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Spatial Analysis of Water Temperature in a Drinking Water Distribution System for Climate Change Adaptation †

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Abstract: The analysis of the spatial distribution of drinking water temperature (DWT) in the drinking water distribution system (DWDS) can allow for the detection of hotspots and the identification of suitable mitigation interventions to enhance the climate resilience. For this purpose, a water temperature model is implemented in EPANET-MSX and coupled with the hydraulic model of the DWDS in the town of Almere (the Netherlands). This model is then used to assess the effectiveness of a range of interventions against the unwanted water warming under a climate scenario of an extreme air temperature increase in a Dutch summer. Finally, a solution scenario is suggested to comply with the Dutch legislative limit of 25 °C on DWT at the tap.

Keywords: drinking water temperature; drinking water distribution system; spatial analysis; climate change; land cover; pipe insulation; heat extraction

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1. Introduction

Temperature is an important determinant of drinking water quality and cool water, besides limiting the absorption of chemicals and the microbial growth, is also more palatable [1]. Drinking water temperature (DWT) may significantly change between the water treatment plant and the customer's tap for a number of reasons, with the main contributing factor being the soil temperature. DWT in the distribution mains typically quickly approaches the undisturbed soil temperatures because pipe diameters are limited, so water heats up rapidly and often faster than the residence time [2]. In the urban environment, green areas alternate with paved streets and buildings and different underground utilities, such as district heating networks or power lines, populate the subsurface. Both ground cover and anthropogenic heat sources highly influence the soil temperature.

The Netherlands is one of the few countries with a specific regulation regarding DWT. The Drinking Water Directive [3] states that the temperature of drinking water at the customers' tap should not exceed 25 °C. In Dutch urban areas, temperatures in the DWDS easily approach the value of 25 °C during a warmer than average summer. DWTs can also temporally and locally exceed this limit, and in a context of climate change and urbanization it is expected that they will rise [4].

This paper investigates the effect on water temperature (and therefore on water quality) of alternating areas of higher and lower temperatures throughout the drinking water distribution network (DWDN) of Almere's DWDS in the Netherlands, both in the current situation and in an extreme future climate scenario. Four types of interventions to counter the unwanted warming of drinking water are selected and combined together to respect the limit of 25 °C on DWT at the taps even in extreme climate conditions.

2. Materials and Methods

The complete hydraulic model of the DWDS of Almere is available. There are approximately 76 thousand properties connected, which are mainly residential. Water enters the DWDN from two sources modelled as reservoirs from which thermal energy can be extracted [5]. All the simulations are carried out for 3 days, with hydraulic and quality time steps of 1 min. A 48-h warm-up period allows to establish more realistic initial conditions and only the last 24 h are taken into account for the analysis, as this period is considered sufficient if compared to the residence times of water in the network.

2.1. Water Temperature Model

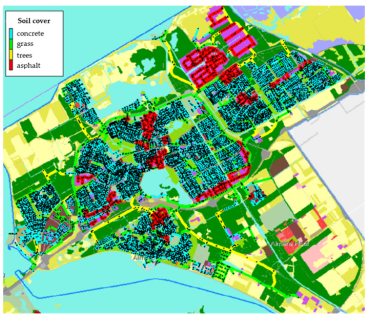
DWT is treated as a water quality parameter and it is calculated in series with the hydraulic variables, thanks to the implementation of the heat transmission model [2] in EPANET-MSX [6]. The water temperature model describes the rate at which DWT varies in the DWDS, depending on the pipe's material, diameter and flow velocity. The equation includes the two phases of heat transfer: by conduction from the outside of the pipe wall to a stagnant liquid film layer between the wall and the fluid medium, and then by convection in the flowing drinking water in the pipe. In the case of insulated materials (e.g., PVC, like in Almere), the rate at which water heats up inside the pipe is mainly determined by its diameter. The boundary conditions of the model are the water temperature at the sources, which are generally measured continuously, and the outer pipe wall temperatures.

2.2. Overall Assumptions

The burial depth of the pipes is considered to be equal to 1 m throughout the network. Soil temperature at the pipe wall is assumed to be a boundary condition for the heat transfer from soil to drinking water, and since soil temperature changes at 1 m depth are much slower than the hydraulic dynamics, the temperature at the pipe wall is assumed to be constant during a 24-h period [2]. An extreme climate scenario of a 4 °C increment in air temperature is supposed for the Dutch city in summer, and given the great likelihood of prolonged heat in the Netherlands [7] it seems reasonable to assume that this increase in ambient temperature will be entirely transferred to the pipe wall. It is supposed that water consumption will not vary much in the future and the DWDS of Almere will have the same layout, so the hydraulics of the system will not change.

2.3. Soil Temperature

A soil temperature map of Almere is not available, so realistic values of soil temperature at 1 m depth on the warmest summer days in the Netherlands (Figure 1b) are derived from measurements and previous analysis on the Dutch territory [2,4,5,8]. The land cover of Almere is assessed thanks to its Corine Land Cover map (Copernicus ESA), which is shown in Figure 1a under the layout of Almere's DWDS.



(**a**)

Soil cover	Pipe wall T (°C)
Concrete tiles/blocks	22
Regular asphalt pavement	25
Grass	19.5
Trees	18.5

(**b**)

Figure 1. (**a**) Almere's DWDS and main soil covers; (**b**) Boundary conditions in the actual scenario.

Four main land covers/uses are identified: residential, commercial/industrial, grass and trees. "Concrete tiles/blocks" are selected as the reference for the residential areas in Almere (typical light traffic solution), while the prevalence of asphalt is assumed in industrial yards and commercial areas.

2.4. Interventions

A range of measures against the unwanted warming of drinking water is proposed, and the impact of each solution is assessed by applying them to their full potential, one at a time, in the extreme climate scenario.

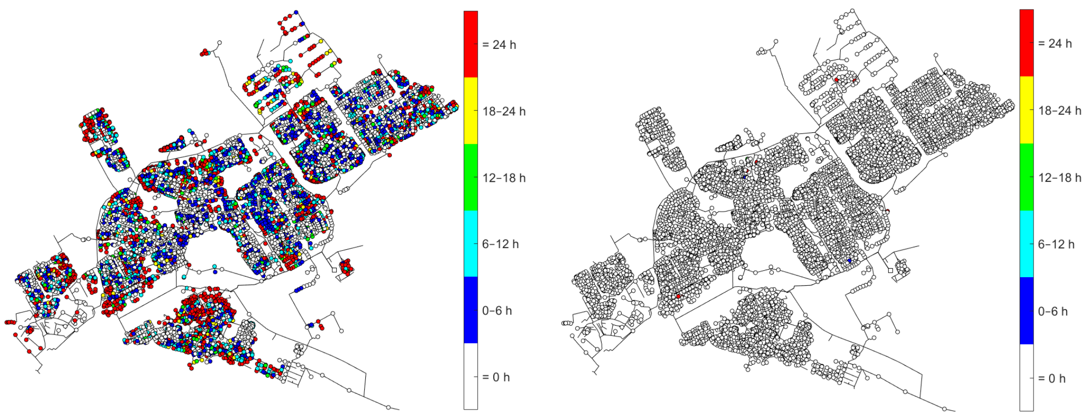
These interventions are listed below:

1. Replacement of regular asphalt and concrete tiles with porous asphalt (PA) and permeable interlocking concrete pavements (PICP). Realistic confidence intervals of soil temperature drop under PA and PICP are assumed based on measurements in the Netherlands [9] and previous analysis of their benefits in terms of stormwater runoff reduction and surface temperature mitigation (PA: 3 ± 0.5 °C; PICP: 2 ± 0.5 °C);
2. Heat extraction from the reservoirs to cool down water at the source (the actual water temperature is restored, so a 4 °C decrement is applied at each reservoir), thus recovering thermal energy that can be delivered to the district heating system [5] or stored in aquifers (ATES) for heating purposes in the winter season [10];
3. Pipe insulation: replacement of pipes with new ones that have the typical multi-layer structure of district heating pipes: a steel carrier pipe, a polyurethane insulation, and a high-density polyethylene outer jacket;
4. Change in land cover: new green areas, which can provide a reduction in the surface and subsurface temperatures and additional benefits on the habitat quality.

3. Results and Discussion

The highest DWTs are observed in industrial and commercial areas, where the presence of asphalt and anthropogenic heat play a decisive role. Luckily, these hotspots hardly influence the surrounding residential areas since the pipeline network is well conceived and water fluxes from industrial areas to residential connections are mostly avoided.

Nevertheless, when an extreme future climate scenario of a 4 °C increment in air temperature in the Netherlands is simulated (Figure 2a), 60% of the total water demand is affected by a temperature above 25 °C, and 19% is supplied above this threshold all day long. Considering both the effectiveness and the practical feasibility, intervention (1) turns out to be the best large-scale solution to improve such a widespread problem. If applied alone, it is not enough to make the system climate-proof since about 4% of the total water demand is still supplied at more than 25 °C.



(**a**) (**b**)

Figure 2. Persistence of DWT above 25 °C in the extreme future scenario +4 °C before (**a**) and after (**b**) the application of the designed mix of interventions.

In addition to that, intervention (2) is applied, and its beneficial effect is only just off the largest diameters (which usually have a transport function), while it rapidly decreases when the cooler water enters the distribution network which consists of smaller diameters and longer residence times [2,5]. Indeed, water can heat up again in interaction with the surrounding soil in the urban environment and the total demand supplied above the legal threshold decreases by less than 1%.

To further cool down DWTs in the network hotspots, intervention (3) is applied by replacing about 8% of the total pipe length. Pipe insulation allows to almost nullify the percentage of water demand affected by a temperature above 25 °C (0.5%).

To address four specific hotspots in industrial areas, in combination with interventions (1)–(3), new green areas are sized to provide enough shade for preventing the excessive warming of drinking water and achieving the final goal of keeping temperatures persistently below 25 °C throughout Almere's network as shown in Figure 2b.

4. Conclusions

This work provides a solution scenario for the unwanted warming of drinking water in the DWDS of Almere and highlights the complexity of combining effective interventions to avoid the health risks related to the proliferation of pathogens and to ensure the palatability of drinking water if an extreme climate scenario occurs.

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