whole city or region. At such scales, a significant feedback between the urban canopy layer and the atmospheric boundary layer may occur and reduction of sensible heat input into the atmosphere may become noticeable as a change in the background temperature. At such scales, effects of mesoscale circulations may also become relevant. Such large-scale effects in terms of T_a and PET (cf. Theeuwes et al., 2013) are beyond the scope of the present research but warrant further systematic investigation.

5.3. Evaluation of the REALCOOL designs

From the results obtained in this study and the aforementioned considerations it is clear that for the water bodies considered here, little can be done through design to make water cool its surroundings. However, the space usually available around water bodies often provides opportunities to create cool environments during heat stress periods, irrespective of the thermal effect of water itself. This can be achieved by combining shading, vaporization and natural ventilation strategies around water.

The combination of these strategies across the different prototypes led to local reductions in PET between 1 °C and 10 °C at 15 CET, at 1.5 m (Table 5). The effects are larger above the water surface than in the street level. However, local reductions covering two-thirds or more of a PET class were also simulated over the street near some of the water bodies.

The computed maximum PET reductions are largely due to shading. This explains the fact that the designs have rather small cooling effects during night-time. The crucial role of shading implies that optimization of tree planting is an important strategy to create local cooling spots during daytime taking into account the orientation of the street and water body. The lack of systematic differences of effects between the North-South and East-West orientation in the results is considered to be a success of the optimization. Because effects of cooling measures on shading and ventilation depend very much on orientation, larger differences in PET reduction would be expected without such optimization.

Since enabling natural ventilation was also found to be important, the optimization of cooling by trees and other vegetation should also take into account effects on the wind field. Vaporizing water through fountains (4 m high water jets) and sprays simulated here is less significant as its maximum cooling effect is 0.5 °C on T_a and PET, with very limited spatial distribution.

Taking the aforementioned cooling principles as the starting point, the REALCOOL designs were created within a Research

Through Designing methodology (Nijhuis and Bobbink, 2012; Lenzholzer et al., 2013). Accordingly, the REALCOOL designs were not evaluated on biometeorological effects only, but also on aspects commonly encountered in design practice, such as functionality, aesthetical appeal, maintenance or health effects. Practitioners from various backgrounds involved in this evaluation also considered the psychological 'cooling' resulting from being close to water to be a relevant strategy (Cortesão et al., 2017, 2019).

Such a pluralistic approach means that the REALCOOL designs do not necessarily represent maximum biometeorological cooling effects, but rather optimized perceived cooling effects. The fact that the prototypes combine biometeorological cooling effects with common aspects of design practice, ensures their applicability and eventually broad realization in urban design and landscape architecture. Although the cooling effects are not maximal, the expected broad implementation of the prototypes in real-life will eventually lead to considerable accumulated biometeorological effects throughout a city. In practice, landscape professionals should look at the cooling effects from an urban water environment conceived as a whole instead of the cooling effects from its different components, particularly from water itself. This implies bringing different spatial elements together, among which the water body, as to enable optimal cooling effects and to create more livable cooler urban spaces around water.

6. Conclusions

The present research confirms that water in small urban water bodies, like the ones considered in the present study, has a small thermal effect on its surroundings. As such, its effect may be neglected in climate-responsive design practice. It is concluded that small water bodies are too small to have relevant cooling effects via the water, which is in accordance with the micrometeorological theory on the development of internal boundary layers. This is equally true for possible warming effects, implying that night-time warming by small urban water bodies may also be neglected in practice. Although water per se does not lead to significant cooling effects, implementing small water bodies can still create cooler urban environments. The common openness of urban water bodies provides the opportunity to increase shade by trees and to enable natural ventilation. Interventions based on these two main cooling principles, both leading to favorable changes in daytime PET, can be used in designs aiming to provide cooling during hot days.

Declaration of Competing Interest

None.

Acknowledgements

This work is part of the research program 'Research through Design' with project number 14589, financed by the Netherlands Organization for Scientific Research (NWO), the Taskforce for Applied Research (SIA), and the Amsterdam Institute for Advanced Metropolitan Solutions (AMS). Two anonymous reviewers and the guest editor are acknowledged for their help to improve the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2020.100607.

References

Broadbent, A.M., Coutts, A.M., Tapper, N.J., Demuzere, M., Beringer, J., 2017. The microscale cooling effects of water sensitive urban design and irrigation in a suburban environment. Theor. Appl. Climatol. https://doi.org/10.1007/s00704-017-2241-3.

Bruse, M., Fleer, H., 1998. Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. Environ. Model Softw. 13, 373–384.

Cortesão, J., Lenzholzer, S., Klok, L., Jacobs, C., Kluck, J., 2017. Creating prototypes for cooling urban water bodies. In: Proc. ECLAS Conference 2017, Greenwich, 10–13 September 2017, pp. 349–364.

Cortesão, J., Lenzholzer, S., Klok, L., Jacobs, C., Kluck, J., 2019. Cooling urban water environments. Design prototypes for design professionals. Smart and Healthy within 2 degree Limit. In: Proc. PLEA 2018 Conference, Hong Kong, 10-12 December 2018, (Accepted for publication as extended paper).

De Lange, H.J., 2000. The attenuation of ultraviolet and visible radiation in Dutch inland waters. Aquat. Ecol. 34, 215–226.

Foken, T., 2008. Micrometeorology, 2nd edition. Springer, Heidelberg.

Garratt, J.R., 1992. The Atmospheric Boundary Layer. Cambridge University Press, Cambridge.

Gomez, F., Cueva, A.P., Valcuende, M., Matzarakis, A., 2013. Research on ecological design to enhance comfort in open spaces of a city (Valencia, Spain). Utility of the physiological equivalent temperature (PET). Ecol. Eng. 57, 27–39.

Gross, G., 2017. Some effects of water bodies on the environment–numerical experiments. Journal of Heat Island Institute International 12, 2.

Gunawardena, K.R., Wells, M.J., Kershaw, T., 2017. Utilising green and bluespace to mitigate urban heat island intensity. Sci. Total Environ. 584–585, 1040–1055.

Hathway, E.A., Sharples, S., 2012. The interaction of rivers and urban form in mitigating the urban Heat Island effect: a UK case study. Build. Environ. 58, 14–22.

Höppe, P., 1999. The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment. Int. J. Biometeorol. 43, 71–75.

Huttner, S., 2012. Further Development and Application of the 3D Microclimate Simulation ENVI-Met. Ph.D. Thesis. Mainz University, Germany.

Jacobs, A.F.G., Jetten, T.H., Lucassen, D.C., Heusinkveld, B.G., Nieveen, J.P., 1997. Diurnal temperature fluctuations in a natural shallow water body. Agric. For. Meteorol. 88, 269–277.

Jacobs, A.F.G., Heusinkveld, B.G., Kraai, A., Paaijmans, K.P., 2007. Diurnal temperature fluctuations in an artificial small shallow water body. Int. J. Biometeorol. 52, 271–280.

Jacobs, C.M.J., Ter Maat, H.W., Elbers, J.A., Stuyt, L.C.P.M., 2009. Conditionering van watertemperatuur in buitenvijvers voor aquacultuur. In: Alterra Report. Wageningen Environmental Research, Wageningen (Dutch text).

Jacobs, C.M.J., La Rivière, I.J., Goosen, H., 2014. Cool water tool. Landschap 3, 132–138.
Klok, L., Rood, N., Kluck, J., Kleerekoper, L., 2019. Assessment of thermally comfortable urban spaces in Amsterdam during hot summer days. Int. J. Biometeorol. 63 (2), 129–141. https://doi.org/10.1007/s00484-018-1644-x.
Lenzholzer, S., Duchhart, I., Koh, J., 2013. 'Research through designing' in landscape architecture. Landsc. Urban Plan. 113, 120–127.
Losordo, T.M., Piedrahita, R.H., 1991. Modeling temperature-variation and thermal stratification in shallow aquaculture ponds. Ecol. Model. 54 (3–4), 189–226.
Matzarakis, A., Mayer, H., Iziomon, M.G., 1999. Applications of a universal thermal index: physiological equivalent temperature. Int. J. Biometeorol. 43, 76–84.
Méndez-Lázaro, P., Muller-Karger, F.E., Otis, D., McCarthy, M.J., Rodríguez, E., 2018. A heat vulnerability index to improve urban public health management in San Juan, Puerto Rico. Int. J. Biometeorol. 62, 709–722.
Monteith, J.L., Unsworth, M.H., 1990. Principles of Environmental Physics, 2nd edition. Edward Arnold, London.
Nijhuis, S., Bobbink, I., 2012. Design–related research in landscape architecture. Journal of Design Research 10, 239–257.
Oke, T.R., 1987. Boundary Layer Climates. Routledge, London, UK ISBN 0-415-04319-0.
Paaijmans, K.P., Jacobs, A.F.G., Takken, W., Heusinkveld, B.G., Githeko, A.K., Dicke, M., Holtslag, A.A.M., 2008. Observations and model estimates of diurnal water temperature dynamics in mosquito breeding sites in western Kenya. Hydrol. Process. 22, 4789–4801.
Steeneveld, G.J., Koopmans, S., Heusinkveld, B.G., Theeuwes, N.E., 2014. Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect. Landscape Urban Plan. 121, 92–96.
Stull, R.B., 1988. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Dordrecht.
Sun, R., Chen, L., 2012. How can urban water bodies be designed for climate adaptation? Landsc. Urban Plan. 105 (1–2), 27–33.
Theeuwes, N.E., Solcerová, A., Steeneveld, G.J., 2013. Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. Journal of Geophysical Research: Atmospheres 118, 8881–8896.
Tsoka, S., Tsikaloudaki, A., Theodosiou, T., 2018. Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications–a review. Sustain. Cities Soc. 43, 55–76.
Van Hove, L.W.A., Jacobs, C.M.J., Heusinkveld, B.G., Elbers, J.A., van Driel, B.L., Holtslag, A.A.M., 2015. Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. [special issue: climate adaptation in cities]. Build. Environ. 83, 91–103.
Völker, S., Baumeister, H., Classen, T., Hornberg, C., Kistemann, T., 2013. Evidence for the temperature-mitigating capacity of urban blue space - a health geographic perspective. Erdkunde 67, 355–371.
Walther, E., Goestchel, Q., 2018. The P.E.T. comfort index: questioning the model. Build. Environ. 137, 1–10.