Identifying (subsurface) anthropogenic heat sources that influence temperature in the drinking water distribution system

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Abstract. The water temperature in the drinking water distribution system and at the customers' taps approaches the surrounding soil temperature at ca. 1 meter depth. Water temperature is an important determinant of water quality, since it influences physical, chemical and biological processes, such as absorption of chemicals, microbial growth and chlorine decay. In the Netherlands drinking water is distributed without additional residual disinfectant and the temperature of

10   drinking water at the customers' tap is not allowed to exceed 25ºC. Routine water quality samples at the tap in urban areas have shown locations with relatively high soil temperatures compared to the expected modelled soil temperatures, which indicate so called 'underground hot-spots'. In the last decades, the urban sub-surface is getting more occupied with various types of sub-surface infrastructures and some of these can be heat sources. A few recent studies tackle the anthropogenic sources and their influence on the underground, at coarse spatial scales. Little is known about the urban shallow underground

15   heat profile on small spatial scales, of the order of 10 m x 10 m. Our research focuses on developing a method to identify and to localise potential underground hot-spots at -1.0 m at a small spatial scale. In this article we describe a method to find anthropogenic heat sources that influence temperature in the drinking water distribution system through a combination of mapping urban anthropogenic heat sources, modelling the soil temperature and extensive measurements in Rotterdam.

1 Introduction

20   The temperature of the water at the customers' tap is largely influenced by the soil temperature (T_{soil}) around the distribution pipes. In the Netherlands for drinking water distribution systems (DWDS) at ca. 1 meter depth, it was shown that the water temperature in the DWDS approaches the surrounding T_{soil} (Blokker and Pieterse-Quirijns, 2013; Müller et al., 2014). Water temperature is an important determinant of water quality. In the Netherlands drinking water is distributed without an additional residual disinfectant and the temperature of drinking water at the customers' tap is not allowed to exceed 25 ºC

25   (Drink Water Directive, 2011). During a warm year, 2006, 0.1% of the routine water quality samples exceeded this norm (Versteegh and Dik, 2007). With a rapid increase of the urbanised area, combined with increasing extreme weather events due to climate change, and with more local variations due to the urban heat island effect and with increasing anthropogenic heat emissions (Menberg et al., 2013b), more samples are expected to exceed this threshold in the future.

Although it is clear that there is a relationship between subsurface temperatures and urban development (Grimmond et al., 2010a; Grimmond et al., 2010b), it is difficult to predict these temperatures at a small spatial scale, i.e. on a grid smaller than 10 m x 10 m. Currently, thermal remote sensing is used to observe and investigate the surface urban heat island (SUHI), which refers to the relative warmth of urban surfaces. The SUHI intensity is defined as the difference between the urban and

5   rural surface temperatures (Klok et al., 2012). An analysis of the SUHI in the Netherlands showed the influence of different surface materials and soil types on the surface temperature. The daytime SUHI intensity of Rotterdam can be as large as 10°C, with variations between the different neighbourhoods, creating "hot-spots" within the city. However, these analyses take place at coarse spatial and temporal scales (Agudelo-Vera et al., 2015a), viz. 1 km x 1 km over the course of a year. Schwarz and Manceur (2015) concluded that mitigating the SUHI might lead to actually increasing mean temperatures. This

10   can partly be explained by the fact that heat sources are not clearly identified. Mitigation measurements are effective when the heat sources are identified and localised and the magnitude and temporal variations are assessed. Anthropogenic heat sources are not only above the ground but also underground as shown by a number of German studies focusing on the sub-surface urban heat island (SSUHI) (Menberg et al., 2013a; Menberg et al., 2013b; Müller et al., 2014 and Benz et al., 2015). These sources are often overlooked in the energy balance of urban areas.

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Agudelo-Vera et al. (2015a) reported 7 °C SSUHI based on drinking water temperatures at the tap in Rotterdam during the summer of 2012. The results of the temperatures at the tap, suggest that the SSUHI effect varies within the city and that there are also "hot-spots" in the underground. Blokker and Pieterse-Quirijns (2013) developed a micrometeorology model to predict T_{soil} at various depths as a function of weather and environmental conditions. Agudelo-Vera et al. (2015a) extended

20   the model adding anthropogenic heat sources using literature values reported by Stewart and Oke (2012). Simulations for urban areas suggested a large influence of anthropogenic sources on the T_{soil} on locations with numerous anthropogenic heat sources. Therefore, different areas have a different risk of exceeding the threshold temperature. The average city and the peri-urban neighbourhoods show a low risk of exceeding the temperature limit. However, hot-spots show higher risks in the current situation and even more in the future. Modelling and random sampling are not enough to identify urban underground

25   hot-spots. Identifying the location of the hot-spots and quantifying their intensity is crucial in reducing the risk of exceeding the temperature limit. To comply with the current legislation in the Netherlands, new methods and tools are needed to assess anthropogenic heat sources that influence the temperature in the DWDS and to monitor and predict drinking water temperature in the network at small spatial scales. Finding the location of anthropogenic sources and their influence on T_{soil} will support the selection of site specific mitigation or adaptation measures. This information can also be used during the

30   planning phase for installation/replacement of new pipelines to determine optimal location (x, y and z), considering the existing urban infrastructure and potential increase of temperature due to climate change. This research focuses on developing a method to identify and to localise potential underground hot-spots at -1.0 m at a small spatial scale.

2. Method

This article introduces a method to identify subsurface (anthropogenic) heat sources that influence the temperature in the DWDS, Figure 1. Various data sources were used, given the complexity of the city, see left side, Figure 1. Measurements and simulations were combined to beter understand T_{soil} in cities. Modelling offers the flexibility to simulate a range of urban
5   configurations and measurements were used to validate the simulated temperatures.
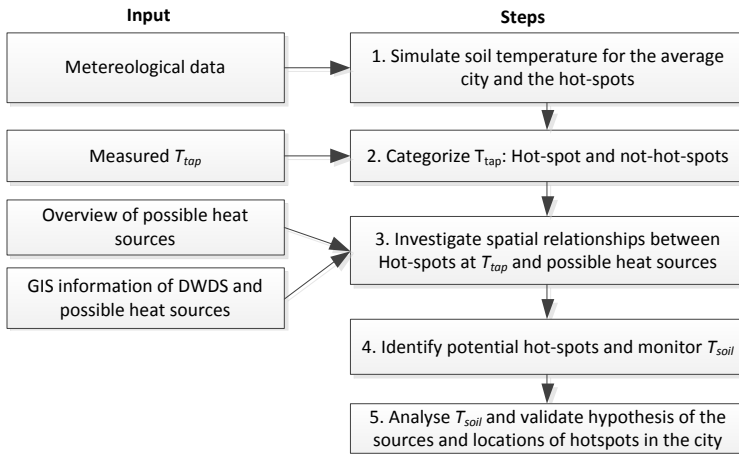
Figure 1 Proposed method to identify underground hot-spots in the city

2.1 Soil temperature simulations

The model developed by Blokker and Pieterse-Quirijns (2013) was extedend to simulate the urban T_{soil}. The extended model
10   describes: i) the heat transfer in the roughness layer (RL), which is driven by the sensible heat fluxes between the atmosphere and the RL and ii) the heat transfer between the soil surface (SS) and roughness layer (RL) ($H_{SS \to RL}$). The energy balance between the RL and the atmosphere was kept from the original model, while the heat balance in the soil surface was complemented with anthropogenic heat emissions (Q_F) and heat storage in the urban environment (ΔQ_s), see eq. 1.

$$\rho_{soil} C_{p,soil} \frac{\partial T_{soil}}{\partial t} = \lambda_s \frac{\partial^2 T_{soil}}{\partial z_s^2} + \frac{1}{\Delta z} (R_{net} + Q_F - \Delta Q_s - LvE - \rho C_p (T_{SS} - T_{RL})/Rg) \qquad (1)$$

15   in which ρ_{soil} [kg/m³] is the soil density, $C_{p,soil}$ [J kg^{-1} K^{-1}] is the soil heat capacity, R_{net} [W m^{-2}] is the net radiation, ΔQ_s [W m^{-2}] is the heat storage on the surface and in above ground urban elements [W m^{-2}] and $L_v E$ is the latent heat flux due to evaporation [W m^{-2}]. $L_v E$ from each surface is calculated with the modified version for urban areas of the Penman-Monteith equation (Grimmond and Oke, 1991) and using empirical values defined by (Berthier et al., 2006; Järvi et al., 2011). A detailed description of the equations is given in Agudelo-Vera et al. (2015a). The heat storage flux is the net uptake or
20   release of energy from an urban system. All surfaces and objects in an area absorb or release energy. The storage heat flux ΔQ_s [W m^{-2}] has been parameterized by (Grimmond and Oke, 1999), eq. 2:

$$\Delta Q_s = a_1 R_{net} + a_2 \frac{\partial R_{net}}{\partial t} + a_3$$

(2)

Where a_1.[-], a_2 [s] and a_3 [W/m²] are empirical coefficients for different surface types. Values of these coefficients for grass are given in (Grimmond and Oke, 1999 and Roberts et al., 2006).

The city of Rotterdam was used as a case study. T_{soil} at -1.0 m in the average city and in the hot-spots were simulated using the extended soil temperature model. The expected maximum daily T_{soil} for the average city ($T_{soil-av}$), and the maximum expected daily T_{soil} for the hot-spots ($T_{soil-hs}$) were determined with the model. A period of 16 year was simulated, (2000 – 2015), to identify inter-annual variations. The input data reported by Blokker and Pieterse-Quirijns (2013) was used, plus the data reported in

Table 1.

Table 1 Additional input data for soil temperature model

Variable	Definition	Unit	Peri-urban	Average city	Hot-spots
α	thermal diffusion coefficient	10^{-6} m²/s	0.35	0.6	1.3
z_0	roughness length	m	0.95	0.95	0.95
Q_F	anthropogenic heat	W/m²	90	100	150
$a_1{}^*$	empirical coefficient	-	0.8	0.8	0.8
$a_2{}^*$	empirical coefficient	s	6	30	42
$-a_3{}^*$	empirical coefficient	W/m²	50	100	120

$\alpha = \lambda_{soil} / \rho_{soil} \cdot Cp$. Where: λ_{soil}: Thermal conductivity [W/m.K], ρ_{soil}: soil density [kg/m³] and Cp: soil heat capacity [J kg^{-1} K^{-1}].

* Values are fitted using data of measurements conducted in 2012.

2.2 Clasification of water temperature measurements at the tap

Temperature measurements from 2008 – 2015 at the tap (T_{tap}) during the summer were analysed. T_{tap} measurements were then classified into four categories, using T_{soil} simulations, as described below and in Figure 2.
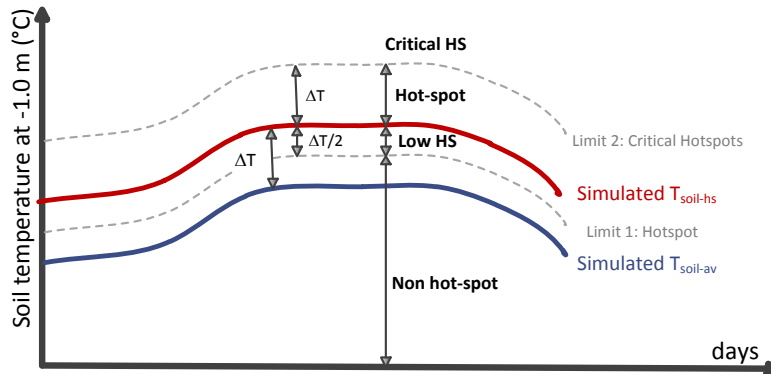
Figure 2: Schematic representation of the hot-spots categories

1) Non hot-spot: $\qquad T_{tap} < \dfrac{T_{soil-av} + T_{soil-hs}}{2}$

2) Low hot-spot: $\frac{T_{soil-av}+T_{soil-hs}}{2} \leq T_{tap} < T_{soil-hs}$

3) Hot-spot: $T_{soil-hs} \leq T_{tap} \leq T_{soil-hs} + (T_{soil-hs} - T_{soil-av})$

4) Critical hot-spot $T_{tap} > T_{soil-hs} + (T_{soil-hs} - T_{soil-av})$

5   For the GIS analysed, the tap temperatures were plotted together with the spatial information from anthropogenic heat sources (from step 1). Data from the location of the DWDS was analysed together with the information regarding the height of the buildings. Using a GIS tool the solar radiation onto each pipe location was determined. Additionally, the hot-spots identified from the T_{tap} measurements and the potential heat sources were plotted. Proximity analyses were used to determine the relationship between the heat sources and the four hot-spots categories. Areas with high density of hot-spots were

10 identified to narrow down the search. For these specific locations a measurement set-up was proposed to validate the hypotheses.

2.3 Soil temperature measurements in Rotterdam

To validate the hypothesis, T_{soil} measurement were conducted in Rotterdam. The measurement locations were defined Based on the analyse of T_{tap}, the location of the anthropogenic sources and the expert knowledge of two representatives of the

15 drinking water company. A characterisation of the locations was done using the information described in Table 2. A detail of the T_{soil} measurement installation is given in Figure 3.
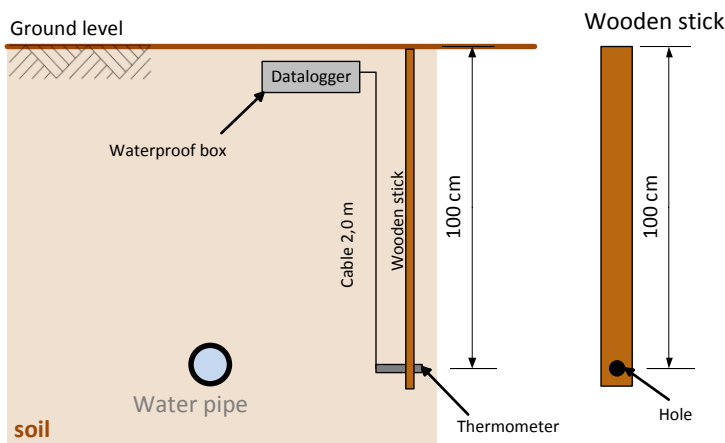
Figure 3: Detail of the soil temperature measurement installation

3. Results and discussion

3.1 Simulating T_{soil} in the average city and in the hot-spots

Figure 4 shows T_{soil} simulated for the months: June, July, Augustus and September between 2000 and 2016 for the average city and for the hot-spots, using hourly meteorological data from the Royal Netherlands Meteorological Institute (KNMI, 2016). The simulations for the average city show 15 °C $< T_{soil-av} <$ 25 °C, and for the hot-spots 17 °C $< T_{soil-hs} <$ 27 °C. The 25°C threshold temperature is approached only in very hot summers in the average city, while it is exceeded in the hot-spots in eight of the 16 simulated years, with a total of 75 days in 16 years. In a cold and wet year, 2011, a maximum $T_{soil-hs}$ of 23°C was simulated.
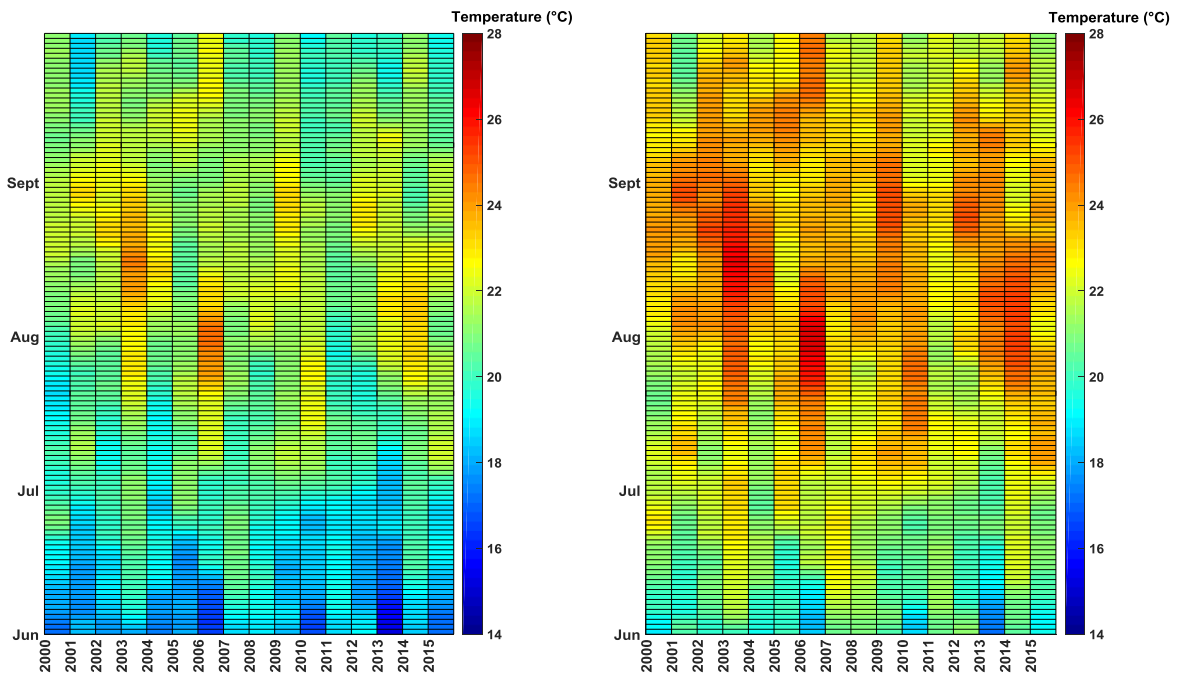
Figure 4: Simulations of T_{soil} at -1.0 meter in the average city (left) and in the hot-spots (right) from 2000 until 2015 during the months: June, July, August and September

3.2 Analysis of the measurements of the water temperature at the tap

The measurements of the water temperature at the tap were categorized as: Non hot-spot, Low hot-spot, hot-spot and Critical hot-spot. Figure 5 shows the results. The number of hot-spots is relatively small compared with the number of non hot-spots. It is important to highlight that current sampling of the locations is random (in time and place) and not focused on finding the warmest locations.
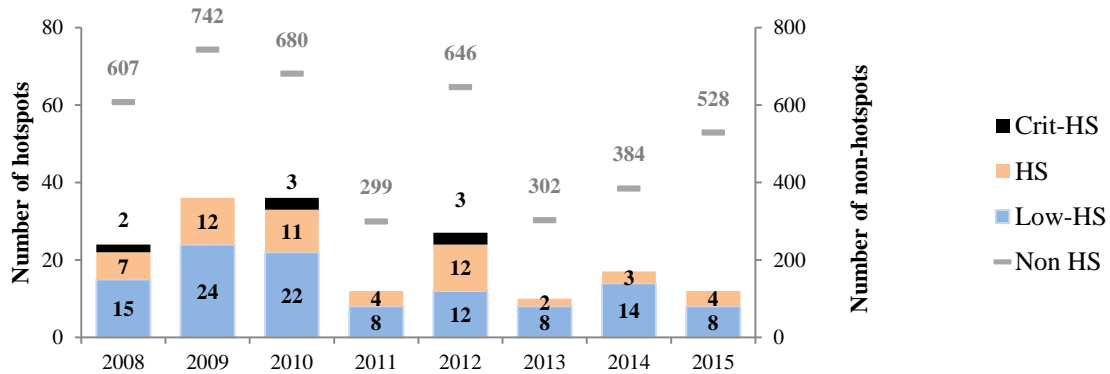
Figure 5: Overview of the categorisation of the measurements of the water temperature at the tap per year

3.3 Identification of the heat sources

Potential factors or heat sources that can influence T_{soil} were identified based on scientific literature and experience of representatives of the Dutch drinking water companies. They were categorised between above and under ground. The factors

5   above ground are: none or little shade, high density of buildings and/or reflection of buildings facades, waste heat of special buildings or infrastructure. Factors under ground are: district heating systems, buried high power cables, basements / underground parking facilities, tunnels (Metro infrastructure), sewer networks, Aquifer Thermal Storage (ATES) systems & underground heat storage infrastructure.

3.4 GIS information to asses solar radiation in the DWDS and potential heat sources

10   Figure 6 shows a detail of the GIS analysis, where the possible heat sources, shade conditions and the categorised tap samples are plotted. A proximity analysis was conducted to identify spatial relationships between hot-spots and sources. Although, no direct relationship was found by evaluating the location of highest and coldest temperature at the tap, it can be seen than changes in the water temperature can change within a few meters. Additionally areas with higher occurrence of hots-spots can be identified. The location of most of the T_{tap}, which are randomly selected by the water company and not

15   directed to identify the hot-spots. In the future a more targeted selection can be determined.

3.5 Soil temperature measurement plan

Five neighbourhoods were selected to perform T_{soil} measurements for three months (18 July until 9 October 2016). To observe different heat sources, 44 locations were selected based on the proximity to the possible heat sources identified in Table 2. The autumn of 2016 was abnormally warm, air temperatures above 30°C were recorded on 20 July, 24 and 25

20   Augustus and 13 and 14 September. The measurements of T_{soil} at -1.0m showed a difference of up to 10°C between the locations. The simulated range shows a good agreement with the measured T_{soil}. The most significant indicators for the

presence of a hot-spot (locations above Tsoil-av) were: no shade, tiles as top layer and the presence of at least one anthropogenic heat source (Agudelo-Vera and Blokker, In preparation).

Figure 6: Detail of the GIS analysis for a small area of the case study

Table 2 Overview of the characterisation of the monitored locations

Shade condition		Shade		Partial shade		No shade	
Urban type		Residential		Industrial	Urban square		Park
Top layer		Tiles			Grass		
Anthropogenic sources	Above ground	Hospital	Laundry facilities	Reflection of buildings	Swimming pool	High density of buildings	Electrical distribution substations
	Under ground	Metro	High tension cable	ATES		Parking	District heating systems

3.6 Outlook and future research

Although today the risk of exceeding the threshold temperature is still low, with climate change, increasing urbanization and increasing pressure on the underground the risk is expected to increase. Therefore, it is important to be able to anticipate and

10   take measures to avoid the creation of new hot-spots and to control the current ones or to avoid hot-spots location when installing the drinking water pipes. "Greening" the cities has been the suggested "strategy" to make climate change proof cities, although this might not always be the best strategy. To achieve climate proof cities, have to include next to climate change, the urban configuration above and below the surface. In busy urban areas, congested with underground infrastructures, several heat sources can be buried and be overseen during urban planning strategies to cope with climate

15   change. By mapping the anthropogenic sources, customized measures can be taken based on the heat sources.

Determining T_{soil} in urban areas is important for different aspects; for instance to predict infrastructure performance, e.g. pavement durability (Diefenderfer et al., 2006), coupled heat pumps (Garcia Gonzalez et al., 2012) and district heating systems (De Pasquale et al., 2017) and to determine the drinking water temperature (Blokker and Pieterse-Quirijns, 2013).

Managers of a specific infrastructure cannot implement the required measurements that often involve urban planning. Collaboration between urban planners and infrastructure managers is crucial to create climate change proof cities. While mitigation measures can reduce the impact of the SSUHI and climatic changes, these measures take time to implement and to have an impact. In the meantime, there is a need to monitor drinking water temperature in the DWDS and prevent drinking

5 water quality problems during heat waves, especially in the high density urban areas.

This research focused on the Netherlands, with a moderate maritime climate with cool summers and mild winters. A similar approach can be used to identify hot-spots in cities worldwide. Earlier research has shown that it is possible to use weather forecast information as an "early warning system" to predict temperature in the DWDS from changes in weather and climate

10 (Agudelo-Vera et al., 2015a; Agudelo-Vera et al., 2015b). Understanding the spatial distribution of anthropogenic heat sources and using models to simulate T_{soil}, will help managers to more specifically anticipate to extreme weather events, such as heat waves.

4. Conclusion

Underground heat sources have been overlooked, although their impact on infrastructure and the urban climate can be

15 significant. This article introduced an applied method to localise underground hot-spots in the city. Given the complexity and heterogeneity of urban soils and the unknown interactions of buried infrastructure in the city, finding these hot-spots needs a combination of various approaches, e.g. modelling T_{soil} temperatures, using alternative data sources, e.g. temperature at customer's taps and performing GIS analysis on shade and reflection off buildings and on the proximity between potential sources and measured higher drinking water temperatures.

20 ## 5. Acknowledgements

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