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 drinking water at the customers’ tap is not allowed to exceed 25 ºC. 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 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

The temperature of the water at the customers’ tap is largely influenced by the soil temperature (Tsoil) 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 Tsoil (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 (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 \(10 \times 10\) 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 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 \(10^\circ\)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 \(\times 1\) km over the course of a year. Schwarz and Manceur (2015) concluded that mitigating the SUHI might lead to actually increasing mean temperatures. This 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 subsurface 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.

Agudelo-Vera et al. (2015a) reported \(7^\circ\)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 \(T_{\text{soil}}\) at various depths as a function of weather and environmental conditions. Agudelo-Vera et al. (2015a) extended 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 \(T_{\text{soil}}\) 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 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 \(T_{\text{soil}}\) will support the selection of site specific mitigation or adaptation measures. This information can also be used during the 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 better understand $T_{soil}$ in cities. Modelling offers the flexibility to simulate a range of urban configurations and measurements were used to validate the simulated temperatures.

\begin{align*}
\rho_{soil} C_{p,soil} \frac{\partial T_{soil}}{\partial t} &= \lambda_s \frac{\partial^2 T_{soil}}{\partial x^2} + \frac{1}{\Delta z} \left( R_{net} + Q_F - \Delta Q_s - \rho C_p (T_{SS} - T_{RL}) / Rg \right) \\
\end{align*}

in which $\rho_{soil}$ [kg/m$^3$] 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, $\Delta Q_s$ [W m$^{-2}$] is the heat storage on the surface and in above ground urban elements [W m$^{-2}$] and $L_E$ is the latent heat flux due to evaporation [W m$^{-2}$]. $L_E$ 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 release of energy from an urban system. All surfaces and objects in an area absorb or release energy. The storage heat flux $\Delta Q_s$ [W m$^{-2}$] has been parameterized by (Grimmond and Oke, 1999), eq. 2:

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 extended to simulate the urban $T_{soil}$. The extended model 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) ($H_{SS,RL}$). 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 ($\Delta Q_s$), see eq. 1.

\begin{align*}
\rho_{soil} C_{p,soil} \frac{\partial T_{soil}}{\partial t} &= \lambda_s \frac{\partial^2 T_{soil}}{\partial x^2} + \frac{1}{\Delta z} \left( R_{net} + Q_F - \Delta Q_s - \rho C_p (T_{SS} - T_{RL}) / Rg \right) \\
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in which $\rho_{soil}$ [kg/m$^3$] 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, $\Delta Q_s$ [W m$^{-2}$] is the heat storage on the surface and in above ground urban elements [W m$^{-2}$] and $L_E$ is the latent heat flux due to evaporation [W m$^{-2}$]. $L_E$ 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 release of energy from an urban system. All surfaces and objects in an area absorb or release energy. The storage heat flux $\Delta Q_s$ [W m$^{-2}$] has been parameterized by (Grimmond and Oke, 1999), eq. 2:
\[
\Delta Q_s = a_1 R_n + a_2 \frac{\partial Q_{net}}{\partial t} + a_3
\]

(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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Unit</th>
<th>Peri-urban</th>
<th>Average city</th>
<th>Hot-spots</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>thermal diffusion coefficient</td>
<td>(10^{-6}) m²/s</td>
<td>0.35</td>
<td>0.6</td>
<td>1.3</td>
</tr>
<tr>
<td>(z_0)</td>
<td>roughness length</td>
<td>m</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>(Q_F)</td>
<td>anthropogenic heat</td>
<td>W/m²</td>
<td>90</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>(a_1)</td>
<td>empirical coefficient</td>
<td>-</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>(a_2)</td>
<td>empirical coefficient</td>
<td>s</td>
<td>6</td>
<td>30</td>
<td>42</td>
</tr>
<tr>
<td>(-a_3)</td>
<td>empirical coefficient</td>
<td>W/m²</td>
<td>50</td>
<td>100</td>
<td>120</td>
</tr>
</tbody>
</table>

\(\alpha = \lambda_{soil}/\rho_{soil} \cdot C_p\). Where: \(\lambda_{soil}\): Thermal conductivity [W/m.K], \(\rho_{soil}\): soil density [kg/m³] and \(C_p\): soil heat capacity [J kg⁻¹ K⁻¹].

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

### 2.2 Classification 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: 
\[ T_{tap} < \frac{T_{soil-av} + T_{soil-hs}}{2} \]
2) Low hot-spot: \[ \frac{T_{\text{soil-av}} + T_{\text{soil-hs}}}{2} \leq T_{\text{tap}} < T_{\text{soil-hs}} \]

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

4) Critical hot-spot: \[ T_{\text{tap}} > T_{\text{soil-hs}} + (T_{\text{soil-hs}} - T_{\text{soil-av}}) \]

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 \(T_{\text{tap}}\) 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 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, \(T_{\text{soil}}\) measurement were conducted in Rotterdam. The measurement locations were defined based on the analyse of \(T_{\text{tap}}\), the location of the anthropogenic sources and the expert knowledge of two representatives of the drinking water company. A characterisation of the locations was done using the information described in Table 2. A detail of the \(T_{\text{soil}}\) measurement installation is given in Figure 3.
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 $15 \, ^\circ\text{C} < T_{soil-av} < 25 \, ^\circ\text{C}$, and for the hot-spots $17 \, ^\circ\text{C} < T_{soil-hs} < 27 \, ^\circ\text{C}$. The $25\, ^\circ\text{C}$ 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 $23\, ^\circ\text{C}$ 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](image)

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.
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 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 assess solar radiation in the DWDS and potential heat sources

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 that changes in the water temperature can change within a few meters. Additionally areas with higher occurrence of hot-spots can be identified. The location of most of the $T_{tap}$, which are randomly selected by the water company and not 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 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 $T_{\text{soil-av}}$) were: no shade, tiles as top layer and the presence of at least one anthropogenic heat source (Agudelo-Vera and Blokker, In preparation).

![Image of a GIS analysis map]

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

<table>
<thead>
<tr>
<th>Shade condition</th>
<th>Shade</th>
<th>Partial shade</th>
<th>No shade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban type</td>
<td>Residential</td>
<td>Industrial</td>
<td>Urban square</td>
</tr>
<tr>
<td>Top layer</td>
<td>Tiles</td>
<td>Grass</td>
<td></td>
</tr>
<tr>
<td>Anthropogenic sources</td>
<td>Above ground</td>
<td>Hospital facilities</td>
<td>Reflection of buildings</td>
</tr>
<tr>
<td></td>
<td>Under ground</td>
<td>Metro</td>
<td>High tension cable</td>
</tr>
</tbody>
</table>

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

Determining $T_{\text{soil}}$ 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 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 (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 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.

5. Acknowledgements

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